Extreme Temperature Events in Australia

Blair C. Trewin

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

October 2001

School of Earth Sciences

The University of Melbourne

This copy printed on acid-free paper

Declaration

This is to certify that:

(i) the thesis comprises only my original work except where indicated in the preface,
(ii) due acknowledgement has been made in the text to all other material used,
(iii) the thesis is less than 100,000 words in length, exclusive of tables, maps, bibliographies and appendices.

26/10/2001

Abstract

A high-quality set of historical daily temperature data has been developed for Australia. This data set includes 103 stations, most of which have data from the period between 1957 and 1996, and some for longer periods. A new technique, involving the matching of frequency distributions, is presented for the adjustment of temperature records for inhomogeneities at the daily timescale, and this technique is used in the development of the data set. A number of additional findings are presented on the impact of changing times of observation and accumulation of observations over periods longer than one day on the Australian temperature record.

This data set was used for an extensive study of extreme temperature events in Australia/ Widespread changes in the frequency of extreme temperature events in Australia were found over the 1957-1996 period. These changes were found both by an analysis of trends at individual stations and by analysis of spatial averages of indices of extreme temperature. In general, increases were found in the frequency of high maximum and high minimum temperatures, and decreases in the frequency of low maximum and low minimum temperatures. The changes were greatest for low minimum temperatures and least for high maximum temperatures, and were generally greatest in winter. The greatest decreases in the frequency of extreme low minima were found in Queensland. The trends were not universal, with trends opposite to those for Australia as a whole being found in some regions in some seasons.

It was found, after examination of several possible models, that the frequency distribution of Australian daily maximum and minimum temperatures was best represented by a composite of two or three Gaussian distributions with different parameters. Using this model, it was found that the observed changes in temperature primarily resulted from changes in the means of the component distributions, indicating that the changes resulted principally from overall warming of the atmosphere rather than changes in circulation or air-mass incidence.

The relationship between the frequency of extreme temperatures and the Southern Oscillation Index (SOI) was examined, with strong relationships being found in some seasons in many parts of Australia for most extreme variables, particularly high maximum temperatures. The weakest relationships were found for low minimum temperatures. Many of these relationships, except in winter, were as strong (or stronger) with the value of the SOI one season previously as they were with the SOI of the current season, indicating potential useful skill in the forecasting of seasonal frequencies of extreme temperatures in many cases.

Preface

Section 6.5.3 is based on work originally submitted as part of my B.Sc. (Hons) thesis, *The Frequency of Threshold Temperature Events*, at the Australian National University in 1993. It has not been published elsewhere.

The remainder of the thesis is my original work carried out during the period of Ph.D candidature.

The following sections of my thesis have substantially appeared in other publications prior to submission of this thesis:

Section 3.2

Trewin, B.C. and Trevitt, A.C.F. 1996. The development of composite temperature records. *Int. J. Climatol.*, 16, 1227-1242.

Chapter 5

Trewin, B.C. 1997. Another look at Australia's record high temperature. *Aust. Meteor. Mag.*, 46, 251-256.

Acknowledgements

Reaching the point at which my formal education ends, a quarter-century (less a few days) after it began, the time comes to reflect on those who have contributed to it, both during the years of writing this thesis and in the years before.

Starting with the last seven years, my foremost thanks go to my two co-supervisors, Ian Simmonds and Neville Nicholls. I could not have hoped for two more supportive or knowledgeable supervisors, even when they must have been wondering if I would ever make it to the finish line. Special thanks must also go to Neil Plummer, as supportive a 'boss' as could be imagined, and recently Anne Brewster, who has managed to put up with one highly distracted employee during the final sprint.

Many people in the Bureau of Meteorology, which has hosted me throughout the period of my candidature, have been extremely helpful. David Jones, for always steering me around the computer system when things were getting tight (among other things), Alex Kariko, for doing much the same thing during my years in BMRC (as well as keeping us all sane), and Dean Collins, Paul Della-Marta, Andrew Watkins and Gary Weymouth, for pointing me in the right direction when it was needed. I have also had very useful dealings with many of the Bureau's Regional staff, and in particular Terry Bluett in New South Wales (on observation and site standards), Doug Shepherd in Tasmania (on data quality) and Alan Kernich in South Australia (for providing the data which formed the basis of section 3.3).

A particular mention must go to the staff of the National Meteorological Library, and, especially, Andrew Hollis, Laurie Long and Jill Nicholls. Whenever I needed an obscure document, they were always on hand to help track it down (and it will be evident from a close inspection of the thesis that they managed to track down many very obscure documents), as well as being great friends during the last seven years.

At this point, I also reflect on those who laid the groundwork for my present course. Four people, in particular, have been responsible for steering me towards this goal. Firstly, Roger Badham, an old neighbour from Canberra, who sparked my interest in the weather by giving me a raingauge for (I think) my sixth birthday; then, two teachers at Canberra Grammar, Geoff Clarke and the late John Allen, for letting me loose on enough information to rekindle that interest as a serious academic pursuit, and, finally, Chris Trevitt, who became my Honours supervisor at ANU. It was ten years ago, almost to the day, that a chance meeting resulted in his offering me a research project to work on; it was the thrill I, as a second-year undergraduate, got out of doing real, original research, that convinced me to turn climatology into a long-term career.

Finally, my thanks go to those who have shared my life along the way. Firstly, to my parents, Dennis and Annette, who will, I am sure, get as much of a thrill out of this moment as I will, and my sister, Cassie, who is just embarking on a Ph.D of her own. Secondly, to those who have managed to cope with living with the occasionally irregular habits of a research student through the last seven years; Sue Trewin and David and Victoria Rayson for the first four years, and Jamie Potter for the last two. Thirdly, to the many great friends I have, at work, in orienteering, and elsewhere, without whom it would have been impossible to retain my sanity during some of the more strained moments.

This work was partially funded by an Australian Postgraduate Award. The Bureau of Meteorology hosted me throughout the period of my study and provided considerable in-kind support, especially in computing.

Blair Trewin
26 April, 2001

Table of Contents

Listing of tables and figures

Tables

Figures

9.2h. SOI tercile 1/tercile 3 event frequency ratio, minima below 10^{th} percentile, lag

List of acronyms and abbreviations

AMO	Airport Meteorological Office
AP	Airport
ARMA	Auto-regressive moving average
ARS	Agricultural Research Station
AWS	Automatic weather station
CET	Central England Temperature
CO_2	Carbon dioxide
ENSO	El Niño - Southern Oscillation
EOF	Empirical orthogonal function
GCM	General circulation model
GCOS	Global Climate Observing System
GHCN	Global Historical Climatology Network
GSN	GCOS Surface Network
IPCC	Intergovernmental Panel on Climate Change
LST	Local standard time
MO	Meteorological Office
NSW	New South Wales
NT	Northern Territory
PO	Post Office
RMS	Root-mean-square
RO	Regional Office
SA	South Australia
SC	Soil Conservation Research Station
SI	Statistical interpolation
SOI	Southern Oscillation Index
USHCN	United States Historical Climatology Network
UTC	Universal Coordinated Time
WA	Western Australia
WMO	World Meteorological Organization

Chapter 1

Introduction and literature review

1.1. Introduction

Climate and weather have always been a critical influence upon life on Earth. At the most basic level, it is climate that is, often, the most important influence determining which species can exist in a given location. It is no less vital in the context of the history of human civilisation. Societies have flourished in places where the climate was favourable to them, and societies have been wiped out (as was the Viking settlement in Greenland (Lamb, 1977)) when the climate shifted against them. Climate is still, despite all the advances in technology and knowledge that have occurred over the last 10,000 years, the most vital influence on agriculture, without which human civilisation cannot exist. As the range of human activities has broadened, so has the number of different ways in which climate affects us, from a heatwave causing the spot price of electricity to skyrocket to a drought leading to a famine in Africa.

Through much of the period in which the climate has been studied scientifically, the dominant paradigm has been that of an essentially static climate, with any fluctuations being, in essence, perturbations from the long-term 'normal' climate. It is only in relatively recent times that the idea of a change in the underlying climate on the decadal-to-centennial timescale (as opposed to changes on geological timescales), and, in particular, that the idea of a possible human influence on global climate, has entered the scientific consciousness. The possibility of global warming as a result of increasing concentrations of carbon dioxide in the atmosphere made increasingly frequent appearances in the scientific literature in the late 1970s, but it was not until 1985, when the WMO's Villach Conference discussed the matter, that it became a central issue of scientific debate and, soon afterwards, public policy. Since then climate change has become one of the world's leading environmental issues, and, accordingly, a scientific and political apparatus has been established, under the auspices of the United Nations, in an attempt to cover the field; the Intergovernmental

Panel on Climate Change (IPCC) on the scientific side, and the Framework Convention on Climate Change on the political side.

One of the major goals of the scientific process, as represented by the IPCC reports, has been to obtain an accurate picture of how climate has varied over history, and, in particular, since the establishment of instrumental records. Originally, much of the effort was directed at changes in the mean values of climate elements – in part because those are the data which are most readily available, on both a global and local scale.

The mean, however, in itself is an abstract concept. Many of the limits to human activity are set by the occurrence of rare events, from the crop whose poleward limit is set by the boundary of where frosts occur to the land that is left undeveloped because it is flooded every few years. Consequently, increasing attention is being given to the consideration of trends in the occurrence of extreme events. This is reflected by the IPCC reports, which act as an indicator of the fields in which scientific activity is occurring. The 1990 report devoted only one paragraph to extreme temperature events (and then only on the seasonal timescale); the 1995 report devoted half a page; the 2001 report two pages, with seventeen papers cited.

This thesis concentrates on one type of extreme climatic event, namely extreme temperatures. This has been a relatively neglected field until very recently, particularly in Australia, where the emphasis on the study of climate has always been on rainfall. Given Australia's history this is understandable. Throughout much of the period of European settlement, drought, or its temporary absence, has been a defining theme in the history of the interaction of Australians with the land, and it is certainly true that rainfall is the most important climatic influence on agricultural production in Australia. Temperature is also an important climatic influence, in the Australian context as well as elsewhere. Frost, particularly in southern Australia, is a significant potential risk to crops, as was illustrated by the estimated loss of several hundred million dollars in Western Australia, western Victoria and southern New South Wales in the spring of 1998 (Bureau of Meteorology, 1998a). The demand on public utilities – electricity, gas and, to a lesser extent, water - is very temperature-sensitive; the estimation of the likely peak demand is critical in planning required production capacity. With the lead times required to build such capacity, climate change must be considered in any rational planning process. (With the spot price of electricity in South Australia increasing 25-fold during a February 2000 heatwave (http://www.nemmco.com.au), and the increasing use of weather derivatives – of which 98% are temperature-related (Stern, 2001) there is money to be made as well – something which is always a powerful impetus for interest in a topic).

Before proceeding further, it is useful to define what an extreme temperature is for the purposes of this study. In a statistical sense, the theory of extreme values is most often used to refer to the highest or lowest value that a variable is expected to reach in a given period of time. This is certainly a valid type of extreme to be investigating in a climatic context. A second type of extreme event is the breaching of a particular threshold – say, the occurrence of a temperature above 35°C or below 0°C. The likely or observed frequency of such an event does not form part of the statistical theory of extreme events. However, in climate this is arguably the more important type of event, especially in agriculture, where the breaching of a critical threshold can be more important than the ultimate value reached. If a plant is going to be killed by a temperature of -1°C, then it is no more dead at -10°C, and hence the probability of reaching -1°C is more important than the ultimate lowest temperature.

Primary consideration in this thesis will be given to events which involve the crossing of a threshold. It is only in the last few years that changes in the frequency of these events have been considered in any depth, either in Australia or elsewhere, as evidenced by the contrast between the 1990 IPCC report (where no such study was cited) and the 2001 report (where 17 separate studies were cited). The original goal was to trace and analyse the frequency of these events throughout the period of the Australian instrumental climatic record. As will be explained later, the availability (or lack thereof) of data in a usable form has placed constraints on the ability to cover this full time period as closely as would have been desirable; once the older data becomes more accessible there is ample scope for this study to be extended.

Two additional types of extreme events which are not considered in this study were the occurrence of extreme mean seasonal temperatures and heat and cold waves (usually defined as a number of consecutive days with temperatures above or below a certain threshold). Both types of events can have substantial consequences in fields such as agriculture (Mearns et al., 1984; Parry and Carter, 1985) and human health and mortality (Andrews, 1994; Changnon et al., 1996) and are of considerable potential interest.

1.2. The structure of this thesis

In order to determine what changes the climate has undergone over the period of instrumental record, it is necessary to be able to obtain records which can be viewed with confidence. This is not a trivial matter, and the development of a high-quality data set for use in the analysis in this thesis forms a major part of it.

Chapters 2, 3 and 4 are devoted to the development of a data set for use in the study. Chapter 2 deals with the availability of data, and the selection of a station network which adequately reflects the full range of Australian climate without unduly sacrificing the quality of the data used. The compilation of a high-quality daily data set of this type, adjusted for inhomogenities, is a task that has not, to the author's knowledge, been undertaken anywhere else in the world for any region. A number of new techniques used in the development of such a set are presented in Chapters 3 and 4.

In Chapter 5, a case study is presented to illustrate the impact that a failure to maintain standard observation conditions can have on a specific observation, namely the highest recorded Australian temperature at Cloncurry.

Chapter 6 describes a model for the frequency distribution of maximum and minimum temperature in Australia. As will be discussed later in this chapter, much of the literature on extreme temperature events is based on the assumption, implicit or explicit, that these variables follow the Gaussian (normal) distribution. It is shown that this assumption is not valid in many Australian climates, and an alternative model is proposed. The concept of linking this alternative frequency distribution model to air mass incidence is explored, but with difficulties in developing such a relationship on an objective basis.

In Chapter 7, the trends in the frequency of extreme temperature events at specific stations are analysed. These trends are compared with changes in the parameters of the frequency distributions developed in Chapter 6, in order to gain a deeper understanding of the influences on the occurrence of extreme temperatures, and how these influences are changing in importance with changes in the climate.

Chapter 8 draws the results presented earlier into a coherent national picture, by analysing spatial averages of extreme event frequency over Australia and regions within it and examining their trends.

Chapter 9 reports on the relationship between the frequency of extreme temperature events and a well-known influence on Australian climate on the seasonal-to-interannual timescale: the El Niño-Southern Oscillation phenomenon. Strong links are found in many parts of Australia.

The thesis concludes with Chapter 10, which is a summary and conclusion.

1.3. The background to this study

1.3.1 The development of climatological data sets

1.3.1.1. Global and regional data sets

As the importance of an accurate picture of past climate has increased, an increasing amount of attention has been given to the development of high-quality data sets of mean temperature on the annual or seasonal timescale. There has been considerable activity since 1980, both in the compilation of data sets for the analysis of global or regional climate, and in the development of techniques for the detection of inhomogeneities in climate records.

At the broadest scale, there have been two major attempts since 1980 to develop a historical data set for the calculation of global mean temperatures. There were a number of attempts to achieve this prior to 1980, most notably by a number of Russian authors (whose results remained largely unknown to the western scientific community for some time). Jones et al. (1982) review these, and then present the data set most commonly used in analyses of global temperature today. This set has been refined and updated through the years, with the use of more advanced methods of interpolating data to fixed grid points, the incorporation of additional data which were not available for use in the original set, and improved assessment of the homogeneity of the station data used (Jones et al. 1986a, b; Jones 1988, 1994). The second major data set has been that of Hansen and Lebedeff (1987, 1988). The major differences of substance between the two sets are that the Jones set includes marine data, whereas the Hansen and Lebedeff set includes only data from land-based meteorological stations, and that the Hansen and Lebedeff set makes use of more incomplete data series (in order to extend the station coverage) than the Jones set does. Nevertheless, a comparison of the two sets (Hansen and Lebedeff, 1987) reveals that they are broadly in agreement.

A recent paper (Peterson et al., 1998a) applies a different approach to the collation of a global data set. They use first differences of monthly mean temperatures, rather than the temperatures themselves, as the data set, taking, as the source data set for their gridded analyses, the difference at each station between the mean temperature in a given month and that in the same month of the previous year. This allows the inclusion of a broader range of data, using stations with relatively short records that were not considered for inclusion in the Jones or Hansen/Lebedeff sets. Peterson et al. find that the trends in global mean temperature derived from these three data sets are similar, but that they differ in characteristics such as the interannual variability of the data. This has implications for the statistical significance of the observed trends, as well as, potentially, for the occurrence of extreme events.

The best-known attempt to develop a data set of temperature for a specific region has been the United States Historical Climatology Network (USHCN) (Karl et al., 1990). This data set, of monthly mean temperature data for the continental United States, has been the subject of many analyses of various types. The concept of a data set for the analyses of historical climate has been extended globally, with the development of the Global Historical Climatology Network (GHCN) (Vose et al., 1992; Peterson and Vose, 1997), and, most recently, the GCOS Surface Network (GSN), which is an initiative of the World Meteorological Organization. Although neither the USHCN nor the GHCN are regional or global means *per se*, both are compilations of high-quality station data which provide the foundation for the calculation of regional or global means, and act as a valuable set of source data for other analyses.

There have been a number of other data sets compiled at the national and regional scale. The best-known of these is the Central England Temperature series, which was first developed by Manley (1953), and extended by Manley (1974) and Parker et al. (1992). These papers discuss in some detail the creation of the series, which extends back to 1659. Whilst some of the earliest years in the series have data estimated from documentary evidence or data from non-British sites, there is an unbroken instrumental record of some kind since 1723. In particular, considerable attention is given to the comparability of eighteenth-century records to those measured using present-day standards.

The USHCN and GHCN have concentrated on the use of historical data. This has meant that these networks, especially the global one, have focussed on monthly mean temperature data, as that is the form of temperature data most readily available for the greatest number of stations for the longest period of time. Whilst many stations have records of mean monthly temperature going back into the nineteenth century – and it is an element whose value has been exchanged on a routine basis by WMO member countries – compiling data sets of mean monthly maximum and minimum temperature has been difficult, for three principal reasons:

- in many countries, mean daily (and hence monthly) temperature is calculated by means of an algorithm using the temperature at fixed hours (rather than the mean of the maximum and minimum as is the case in Australia, the United Kingdom and the United States), and daily maximum and minimum temperature were not measured (or measured, but not archived), until some time during this century (Nordli, pers.comm.). Where the mean was calculated using temperatures at fixed hours, the algorithm for doing so has changed in many countries through the course of their observational history (Heino, 1994).

- mean monthly maximum and minimum temperatures at stations were not routinely exchanged by WMO members until the early 1990's (Peterson and Vose, 1997).
- as a result of the data not being regularly exchanged, access to historical maximum and minimum temperature data is dependent on the national meteorological service concerned – many of which levy charges beyond the reach of scientific researchers (Hulme, 1994; Karl and Easterling, 1999)

The position is even worse for records of daily maximum and minimum temperature. Attempts are being made at WMO level to make such data available for GSN stations to the scientific community, but it is likely that this will take some time to reach fruition, with only a limited number of countries having contributed data at the time of writing (Diamond, 2001).

A long-term series of regional daily mean temperature data was compiled by Parker et al. (1992), who built on the previously-mentioned monthly series of Manley (1953, 1974) by creating a set of daily Central England temperatures from 1778 to 1991, adjusted (by a flat amount in each month) such that the monthly means of the daily values would match the monthly series.

The principal Australian set of high-quality national temperature data is described in Torok and Nicholls (1996) and (in more detail) in Torok (1996). This set is of mean annual maximum and minimum temperature data, and covers most of Australia for the period since 1910. Whilst the annual timescale makes this set, *per se*, of limited use for this study, many of the same principles have been used in the selection of stations, as described more fully in Chapter 2. Torok and Nicholls also describe the trends of mean temperature that were found using this data set.

A number of studies also concentrate on specific stations with very long records. Examples of these are the long records at Toronto, Canada (Crowe, 1990), Sitka, Alaska (Parker, 1981) and Uppsala, Sweden (Bergström, 1990). As with studies undertaken with the Central England Temperature series, these papers concentrate on the inclusion of the maximum possible amount of data (extending backwards in time), and the techniques required to make those early observations comparable with the data recorded at the present-day stations in those locations. Limited attention has been given to the homogeneity of the series since the stations shifted to being something akin to current standards.

As all of these data sets, except for the daily Central England Temperature series, are at the monthly, seasonal or annual timescale, none of them are of much use in an examination of extreme events of the type examined in this thesis, which are on the daily timescale. As described in section 1.3.2., such work as has been carried out on extreme events has been carried out using a variety of national data sets.

1.3.1.2. Data quality and homogeneity

The quality and homogeneity of climatic data sets has been recognised as being of importance for many years. Brooks (1948) was one early author to recognise this, and Manley (1953), as noted earlier, considered the question in the context of the incorporation of pre-19th century data into a long-term climatic series. Whilst this importance has been noted from time to time, it is only in comparatively recent times that the homogeneity of data has been systematically incorporated in studies of climatic trends. It is an ongoing issue: as Karl et al. (1995b) state, "virtually every [climate] monitoring system and data set requires better data quality, continuity and homogeneity if we expect to conclusively answer questions of interest to both scientists and policy-makers".

This was especially true within Australia, where the first studies of temperature over large areas which incorporated adjustments of data sets for inhomogeneities did not appear until the early 1990s (Torok, 1996), although there had been earlier studies at individual stations (e.g. Shepherd, 1991). Some papers acknowledged the problem of data reliability (e.g. Coughlan, 1979), but did not attempt to correct for it. A consequence of this is that a number of studies (e.g. Deacon, 1953; Balling et al., 1992), using unadjusted data, reached conclusions about Australian temperature trends which were heavily influenced by non-climatic influences (which will be discussed in more detail in Chapters 3 and 4), such as changes in instrument shelters during the early twentieth century and the widespread movement of stations from town centres to airports.

Non-Australian data sets have included adjustments for inhomogeneties, but have done so inconsistently. In some data sets (e.g. Hansen and Lebedeff, 1987) the process merely involves the removal of gross errors and stations with clearly identifiable inhomogeneities, such as stations in cities influenced by intensification of urban heat islands. On the other hand, the various Jones et al. data sets have included adjustment of station data for inhomogeneities, using a subjective assessment of temperature differences between station pairs. The USHCN and GHCN have also incorporated considerable adjustment for inhomogeneities, using techniques outlined in Karl et al. (1986, 1988) and Karl and Williams (1987). In the case of the USHCN, the stations incorporated have all been given an objective rating, based on factors such as the length of record, the proportion of missing data, the number of adjustments required to the data, the confidence level attached to these adjustments, and the consistency of the station's data with its neighbours.

There has been considerable further work in the last decade; an extensive review has been carried out by Peterson et al. (1998b).

The production of a homogeneous data set involves three major steps: the identification of potential inhomogeneities, the determination of their statistical significance, and the adjustment of data to eliminate the inhomogeneities. Methods of compilation of adjusted data have concentrated on the identification of inhomogeneities and the determination of their statistical significance, including statistical techniques for the detection of discontinuities in time series, experimental comparisons of data taken under differing conditions, and the examination of documentary evidence (metadata) pertaining to the station(s) concerned. Somewhat less attention has been given to methods of adjusting data once inhomogeneities are identified, although Karl and Williams (1987) consider the question extensively. In the context of this study, this is a substantial issue and one which is discussed more extensively in Chapter 4. Nicholls (1995) noted that it is often more difficult to construct long-term, homogeneous data sets for climate extremes than it is for means.

Statistical detection of discontinuities

The detection of discontinuities in time series is a subject which has received extensive attention in the statistical literature. Early examinations of the problem in the climatological context were those of Merriam (1937) and Kohler (1949). Both used double-mass curves, and Merriam also used plots of accumulated departure of variables from the climate normal. Another test which was regularly used was a test for the randomness of the residuals of departures of a variable in individual years or months from the climate normal (WMO, 1966).

Two significant advances were made by Potter (1981) and Alexandersson (1986). Both pointed out difficulties with 'traditional' methods of detecting discontinuities, and both used the concept of a 'reference series'. In this technique, rather than a time series being tested in isolation, the series which is tested is that of the difference between that time series and an approximately homogeneous set of aggregated data which is highly correlated with the series under examination – for example, a weighted mean of neighbouring stations. The desirable attributes of a 'reference series' are discussed more extensively in Chapter 4. The concept of a reference series was developed further by Peterson and Easterling (1994).

Potter, in an example using precipitation data from a set of 19 stations, used the arithmetic mean of the data from the 18 stations not being tested as a reference series. He also minimised the impact of potential inhomogeneities on the reference series by carrying out a number of iterations; series found to contain inhomogeneities were removed from the reference series, and the test carried out again. He then used the test of Maronna and Yohai (1978) to detect inhomogeneities in the difference series, although he notes that this test assumes that the time series is not autocorrelated and is normally distributed. (As discussed in Chapter 6, this assumption is doubtful in the case of temperature data, but is less problematic for a difference series). He noted that the double-mass test carried no indicator of the statistical significance of an inhomogeneity, while a test on the randomness of residuals can indicate that a statistically significant inhomogeneity has occurred in a time series, but gives no indication of the timing or magnitude of the inhomogeneity.

Alexandersson, who was dealing with precipitation, created a reference series as a weighted mean of neighbouring station data, with the weighting function being a distance-based exponential formula developed such that it would normally approximate the squared correlation of the data at the neighbouring station with that at the test station (r^2). He then generates the comparison series for testing by taking the ratios, rather than the differences, of the test series to the reference series (a practice specific to precipitation). Discontinuities in the comparison series are then located using likelihood ratios. Like the Potter test, this assumes that the comparison series is normally distributed, and it also assumes that the variance of the comparison series remains constant on either side of a discontinuity. Alexandersson and Moberg (1997) and Moberg and Alexandersson (1997) later adapted this technique to annual mean temperatures in the course of preparing a homogenised gridded air temperature data set for Sweden.

Crummay (1986) produced a reference series, in his study of the homogeneity of United Kingdom temperature and sunshine data, by using principal component analysis to estimate the mean annual value at the station of interest. He then used a student's t test to test for statistically significant changes between 5-year periods in the difference between the station's mean temperature or sunshine and the estimated value.

Easterling and Peterson (1992,1995) used a two-phase regression model to locate inhomogeneities in a comparison series, by dividing the series into two parts and fitting regression lines to each part; the point of division with the smallest combined sum of residuals from the two parts was then flagged as the site of a potential inhomogeneity, and its significance tested. This was the method used in this study, and details of its application, including the compilation of a reference series for comparison, are given in Chapter 4. A similar technique was used by Taubenheim (1989), whilst a multiple linear regression technique was used by Vincent (1998).

Inhomogeneities become much more difficult to detect by statistical methods if they occur at a similar time across a network, as spatial intercomparison is lost as a potential method of detection. Examples include changes in the formula used for the calculation of daily mean temperature (as occurred in various Scandinavian countries

(Heino, 1994)) or nationwide changes in the type of instrument shelter used, as occurred with the change from wall-mounted screens to free-standing Stevenson screens in Denmark around 1920 (Frich, 1993), the introduction of the Stevenson screen in Australia (Torok and Nicholls, 1996), or the change to an electronic temperature measurement system at co-operative stations in the United States in the 1980's and 1990's (Quayle et al., 1991). Frich suggests that a possible technique for detecting inhomogeneities of this type is to compare variables with another variable that may not be affected by the change involved (for example, comparing cloudiness with diurnal temperature range, or mean maximum and minimum temperatures with the mean temperature at a fixed hour). In some cases, especially in remote areas or on isolated islands, there will be no comparison data to allow the compilation of a reference series. Rhoades and Salinger (1993) described a technique for detecting inhomogeneities in a single-station time series.

Instrument and site comparison

Where it is known that a change has taken place at a site – or across a network – a method for assessing whether a significant discontinuity has occurred, and if so, its magnitude, is to carry out a comparison of measurements under the old and new conditions, either *in situ* or at a dedicated experimental site. There are numerous examples of this in the literature, for example, for wind (Logue, 1986), humidity (Skaar et al., 1989) and precipitation (Sevruk and Hamon, 1984). It is now Australian Bureau of Meteorology policy (Evans, pers. comm.) to carry out comparison measurements for at least two years, if at all possible, in the event of any significant change at any Reference Climate Station. Similar policies are also in place in many other countries (Peterson et al., 1998b).

Side-by-side comparisons of instruments or instrument exposure have been conducted for many years. Two examples of comparisons of various types of instrument shelters were carried out in Britain between 1868 and 1870 (Laing, 1977) – an experiment which led to the Meteorological Office and the Royal Meteorological Society recommending the Stevenson screen as a standard – and at Adelaide, where a Glaisher stand and Stevenson screen were operated in parallel between 1887 and 1947 (Richards et al., 1992; Nicholls et al., 1996b). Many such experiments have been carried out internally within national meteorological services, without the results being documented in the external scientific literature. Nordli et al. (1997) present a review of instrument comparison experiments carried out in Scandinavia, after describing the evolution of screen types in the countries concerned, whilst Parker (1994) presents a more global review.

Metadata

A more recent development in the detection of discontinuities in climate records is the use of metadata. Whilst information about the siting of, and instruments at, meteorological stations has been collected for as long as the data itself (for example, handwritten 'instrument journals' from the late 19th and early 20th century, containing details of the instruments installed at meteorological stations, exist for several Australian states and are held in the National Meteorological Library), it is only in relatively recent years that a concerted effort has been undertaken in various countries to compile metadata systematically for a climate network and apply this knowledge to an assessment of the homogeneity of the records within that network. Torok (1996) relied extensively upon metadata in order to compile his high-quality set of annual mean Australian temperatures, as did Karl et al. (1990) in the compilation of the USHCN.

Metadata are a powerful tool for the identification of a potential discontinuity, as documentary evidence of a station move or instrument change on a specific date is unquestionable evidence of a potential discontinuity on that date, whereas statistical techniques can often only identify the approximate timing of a discontinuity. The problem then becomes one of determining whether such a discontinuity has a statistically significant impact on the climate record, and, if so, what adjustment is appropriate. Easterling et al. (1996) suggest that, where metadata exist, the most effective scheme for the production of homogeneous data sets involves the combination of metadata and statistical schemes.

The principal limitations of metadata are that they are often unwieldy to work with, and that they are not necessarily complete. Whilst some nations have made efforts towards making their metadata available in digital form (Frich et al., 1996; Arnfield, 2001), much of it is only available in paper form, is not archived systematically or in a single location, is rudimentary (Shein, 1998), or contains much irrelevant information which makes the extraction of useful data time-consuming (Peterson et al., 1998b). Whilst these problems could all be overcome given sufficient effort and resources, a more intractable problem is that metadata is not necessarily complete (and, by its nature, it is impossible to know definitively that it is complete). This may be because of the loss of documents – for example, much information pertaining to stations in the Northern Territory was destroyed as a result of Cyclone Tracy (Bureau of Meteorology, 1992) – but is more commonly because the information was never collected in the first place. This applies more to some aspects than to others. As an example, in Australia, historically, matters involving the expenditure of public money , such as the supply of instruments, tend to be better-documented on station history files than matters that do not, such as site changes or conditions (Kariko, pers. comm.).

1.3.2. Extreme temperature events

Extreme events have been considered in the meteorological and statistical literature for much of this century, but, as noted earlier, it is only in very recent times that serious attention has been given to trends in the frequency of extreme events, and to likely changes in their frequency associated with more general changes in the climate.

The statistical theory of extreme events, where these events are defined as being the highest or lowest values in a time series, has been well-developed since Fisher and Tippett (1927) developed three distributions for use in estimating the likely frequency of a given extreme event, the particular one being used depending on whether the variable is bounded or unbounded. This was further developed by Gumbel (1958). The techniques developed by Fisher and Tippett, and Gumbel, have been extensively used in meteorology. While these applications have mainly been in the field of precipitation (and consequently hydrology), there have been a large number of studies in which Gumbel's theory or a variation on it has been used in order to determine expected extreme maximum and minimum temperatures for a given return period over a region. Dury (1972) carried out such an analysis of expected maximum temperatures for a variety of return periods, from 1.58 to 100 years, for Australia. Other studies of this type have been carried out for such regions as Great Britain (Jenkinson, 1955), the United States (Court, 1953), India (Jayanthi, 1973), Belgium (Sneyers, 1969) and Greece (Flocas and Angouridakis, 1979). A variation on this theme has been the assessment of the likely return period of a specific event; Policansky (1977) examined the estimated return periods of mean temperatures recorded during the (very cold) winter of 1976-77 in the eastern United States.

Reviews of the statistical theory of extreme values in the meteorological context were carried out by Tiago de Oliveira (1986) and Katz and Farago (1989). Tiago de Oliveira concentrates upon the practical aspects of the theory and its application, without discussing the limitations of the theory in the meteorological context. Katz and Farago point out that most of the frequency distributions fitted to meteorological data converge towards Fisher and Tippett's Type I (unbounded) distribution in the extreme-value case. They also note that, although many meteorological time series are autocorrelated and therefore the observations are not independent (a necessary condition, in theory, for the Type I distribution to be a valid model for extreme values of the data), the autoregressive-moving average (ARMA) process used by some authors (as discussed more extensively in Chapter 6) to model autocorrelated meteorological time series falls within the 'domain of attraction' of the Type I extreme value distribution. He only mentions in passing the problem of seasonality in the statistical theory of extreme values, as applied to meteorological data.

Another type of study that has been carried out for many years has been the compilation of static climatologies of the occurrence of extreme or threshold events. An early Australian example was the work of Foley (1945), who compiled an extensive climatology of the frequency of frosts, using various threshold definitions to define severity of frost, in addition to analysing the synoptic conditions under which frosts occurred and the impacts on specific crops. Similar analyses of frost frequency have been carried out in such regions as England (Lawrence, 1952), Java (Domrös, 1976), Hungary (Fekete, 1987), southern India (von Lengerke, 1978) and New Zealand (Goulter, 1991).

Climatologies of the frequency of very high temperatures have been less common, but are still relatively widespread in the literature: examples are the works of DeLisi and Shulman (1984) and Petrovic and Soltis (1985).

Tattelman and Kantor (1976a, b) produced maps, covering the full Northern and Southern Hemisphere, of the estimated 1, 5, 10, 90, 95 and 99 percentile values of hourly temperatures over the course of the year, using a regression relationship they derived between the frequency of such hourly temperatures and monthly mean maximum and minimum temperatures, using data from those relatively few regions of the world where hourly temperature data are readily available. A less obvious type of threshold event, the mean annual frequency of freeze-thaw cycles, was analysed for the United States by Hershfield (1974).

A specific type of threshold event (where a 'threshold event', a term used extensively in the remainder of this thesis, is defined as the occurrence of a temperature above or below a specified threshold) that has aroused particular interest for many years is the date of the first and last days below or above a certain threshold – for example, the length of the season during which the temperature is above a certain critical level. This (often described as the 'growing season') is an important parameter in regions where temperature renders certain types of agriculture marginal, as is the case in many parts of North America and northern Europe. Examples of studies of this type are those of Davis (1972), who attempted to define the onset of spring by using an air temperature surrogate for the occurrence of earth temperatures above 6.1°C (43°F), an agriculturally important variable, and analysed the frequency distribution of these dates, and that of Bootsma and Brown (1989), who sought to develop a climatology of spring and autumn freeze risk in Ontario, Canada by deriving a regression relationship between the dates of last spring and first autumn freeze and a number of other long-term station-specific variables.

A number of studies have examined trends in parameters relating to the frequency of extreme or threshold temperature events. The results from these are mixed, depending on the region under review (in the case of regional studies) and the period over which the trend was measured – a number of studies carried out at the end of the cooling over the northern hemisphere between 1940 and 1975 produced different results to those carried out for periods starting earlier and/or finishing later. This aspect was explicitly studied by Downton and Miller (1993), who found that the observed trends in winter temperatures in Florida differed substantially depending on the period under review – and the parameter(s) considered.

Examinations of trends in the length of the growing season, defined in various ways (usually in the form of the period for which the mean temperature is above a certain threshold), or alternatively, the date of occurrence of the first or last frost, have been carried out by a number of authors. Overall, the trends defined depend on the region, the period under consideration and the definition of a growing season used – Brinkmann (1979) found opposite trends in the length of growing seasons calculated for the same locations using different definitions. Lamb (1977) found that the growing season at Oxford had increased in length by 1-2 weeks between 1900 and 1940, then had declined to near its 1900 level by 1975. Jones and Briffa (1995) found that, despite an increase in mean annual temperature over the region of about 1°C over the period, there was little evidence of any significant change in the length of the growing season, or its starting or finishing dates, over the former Soviet Union over the 1881-1989 period, due to the warming in mean temperatures being concentrated in the winter months. Bootsma (1994) found a trend towards lengthening of the frost-free and growing-season length over the last 100 years at three stations in western Canada, but a mixture of trends in eastern Canada.

Karl et al. (1991) examined the highest and lowest temperatures recorded in each season and year (an inherently noisy indicator) at each station within a network in the United States and the former Soviet Union. They found that the difference between high and low extremes decreased in most seasons over the period examined, significantly so over the former Soviet Union at the annual timescale. Over the period between 1936 and 1986, no trend was observed in the annual extreme maximum in the former Soviet Union, but an upward trend of 1.6°C/100 years was observed in the annual extreme minimum. Over the United States between 1911 and 1989, the annual extreme maximum decreased by 0.2°C/100 years, and the annual extreme minimum increased by 0.2°C/100 years. A similar study was carried out by Tuomenvirta et al. (2000), who examined trends in the value of the highest and lowest recorded temperature in each year at a number of Scandinavian stations. They found few consistent trends, noting that the series suffered from a lack of homogeneity, but in general observed that these extremes roughly followed the (generally increasing) trend of seasonal mean temperatures.

Trends in the frequency of threshold events have become a point of scientific interest much more recently – as evidenced by the fact that no study in this field was cited in the 1990 IPCC report (although many have been in the 2001 report). There have been numerous works on a regional scale, but the first major attempt to obtain results over a large part of the world came with the Workshop on Indices and Indicators for Climate Extremes, which took place in Asheville in June 1997 (Karl et al., 1999). The papers presented at this workshop, of which several are discussed in the following paragraphs, represented a collection of analyses of threshold event frequencies over a number of regions.

In addition, it was recommended at this workshop (Folland et al., 1999) that a number of indices of extreme (or threshold) temperature events be developed and implemented on a global basis, based on data from a selection of stations in the GCOS Surface Network (GSN) (Peterson et al., 1997). The recommendations for these indices were of a generalised form and it was noted that further investigation was required to determine specific details of optimal indices.

The major published works in this field in Australia are those of Plummer (1995) and Stone et al. (1996). Whilst Stone et al. state that their primary aim was to 'develop a system for seasonal forecasting of frost likelihood' (their results in this respect will be discussed more extensively in Chapter 9), they carried out a study of trends in the frequency of frosts, and the date of the last frost, over the last century at nine stations in inland Queensland and northern New South Wales, using seven thresholds in steps of 1°C from -3°C to 3°C. They found a downward trend, significant at the 95% level, in the number of frosts at six of the nine stations, and a significant trend towards an earlier date of last frost at five of those stations, the major exceptions being the stations of Moree and Dubbo. One caveat to these results is that, although some care was taken in the selection of stations to eliminate data of poor quality, the data were not adjusted for potential inhomogeneities.

Plummer (1995) used a network of 40 stations to examine changes in temperature variability and the frequency of extreme events in Australia between 1961 and 1993. His study took two separate approaches. He examined extremes of maximum and minimum temperatures by finding the 5th, 50th (median) and 95th percentile values of daily temperature anomalies for each individual season during the period of record. He then examined the trends in these percentile levels over that period, combined into time series for six regions of Australia. He found that the temperature at each percentile level had risen in most regions and seasons, with the 5th and 50th percentiles increasing more rapidly than the 95th percentile level, but that few of the changes were statistically significant.

He also examined changes in intraseasonal variability of temperature on a variety of timescales from 1 to 30 days, by calculating the differences in mean temperature between successive periods and examining trends in those values. He argues that the mean interdiurnal temperature differences reflect trends in high- and low-frequency temperature variability more accurately than do the standard deviation of daily temperature, because the latter measure does not distinguish adequately between variability on the low- (10-30 day) and high-frequency (1-5 day) timescales. He found few significant trends in any of these variables over the 1961-93 period, with small upward trends in the intraseasonal variability of daily maximum and mean temperatures at most timescales, and similarly small downward trends in the intraseasonal variability of daily minimum temperatures.

These results were incorporated in the more broad-ranging study of Karl et al. (1995a), which investigated intraseasonal variability in a similar manner in Australia, China, the United States and the former Soviet Union. In contrast with the Australian results, all three elements (maximum, mean and minimum) showed decreasing trends in intraseasonal variability at almost all timescales up to 10 days in the three northern Hemisphere countries, although only in the United States were the trends generally significant at the 99% level. However, variability at the 30-day and interannual timescale increased in the former Sovier Union, and downward trends in the United States were much weaker than they were at shorter timescales. Earlier studies of changes in temperature variability, such as those of Diaz and Quayle (1980) and van

Loon and Williams (1978), focused on changes in the interannual variability of mean monthly or seasonal temperatures.

Whilst Plummer's study may appear to follow very similar lines to those of this study, specifically Chapters 7 and 8, it is a more limited study in a number of respects. The most significant is that he confined his network to a set of stations that had been examined and found to be homogeneous over his period of interest. Whilst this obviated the need to adjust data for any inhomogeneities, it did mean that the station network used was small and had uneven areal coverage. It did not contain any stations from the Northern Territory, northern South Australia or western Queensland (as no stations in those regions met the criteria for inclusion), and only included two from tropical Western Australia. Furthermore, stations were combined into regional averages as an arithmetic mean, which meant that areas of high station density were over-represented in the analysis (although the choice of regional boundaries took this into account to some extent). No additional screening of data for short-period errors (as discussed in Chapter 3) was carried out over and above that routinely undertaken by the National Climate Centre. The other difference of consequence between the two studies lies in the choice of extremes to be analysed and the way in which they are calculated. This is discussed more extensively in Chapter 8.

Generalised indices of the occurrence of threshold events were considered by Ratcliffe et al. (1978), Nese (1993) and Henderson and Muller (1997). Each of these studies calculated an index of extreme events as a number of days or months with the observation being more than a certain number of standard deviations from the mean. Ratcliffe et al. found no evidence of significant changes over the period from 1878 to 1978 in the frequency of extremes in the variables they studied: monthly means of Central England temperature, England and Wales rainfall, and surface pressure over the Northern Hemisphere. Nese calculated the frequency of days in each year between 1901 and 1986 with daily mean temperatures more than 1.5 standard deviations from the climatological mean for 39 locations in the eastern United States. His paper focused on the nature of the fluctuations, and potential periodicity, of this time series, and did not consider its trend, nor did he distinguish between high and low extremes. An inspection of his data suggests a slight declining trend in his extremes index between 1901 and 1986. Henderson and Muller, in their study of the south-central

United States, defined an extreme day as one with a maximum temperature more than 1 standard deviation above the normal, or with a minimum temperature more than 1 standard deviation below. They found that there had been an increase in the frequency of cold days in this region, particularly in winter, and a weaker decrease in the frequency of warm days, most pronounced in autumn.

Jones et al. (1999) and Horton et al. (2001) examined the frequency of values above the 90th percentile and below the 10th percentile in the previously discussed daily Central England mean temperature (CET) series, extending from 1772 to 1996. They found that the frequency of days below the 10th percentile had decreased during the 20th century, especially since 1930, although Jones et al. (1999) caution that the frequency of extremes prior to the 20th century may be exaggerated as a result of changes in screen type. There was little change in the frequency of days above the 90th percentile. Jones et al. (1999) also presented time series of the frequency of days with daily CET above 20°C or below 0°C, but did not discuss trends in these.

A number of results on threshold and extreme events for northern and central Europe were presented by Heino et al. (1999). Amongst their key results were that the frequency of minima below 0°C showed a negative trend between 1931 and 1995 at six of seven stations studied, with trends significant at the 95% level observed at two Swiss and two Czech stations. The three Finnish stations in the study showed non-significant trends (two negative, one positive). It was noted that the frequency of temperatures below a fixed threshold has different meanings at different stations; in warmer regions it reflected changes in winter temperatures, whereas in northern Finland (where virtually all days in winter, even in the mildest years, have minima below 0°C), it was more representative of events in autumn and spring. They also found that at Davos, Switzerland, there was a marked shift in the entire frequency distribution of minimum temperature towards higher values in the warmest six-year period, as opposed to the coldest. This has been accompanied by a change from an approximately symmetric frequency distribution to one which is negatively skewed.

DeGaetano et al. (1994) and Cooter and LeDuc (1995) both consider trends in the frequency of threshold events in the northeastern United States. DeGaetano et al. found mixed results for most thresholds over the 1950-1992 period, except for the frequency of minimum temperatures above 65°F (18.3°C) and 70°F (21.1°C), which exhibited a statistically significant increase over the period, especially in the southern part of the region (at the northern stations such events are rare in any case, possibly explaining the lack of a significant trend). Cooter and LeDuc found a statistically significant trend towards an earlier date of the last spring temperature below 0°C in most of the region.

Zhai et al. (1999) examined the frequency of various threshold events, and the trends of the highest and lowest air temperatures occurring in each season, in China over the 1951-1990 period. They found that the lowest air temperature in each season showed an increasing trend over the period, with the largest increase (2.5°C over the 40-year period) in winter and the smallest in summer. For the highest air temperature in each season, no statistically significant trends were found, although slight decreases (peaking at 0.6°C/40 years in summer) were found in summer and autumn. They also found a statistically significant decrease (level unspecified) in the frequency of minimum temperatures below -20°C in northern China, and a slight decreasing trend in the frequency of maximum temperatures above 35°C over China as a whole, although an increase was observed in southern China.

An examination of the frequency of extremes at the monthly timescale was carried out by Horton et al. (2001) This used monthly temperature anomaly data for the 1961-90 (standard normal) period interpolated onto a 5 x 5 degree grid to develop fields of the expected 2, 5, 10, 20, ..., 90, 95 and 98 percentile anomalies globally. As 30 data points (one for each year) are insufficient to determine the highest and lowest percentile values empirically from the data, a two-parameter gamma distribution was fitted to the observed anomalies for each month at each grid-point. The authors, whilst noting that no one distribution is likely to be valid for all grid-points (in particular, the gamma distribution assumes unimodality) commented that the gamma distribution allows varying skewness. Checks of skewness and chi-square values showed that the Gaussian and gamma distributions fitted the actual distribution similarly well for annual data, but the gamma distribution was far superior for monthly data. A similar analysis was presented at the 1997 Asheville workshop by Jones et al. (1999).

Horton et al. also examined trends in the frequency of monthly temperature anomalies above the 90th percentile (warm) or below the 10th percentile (cold). They found that the frequency of cold anomalies decreased sharply between 1900 and 1940, and the frequency of warm anomalies increased moderately over the same period. Following a period of relative stability between 1940 and 1980, both trends have resumed sharply since 1980. A seasonal breakdown found that the frequency of cold anomalies had decreased in all seasons, and that of warm anomalies has increased, with the trend in cold anomalies being stronger in all seasons. Once the overall trend in mean temperature was removed, the frequency of extremes at both ends of the scale over land had decreased over the century, although they suggest that this may be a consequence of the decreasing variance of grid-point anomalies as a result of an increased number of stations contributing to each grid-point value after the early years of the record.

Gruza et al. (1999) examine Russian data on both the annual and seasonal timescales. At the annual timescale, they found an increasing trend in the proportion of Russia reporting annual mean temperatures above the 80th and 90th percentile in any given year over the period 1901-1995, and a weaker decreasing trend in the proportion reporting annual mean temperatures below the 20th and 10th percentile. They aggregated these values into a Climate Anomaly Index (CAI), which was the sum of the area with annual or seasonal mean temperatures in the highest or lowest 10 percent of observations. This index shows an increasing trend for the year as a whole, and for the cold season (October-April), but little change for the warm season (May-September).

At the daily timescale, they examined trends in the frequency of maximum air temperatures above the 95th percentile (derived from data for the 1961-1995 period) and minimum temperatures below the 5th percentile for winter (December-February) and summer (June-August). The frequency of low minimum temperatures decreased at most stations in both seasons, particularly in winter, whilst high maximum temperatures increased in frequency at most stations, with particularly marked trends in summer in western and eastern Russia.

Manton et al. (2001) analyse data for southeast Asia and the South Pacific for the period from 1961 to 1998, including the trends in frequencies of maximum and minimum temperatures above the (annual) 99th percentile, and below the 1st percentile. They found that increases in the frequency of extreme high maximum and minimum temperatures, and decreases in the frequency of extreme low maximum and minimum temperatures, were found with considerable consistency across that region.

In summary, the bulk of these studies have reported, in some form, a decrease in the frequency of cold extremes, particularly in the cold season. Results concerning the frequency of warm extremes are more mixed, although increases have been reported more widely than have decreases.

1.3.3. The statistical nature of the frequency of extreme temperatures

Many studies of the likely impact of a change in mean temperature on the frequency of extreme events have simply retained the existing shape of the frequency distribution and shifted, explicitly or implicitly, all daily temperatures by the amount of the assumed change in the mean. This was illustrated by Pittock (1988), who stated that 'short-lived climatic extremes such as floods and droughts normally occur as part of statistical fluctuations about some average value', thereby implying that a change in the mean would shift extremes in the same direction in the absence of a change in the nature of the 'statistical fluctuations'. In the same volume, Salinger (1988), in an early consideration of possible changes to threshold event frequency in Australasia, used a shifting of the frequency distribution to model the impact of a rise in mean temperature on the length of the growing season and the speed of crop maturation, using a total-degree-days model. He found that a 1°C increase in mean annual temperature in New Zealand would advance crop maturation time by 2-4 weeks, thus extending the latitudinal and altitudinal limits for the growth of pasture and various crops. He also found that the frost-free season at various New Zealand sites would be lengthened by between 15 and 65 days for such a mean temperature increase, with the greatest lengthening at relatively warm sites with a low annual temperature range, such as those in the north of the North Island, and the least at interior sites in the South Island; he suggests that the sensitivity of the length of the frost-free season is likely to be less in a more continental climate. He does note that the actual change in the length of the frost-free season will depend on both the change in mean annual minimum temperature and the change in temperature variance, but does not address this question quantitatively. On a larger scale, Hansen et al. (1981) assumed that the frequency of extreme temperatures could be estimated by shifting the existing frequency distribution by the model-estimated change in mean temperatures.

A more recent study of this type was carried out by Hennessy and Pittock (1995). They assessed the impact of various warming scenarios for the state of Victoria, derived from a regional general circulation model (GCM), on the frequency of threshold temperature events. Like Salinger, they recognised that the use of a mean-shifted frequency distribution was an oversimplification, but used it nonetheless. They found that under the GCM's 'low warming' scenario, the expected frequency of summer maximum temperatures above 35°C increased by more than 25%, while a decrease exceeding 25% was found in the frequency of winter minimum temperatures below 0°C. The frequency of runs of hot or cold days was less affected under this scenario, with the frequency of runs of five consecutive days exceeding 35°C in northern Victoria increasing by about 20%, and that of five consecutive days below 0°C decreasing by 20% in western Victoria and 25-40% in the north-east highlands. They note that, with the use of static thresholds, results vary considerably between stations.

The first major studies to examine, in detail, the influence of changes in the nature of the temperature regime, other than changes in mean temperature, were those of Mearns et al. (1984) and Katz and Brown (1992). Both examined the probability of extreme high temperatures in the midwestern United States. Mearns et al. examined the probability of July maximum temperatures exceeding 35°C at four stations in that region, concentrating on the probability of three types of event: that of the maximum temperature on any given day exceeding that value, that of at least one run in a given July of at least five consecutive days with maxima exceeding that value, and that of at least five days in a given July (not necessarily consecutive) having maxima exceeding that value. They used a first-order autoregressive (AR(1)) process to generate a synthetic time series of daily maximum temperature, with the parameters (the mean, standard deviation and lag-1 autocorrelation of July daily maximum temperatures at each station) being determined from station data. The parameters of the AR(1) process were then varied to model the impact of possible climatic changes on the frequency of the three events they were considering. It should be noted here that, as the authors point out, the mean and standard deviation of real data can be transformed relatively easily by a shifting and transformation of the time series, but autocorrelation cannot be readily altered in this way – hence their use of a synthetic time series. The use of an AR(1) process to model daily temperatures is discussed further in Chapter 6.

They considered a wide range of scenarios of changes in mean temperature, its variance and autocorrelation. As an example, they found that a 3°F (1.7°C) increase in mean maximum temperature, with the variance and autocorrelation held constant, would lead to the probability of five or more consecutive days exceeding 35°C at Des Moines increasing to approximately three times its current value. They also found that the frequency of such events was highly sensitive to changes in the variance and autocorrelation, with various scenarios resulting in increases to between two and six times present levels.

Katz and Brown (1992) present a statistical model for climate change which defined the probability distribution of a climate variable in terms of a location and scale parameter (in a normal distribution, these will be the mean and standard deviation respectively). They found that the sensitivity of an extreme event (defined in terms of the exceedance of a threshold) to changes in the scale parameter, relative to the impact of changes in the location parameter, increased as an event became more extreme.

They apply this theoretical result to the time series of July daily maximum temperature at Des Moines (the same data set analysed by Mearns et al.). They find that, assuming a normal distribution, an increase of 0.5°C in mean maximum temperature increases the probability of a day's maximum temperature exceeding 38°C by 35%, while an increase of 0.5°C in the standard deviation increases that probability by 71%. These results were found to be representative of those obtained by a change in the parameters of an AR(1) model, of the type used by Mearns et al., and they use these results to argue for the importance of the consideration of changes in climatic variability as part of any consideration of climatic change. Tarleton and Katz (1993) and Katz (1993) apply the concept of temperature changes being represented by both changes in the mean and changes in the standard deviation to two specific examples - the way in which temperature changes spatially over a region and changes over time with the development of an urban heat island - and find it to be a satisfactory model for the observed changes.

Wagner (1996) applied this model to data for Potsdam, Germany. He assumed for the purposes of his study that daily maximum and minimum temperature were normally distributed (although, in testing this, he found that such an assumption under-estimated the number of days with maxima above 30°C and over-estimated the number of days with maxima below 0°C). He determined trends in the mean and standard deviation of daily temperature by breaking the time series up into 5-year segments and separately calculating the mean and standard deviation of the temperatures for each month of the year within those 5-year period. Using this, he found that mean temperature showed a warming trend in all seasons, while the standard deviation showed an increasing trend in summer, but a decreasing trend in winter. This was consistent with his observed trends towards more hot days in summer and fewer frosts in autumn.

The relationship between mean and extreme temperatures has been investigated by several authors. Vedin (1990) compared the length of the growing season, and the frequency of summer frosts, at Karesuando in northern Sweden between a decade with warm annual mean temperatures in the region (1931-40) and a colder decade (1979-88). Despite a 1.5°C decrease in mean annual temperature (and a 1°C decrease in mean summer temperature) in the latter period, there had been a slight increase in the length of the growing season and little change in the frequency of summer frosts.

Rebetez and Beniston (1997) compared the frequency distribution of daily minimum temperatures in the warmest and coldest 5-year periods of the century at various sites in alpine Switzerland. They found that the extremes, defined as the 1st and 99th percentile of daily minima (over the year as a whole), had shown a stronger response than the observed trend in the mean annual temperature, particularly for the high extreme. They suggest that this is consistent with the results for the gridpoint centred near Zurich for a doubled-CO_2 climate in a general circulation model.

Balling and Idso (1990) compared trends in the frequency of extreme high summer temperatures (defined as daily maximum temperatures more than two standard deviations above the seasonal mean maximum temperature) with trends in mean temperatures, over the 1948-1987 period, at two groups of stations in the United States; a set of 17 stations which exhibited a warming trend in mean summer temperatures of greater than 1.5°C over this period, and a set of 10 stations which exhibited a cooling trend of greater than 1.5°C. They found that both sets of stations (those which have cooled and those which have warmed) showed an increase in the frequency of extreme high temperatures, with 3 of the 17 'warming' stations and 2 of the 10 'cooling' stations showing increases significant at the 95% level, and the 'cooling' stations exhibiting a greater overall increase in the frequency of extreme high temperatures. They argue that this result shows that there is no discernable relationship between trends in mean temperature and trends in the frequency of extreme high temperatures. They did not consider possible relationships between trends in mean maximum temperatures and the frequency of extreme high temperatures (although they did note that, averaged over the continental United States as a whole, mean maximum temperatures showed a different trend to that of mean minimum temperatures), nor did they make any explicit consideration of the homogeneity or quality of the station data that they used. This is a particularly significant point in light of their method of station selection; a station with a large inhomogeneity is likely to display a large (artificial) trend in their mean temperature, and is therefore disproportionately likely to be included in the set of stations with the largest absolute trends. Furthermore, as will be discussed in Chapters 3 and 4, an inhomogeneity may affect maximum and minimum temperatures, or different parts of the frequency distribution of maximum and minimum temperature, differently.

Balling et al. (1990) also undertook a study on a more local scale, investigating the relationship between seasonal mean temperatures and the frequency of maximum and minimum temperatures exceeding (or falling below) certain thresholds at Phoenix, Arizona in the July-August period. (In effect, the implied extrapolation to climate change in the paper is using anomalously warm months in the present climate to simulate average months in a warmer climate – an approach which will be discussed further in Chapters 6 and 7). They found that the frequency of the exceedance of high thresholds was positively correlated, and the frequency of exceedance of low thresholds negatively correlated, with the seasonal mean temperature, but that the magnitude of the relationship, especially for maximum temperatures, was weaker than would be expected from simply shifting the frequency distribution by a given increment of change in mean temperature. Again, this study did not address the possibility of differential relationships between mean maximum and minimum temperatures, and the frequency of threshold events. An implied extrapolation of a different type was carried out by Brown and Katz (1995), who argued that stations in a warmer part of a region under the present climate could be used as an analogue for those in a cooler part under a warmed climate, using high maxima in the midwestern United States and low minima in the southeast as examples.

In addition to the previously discussed work of Tattelman and Kantor (1976a, b), Essenwanger (1963) and Hinds and Rotenberry (1979) both attempted to derive regression relationships between mean monthly temperatures and extremes. Essenwanger compared the mean annual extreme maximum and the mean daily maximum temperature of the warmest month at a wide variety of stations globally with a mean annual extreme maximum exceeding 40°C; Hinds and Rotenberry compared the highest maximum and mean maximum, and lowest minimum and mean minimum, for each month over a 2-3 year period at 'several' locations within a topographically diverse 300 km^2 experimental site in Washington state (USA). Both found strong correlations between their extreme and mean variables, with Hinds and Rotenberry finding a stronger relationship for maximum than for minimum temperatures.

Changnon and Laffey (1994) investigated the correlation between mean monthly and mean daily maximum temperatures for the summer season on one hand, and the total number of days, and the length of the longest run of consecutive days, with maxima above 32°C, on the other hand, for the southeastern United States. They found that the mean daily maximum temperatures were more highly correlated with the frequency of high maxima than the mean monthly temperatures were, and that the correlations of both were stronger with the number of hot days than with the length of the longest run of consecutive hot days.

Salinger (1997) developed regression relationships between mean monthly (or annual) maximum and minimum temperatures and the number of days with maxima exceeding 30°C and minima below 0°C at a network of stations in New Zealand. He found that, using these regression relationships, a 1°C increase in mean annual minimum temperature led to a decrease of between 7 and 25 days per year in the number of days below 0°C, with the greatest sensitivity in the interior of the South Island. A weaker relationship exists between mean annual maximum temperature and the frequency of maxima above 30°C, due in part to the low frequency of such days at any of the sites studied. Although he did not undertake a detailed analysis of trends in the frequency of threshold events across New Zealand, results from four sample stations suggested a decrease in the frequency of minima below 0°C since 1950, and a slight increase in the frequency of maxima above 30°C.

1.3.4. Model experiments and extreme temperatures

Until very recently, there has been a paucity of work carried out in attempting to use the output of general circulation models (GCMs), which have been used very extensively to estimate likely changes in mean temperature (IPCC, 1995), to estimate the likely occurrence of extreme temperatures. Models vary considerably in their assessment of likely changes in temperature variability with increasing CO_2 concentrations, although Meehl et al. (2000) note that most simulations project larger changes in mean temperatures than in their standard deviations. Whetton (pers. comm.) noted that experiments involving the intercomparison of different models, which are commonplace in the assessment of likely changes of mean temperatures, are, so far, very limited in the case of extremes.

The papers in this field adopt various approaches. Brinkmann (1993) takes as his starting point the likelihood that different air masses will respond in different ways to climate change forced by an increased atmospheric concentration of carbon dioxide. Using daily temperature and humidity data output from a GCM for the present climate (1 x CO_2) and a climate with a doubled level of carbon dioxide (2 x CO_2), and defining air mass occurrence for a location in the north-central United States by means of the location of ridging at the 700 hPa height, he found that northerly flow in December was 7.7°C warmer in the 2 x CO_2 climate than it was in the 1 x CO_2

climate, but southerly flow was only 2.3°C warmer. This would imply a marked decline of temperature variability.

Takle and Bian (1993) did not examine extreme temperatures directly, but instead examined the mean, standard deviation and autocorrelation of daily maximum and minimum temperatures at six GCM gridpoints in the US Midwest, then used the statistical model of Mearns et al. (1984) to estimate the impact that the modelled changes in these would have on the frequency of various extreme temperature events at specific stations. They found that, over the region they were studying, July maximum temperatures in the 2 x CO_2 climate showed an increase in mean of 6.1°C, an increase in standard deviation of 0.66°C and an increase in autocorrelation of 0.13 compared with the modelled 1 x CO_2 climate. This led, as would be expected from the results of Mearns et al. (1984), to a marked increase in both the expected frequency of extreme high temperatures at various thresholds, and the expected length of runs of days above certain thresholds. A similar study, with broadly similar results, was carried out for nine Canadian stations by Colombo et al. (1999).

Mearns et al. (1990) examined the behaviour of temperatures at GCM gridpoints in the central United States. Their analysis was confined to a direct examination of the GCM results, using the interannual variability of monthly mean temperature and the daily variability of temperature. Their results were mixed, with increases in variability at some gridpoints and decreases at others.

Zwiers and Kharin (1998) used GCM data to simulate the expected 10-, 20- and 50-year return period temperatures, using Gumbel analysis on annual extremes, and the expected frequency of threshold events, for various model gridpoints over Canada. They found more response for low minima than high maxima in the (2 x CO_2) climate compared with the (1 x CO_2) climate, with the return period temperatures for low minima increasing by a mean of 5.0°C compared with those for high maxima, which increased by a mean of 3.1°C. (By comparison, annual mean temperatures in this model increased by 3.5°C).

McGuffie et al. (1999) used five separate models to estimate changes in the return periods of certain temperature events, noting that the models differed widely in their ability to accurately simulate extremes in the present climate. They found that, in the 2 x CO_2 climate, the frequency of warm extremes increased, and the frequency of cold extremes decreased, consistently across the five models, but they differed considerably in the regional distribution of the greatest and least warming. They note that evaluation of local extremes from models requires either downscaling to nested models, or the development of GCMs with very much higher resolution.

Hennessy et al. (1998) use a nested regional model to develop scenarios of climate change for New South Wales. They include an assessment of changes in extreme temperatures in this, concluding, from gridpoint results (on the 60-kilometre grid that they used) that the frequency of minimum temperatures below 0°C, averaged over New South Wales, is expected to fall by approximately 50% by 2050. Whetton et al. (2000) reached a similar conclusion (by similar methods) for Victoria, as well as estimating a likely increase in the frequency of maximum temperatures above 35°C of 40% in northern Victoria and 100% in southern Victoria, although they note that their model has a warm bias in simulating the present summer climate over Victoria.

1.4. Summary

The study of extreme temperature events is becoming an increasingly active field, with a proliferation of published material appearing since 1995. Current research is proceeding in three principal directions: the development and rehabilitation of historical data sets (including metadata), the production and analysis of indices of extreme temperature occurrence, and the development of scenarios of changes in the likely frequency of extreme events derived from the output of climate models.

This thesis will concentrate on the first two areas, commencing with the development of a high-quality daily data set, something which is not known to have been carried out previously, and continues with the analyses of changes in the observed frequency of extremes.

Chapter 2

Data Availability and Station Selection

2.1. Historical availability of temperature data in Australia

2.1.1. A brief history of Australian temperature measurement

Temperature has always been something of a poor relation in Australian climatology. Rainfall has, historically, been the major priority in the climatological observing network. This is a natural response to Australia's climate, in which rainfall and its variability have been a critical limiting factor for agriculture, with temperature being of secondary importance. This is in contrast with the situation in much of North America and Europe, where the length of the growing season is largely determined by temperature and temperature measurements have received an accordingly greater priority. Rainfall observations have been made on many farms for a century or more, but virtually none of these rural sites also made temperature observations. Only about 10% of the meteorological stations that have operated in Australia during its history have measured temperature, and, at many of these, the temperature measurements were not made as meticulously as those of rainfall (Torok, 1996).

The first temperature observations in Australia date from the arrival of the First Fleet in 1788 (Torok, 1996). While observations were made in a number of places at a number of times during the early years of European settlement, the first organised long-term record commenced in 1855, at Melbourne. These are the earliest temperature data in the Bureau of Meteorology's archives, apart from some brief records at a Hobart site in the 1840's. The observational network expanded gradually through the second half of the nineteenth century, with large numbers of stations being opened in individual colonies (as they were then) at certain times, often coinciding with the appointment of a particularly enthusiastic government astronomer or meteorologist, such as Henry Russell in New South Wales, Charles Todd in South Australia and Clement Wragge in Queensland.

The Commonwealth Bureau of Meteorology was founded in 1908. Meteorology became a federal responsibility at this point. This prompted a considerable improvement in the collection and archiving of data, with many stations having data in the Bureau's archives starting in 1908 or in the year or two after. (The existence of pre-1908 manuscript records from a number of the stations concerned (Clarkson, pers. comm.) suggests that this may reflect improvements in archiving data rather than the opening of stations). By 1910 there was a sufficient national coverage of data for it to be feasible to analyse temperature trends over Australia from that date, as Torok did in his 1996 study. The one major gap remaining was over the western interior. This remained until it was partially filled by the opening of stations at Giles (1956) and Rabbit Flat (1969), and significant data voids remain today over the eastern half of Western Australia and north-western South Australia.

Historically, much of the temperature network was based at Post Offices, although there was always a smattering of other sites, such as coastal lighthouses and pilot stations, experimental farms, private residences and prisons. The astronomical observatories in the state capitals were also the original observing sites in most of those cities. The Bureau of Meteorology started to establish its own range of staffed observing sites during the Second World War, as aviation (and the role of meteorology in its safe operation) became increasingly important. A number of additional Bureau-staffed sites in remote areas, notably Woomera and Giles, were established in the late 1940's and 1950's to support rocket and nuclear tests.

2.1.2. Archiving and accessibility of historical temperature data

Many, although not all, of the temperature observations that have been made in Australia have been incorporated in the Bureau of Meteorology's digital archives in the form of monthly means. The main exceptions are in the period between 1957 and 1964 (inclusive), when much data are missing, especially in the eastern states. There are also some early data (e.g. the pre-1938 Winton record, which is referred to again in Chapter 5) which have not been incorporated in the archive, possibly because of the station receiving a low processing priority at the time.

The greatest difficulty which confronts a study of this type, which requires daily temperature data, is the limited availability of daily data in digital form. In general, digital daily data are only available since 1957, and in some cases (principally in New South Wales and Queensland) since 1965. Earlier data are generally only available for the state capitals (from the start of the record, except at Hobart and Perth where it commences in 1944 - although the pre-1941 Darwin Post Office data are of poor quality at times (Butterworth, 1993) and have not been used here) and for Bureau-staffed sites (which, as mentioned above, generally opened in the late 1930s and early 1940s, although some have a break in observations following the end of the Second World War). The latter group of sites are particularly useful for this study, as most are located at airports outside urban areas, thereby minimising the impact of urbanisation, are staffed by trained personnel, and have the longest readily-available daily records over most of the country.

Earlier daily temperature data exist only in paper form, and are spread between several archiving sites in the various states. A project is currently under way at the Bureau of Meteorology to digitise some of these data, but at present rates of progress it is likely to take many years to complete (Plummer, pers. comm.). Similar difficulties affect the accessibility of daily temperature data in many other countries (Easterling et al., 2000).

Fig. 2.1 shows the number of available stations with digital daily and monthly maximum and minimum temperature data in each year of the record. (Appendix B contains a listing of the exact number of stations with data in each year). A station is assumed to have data if there is at least one daily value, or monthly mean as appropriate, in the Bureau's digital database. Since 1994 monthly means have only been archived once a station's data have been quality-controlled; a backlog of data awaiting quality control (including some 1986-1991 data that were not processed until after 1994) accounts for the reduced number of monthly means available since 1986.

(All available daily rainfall data *have* been digitised - another reflection of the high priority that rainfall has enjoyed, relative to temperature, in the Australian climatological consciousness).

While the digitisation of all available historical data for the stations used was well beyond the scope of this study (the task would require several person-years in itself), a number of records were digitised, either as a part of other projects or in order to place the stations on a uniform footing (for example, 1957-64 data were obtained for the stations where the digital record commenced in 1965). Nevertheless, only in New South Wales was a substantial amount of data available from prior to about 1940 outside the major cities.

2.2. The development of a station network

2.2.1. The philosophy of selecting a network for climate monitoring

Ideally, all portions of the globe would have meteorological stations with long, continuous, homogeneous records spaced on a grid at regular intervals. In practice we have to make do with an imperfect sampling of the temperature field, through such stations and data as are available.

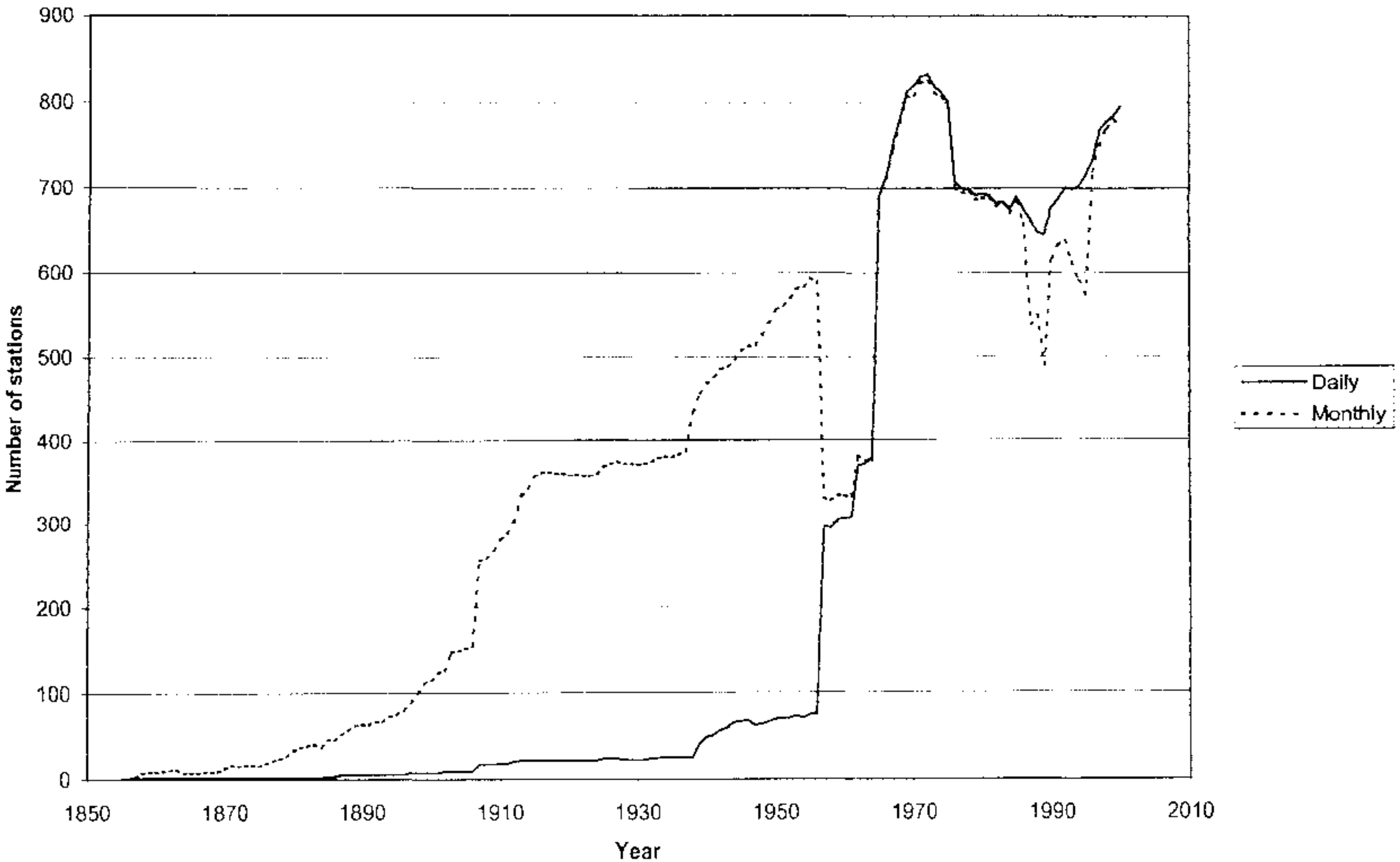
The Bureau of Meteorology (1995) has identified the characteristics of an ideal climate station as follows:

- very few problems throughout a history exceeding 100 years;
- a small turnover of enthusiastic and diligent observers who were responsible for adhering to internationally agreed standards in observation methods and instrumentation;
- a location in an environment far away from urban influences such as multi-storey buildings and motor vehicle traffic, which may affect the local climate;
- few changes in its local environment, including nearby trees and buildings.

Three principal factors determine the suitability of a station for use in the analysis of historical climate events:

1. The amount of data available;
2. The quality of the data available, and their representativeness as a sample of the

Fig. 2.1. Number of stations with available digital daily and monthly temperature data



regional climate;

3. The availability (or lack thereof) of other climatic data in the region.

The criteria for judging stations based on these three general principles will depend how the data are being used. To give a simple example in the context of Australian temperature data, if there are two stations of equal data quality, one with monthly data from 1890 onwards and daily data from 1957 onwards, and the other with monthly and daily data from 1939 onwards, the former station is more suitable for studies involving the analysis of monthly data, the latter for daily data.

Two broad approaches can be adopted to the development of a station network. One approach is to use data from all stations which meet specified criteria of length and completeness of record, adjusted if necessary to correct for inhomogeneities; the other is to use a subset of the data selected on the basis of spatial representativeness, data quality or both. Torok (1996), in his study of long-term Australian temperature data, took the former approach, on the grounds that there were insufficient long-term data available to select only the high-quality stations (see section 2.2.2.4). This approach was also followed by Karl et al. (1990) in the construction of the United States Historical Climatology Network, although they had the luxury of having sufficient stations to draw on to be able to set a high standard of record length (80 years or greater) and still have in excess of 1200 stations meeting that standard.

In contrast, Lavery et al. (1992), in their study of Australian rainfall, with its large number of available records, were able to be selective over parts of the continent, and use only the highest-quality records from those regions. A selective procedure is also being used in the selection of stations for the WMO Global Surface Network (Peterson et al., 1998a), with the use of an objective algorithm to measure the quality of stations.

2.2.2. Existing climate networks

There have been networks developed previously for the detection of climate change in general, and temperature changes in particular. These networks include:

- The Reference Climate Station (RCS) network
- The Plummer network of 40 stations
- The Australian part of the global network compiled by Jones et al. (1986c)
- The Torok network of pre-1910 Australian temperature stations

While all of these networks were established in order to analyse historical trends in climate, each of the last three have a particular emphasis, as a result of the way in which the networks were chosen. The Plummer network contains stations with a high quality of recent data, the Jones network contains stations whose data have been exchanged internationally, and the Torok network contains stations with long records.

These networks will now be described in detail. The stations included in each network are listed in Appendix B.

2.2.2.1. The Reference Climate Station network

This is an official network selected by the Bureau of Meteorology, in response to a request made by the World Meteorological Organization in 1990 for its member nations to identify a network of recommended reference climate sites. A reference climate station has the following definition (Bureau of Meteorology, 1995):

"A climatological station, the data of which are intended for the purpose of determining climatic trends. This requires long periods (not less than thirty years) of homogeneous records, where human-influenced environmental changes have been and/or expected to remain at a minimum. Ideally the records should be of sufficient length to enable the identification of secular (over time) changes of climate."

In Australia, the Bureau of Meteorology selected stations which had long records and had been subject to few changes in exposure and measurement techniques, with preference being given to stations which had had few moves, were not affected by urbanisation and had a reasonable likelihood of not being moved or closed in the foreseeable future. The need for good spatial coverage also led to the inclusion of a number of stations which did not have 30 years of available records.

The maintenance of the Reference Climate Station network has been given a high priority by the Bureau, with a station's status as a Reference Climate Station carrying considerable weight in decisions on rationalising station networks, maintaining parallel observations where there has been a site or instrument change and other changes potentially affecting the stations.

A number of sites have also been designated as secondary Reference Climate Stations. These do not have RCS status but have the potential to be drawn on should an existing Reference Climate Station in the region be forced to close. As an example, the station at Wittenoom is likely to close in the near future as a result of the near-total depopulation of the settlement and the withdrawal of services from it; in this event, Marble Bar will probably replace it in the RCS network.

101 Reference Climate Stations have been designated by the Bureau (including four on offshore islands and three in Antarctica). Of these, six did not have thirty years of record at the time of defining this data set:

- Learmonth (1975)
- Gove (1966, but with 12 years' missing data)
- Tindal (1985)
- Rabbit Flat (1969)
- Cape Grim (1985)
- Liawence (1985)

The four of these with the shortest records (Gove, Tindal, Cape Grim, Liawence) were not considered further for inclusion in this study.

Fig. 2.2 shows the locations of the Reference Climate Stations with 20 years or more of record.

2.2.2.2. The Plummer 40 station network

This is a network of 40 stations for which mean monthly maximum and minimum temperatures satisfied homogeneity tests for the period 1961 to 1995 (Plummer et al., 1999). This was a subset of a 92-station network used by Plummer et al. (1995), using the same general principles for station selection as was described above for the choice of Reference Climate Stations. (As might be expected, most of these 92 stations were also Reference Climate Stations).

The locations of the stations are given in Fig. 2.3.

The 40 stations failed to show any inhomogeneities for mean monthly maximum and minimum temperatures in the 1961-1995 period, using the bivariate test of Maronna and Yohai (1978). A consequence of this selection criterion is that the geographical coverage of the stations is incomplete, as there were a number of large regions in which no station satisfied this test. Of the 40 stations, there are none in the Northern Territory, one in Tasmania and two in South Australia. Nevertheless, as part of a larger network, it provides a strong indication as to which stations can be considered as being of high quality over that time period, which corresponds fairly closely with the principal time period (1957-1996) of interest to this study.

2.2.2.3. The Jones et al. network

This is the Australian part of the global network of stations described by Jones et al. (1986c). The principal criterion for selection in this network was that at least 20 years of data for the station concerned were available in the volumes of World Weather Records (e.g. U.S. Weather Bureau, 1965). This will be a subset of the full Australian data set, as not all Australian stations reported internationally.

The locations of the stations are given in Fig. 2.4.

Fig. 2.2. Locations of Reference Climate Stations in Australia

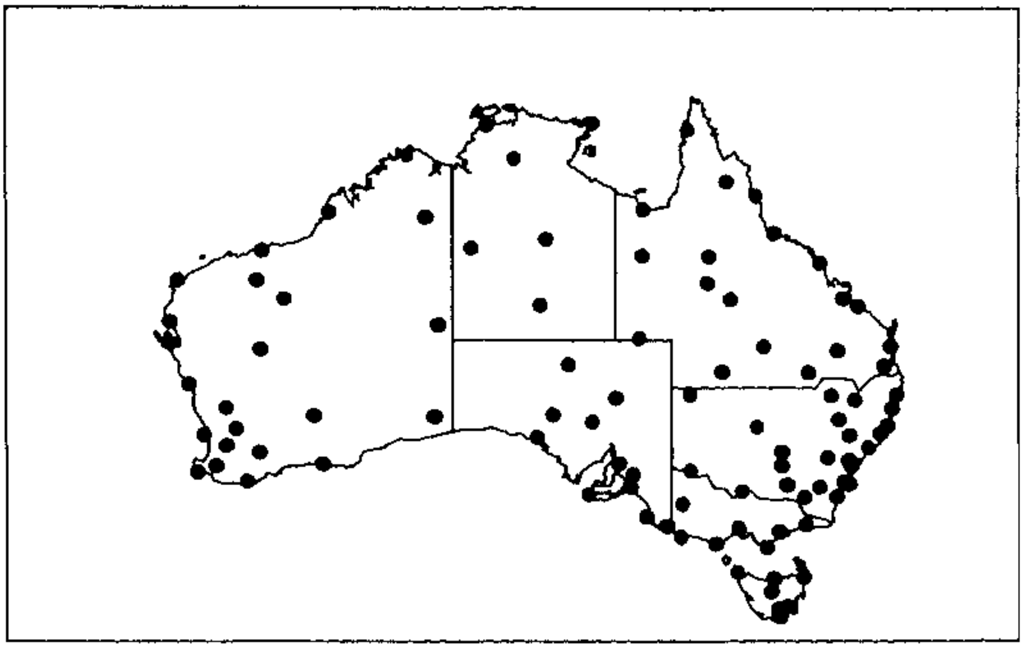


Fig. 2.3. Locations of the 40 stations used by Plummer et al. (1999)

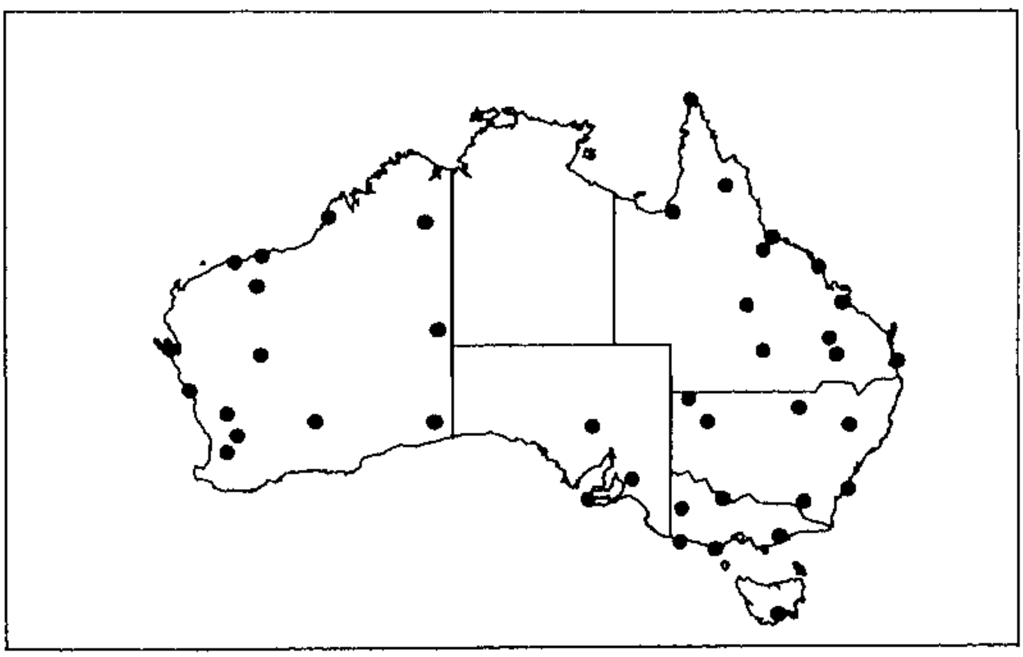


Fig. 2.4. Locations of the stations used by Jones et al. (1986c)

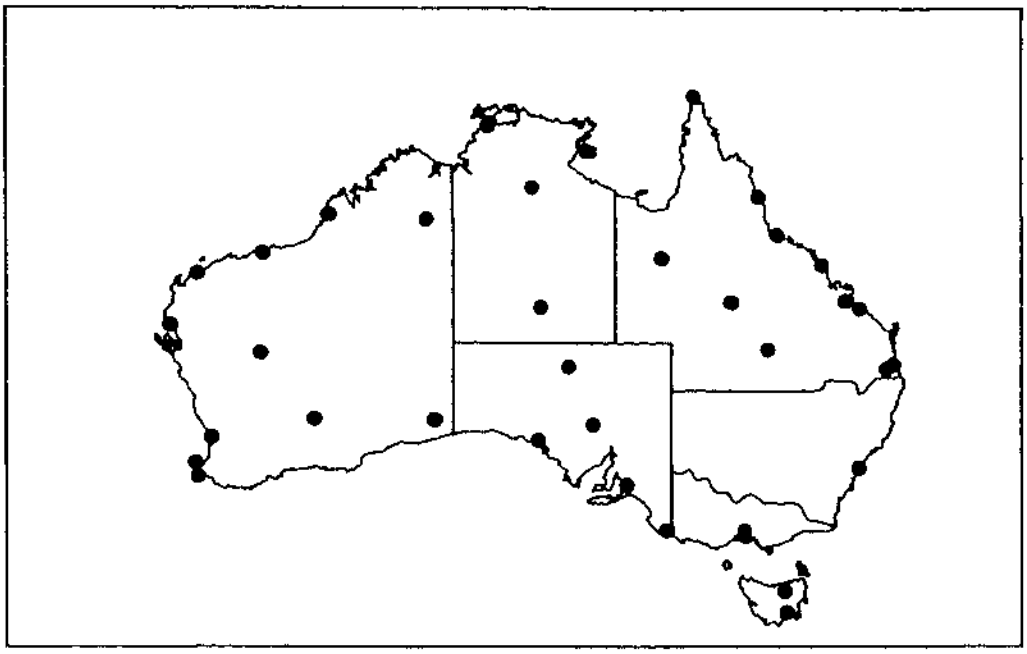
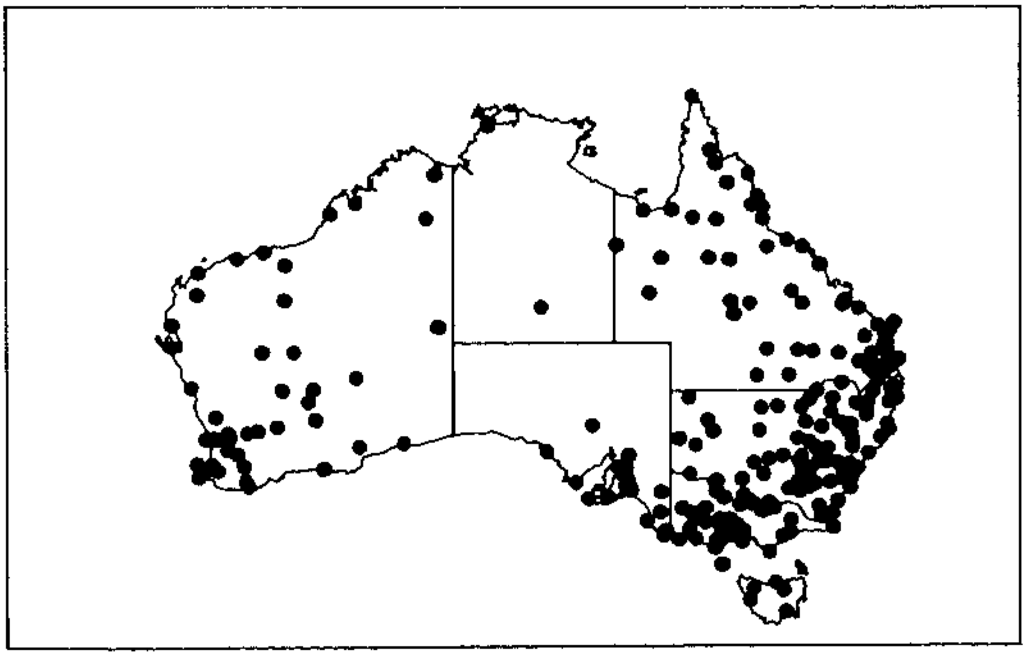


Fig. 2.5. Locations of the 224 stations used by Torok (1996)



A homogeneity assessment was carried out on the stations, using neighbouring stations (from the sparser World Weather Records network, not the full Australian network) and station history information (again, only a subset of the information that could potentially be used). Stations with discontinuities at one or more identifiable points in time were retained in the analysis, but those with trend inhomogeneities (e.g. due to urbanisation) were discarded.

While the selection process for these stations does not add any significant information on station quality to that already available for Australia through more detailed analyses of station histories and data homogeneity, particularly that of Torok (1996), it does provide an indication of those stations which are being used in analyses of the global climate, which is a relevant consideration in settling on a final set of stations.

A new global data set which is in the process of being developed is the GCOS Surface Network (GSN), a project of the World Meteorological Organization (Peterson et al., 1997). It will be of interest in the future, as it is likely to form the basis of routine global climate analysis, given its 'official' status. The final list of stations to be included in the GSN had not, however, been determined at the time of determining the data set for this study, although it has now (http://www.wmo.ch/web/gcos/gsnlist.htm).

2.2.2.4. The Torok network

This network, described in Torok (1996), included all stations in Australia that commenced temperature records prior to 1915 and were still open in 1985. This includes a number of composite records where overlapping data were available from two or more stations in the same general area. A total of 145 stations satisfied this criterion individually, and a further 79 as composite records. (It is worth noting that a station was considered a composite record if it included two or more records with different station numbers as allocated by the Bureau of Meteorology; it was quite common for stations to move substantially without changing station number). The locations of the stations are listed in Fig. 2.5.

All stations meeting the data availability criterion were included in Torok's analysis, because of a lack of high-quality data. He did, however, rate all his stations on a scale of 1 to 5, based on a subjective assessment of the state of the site, the diligence of the observers and the number of changes that had occurred through the record. The rating applies to the entire period of the record; there are some stations which rate poorly over the record as a whole but are good for some parts of the record.

In the context of this study, the main purpose of the Torok network is to provide an indication of station quality (through the subjective ratings) and which stations have long-term records. While the existence of long-term records is not critical for this study, in which the major constraint on the period of record used is the availability of daily digital data rather than the overall length of record, if a station does have long-term data and is included in the network, it allows this study to be extended backwards in time without changing the station network should older daily data become available at some time in the future.

2.3. The choice of a station network for this study

The Reference Climate Station network was used as the initial basis for the station network in this study. This provides a good initial set of stations, to which modifications can be made as necessary. While it would have been possible to include all Reference Climate Stations, it was considered appropriate to exclude some from the data set, on the grounds that they had insufficient data, poor recent data or duplicated other stations in the RCS network.

The principal criteria used in selecting stations were the length of daily digital data available (with 20 years being an absolute minimum), the quality of the data (either as determined by Plummer and/or Torok, or by a station's standing as a RCS), and achieving the broadest possible geographical coverage. The length of monthly data available was a secondary consideration.

A total of 16 Reference Climate Stations were not included in this study. Four (Gove, Tindal, Cape Grim and Liawenee) were excluded because they did not have 20 or more years of data available, two (Rottnest Island and Liverpool) because of substantial missing data in the last few years, and one (Mount Isa) because of a major station move towards the end of the record. The other nine stations were discarded because they were considered to be sufficiently close in distance and similar in climate to other sites in the network to be surplus to requirements. Of these nine stations, seven were not in either the Plummer or Jones network (the exceptions being Gladstone, which duplicated Bundaberg and Rockhampton as central Queensland coastal stations, and Cape Nelson, which duplicated Cape Otway as a western Victorian coastal station and was also close to, although somewhat more exposed than, Mount Gambier), and three had digital daily data commencing in 1964 or later.

Thursday Island was included, even though it is now closed, as it only closed in 1995 and no other record of any length exists from the Torres Strait islands. It may, in the future, be possible to continue the record using data from Horn Island, 10 kilometres away.

Twenty-five stations were then added to the network. These were chosen on the following basis:

Capital cities: The six state capital city sites were added to the network because of the length of their records and the potential interest of the statistical nature of changes in their climate, even if they are urbanisation-induced. These stations were excluded from certain parts of the analysis where it was considered desirable to exclude data which might be subject to an artificial warming trend.

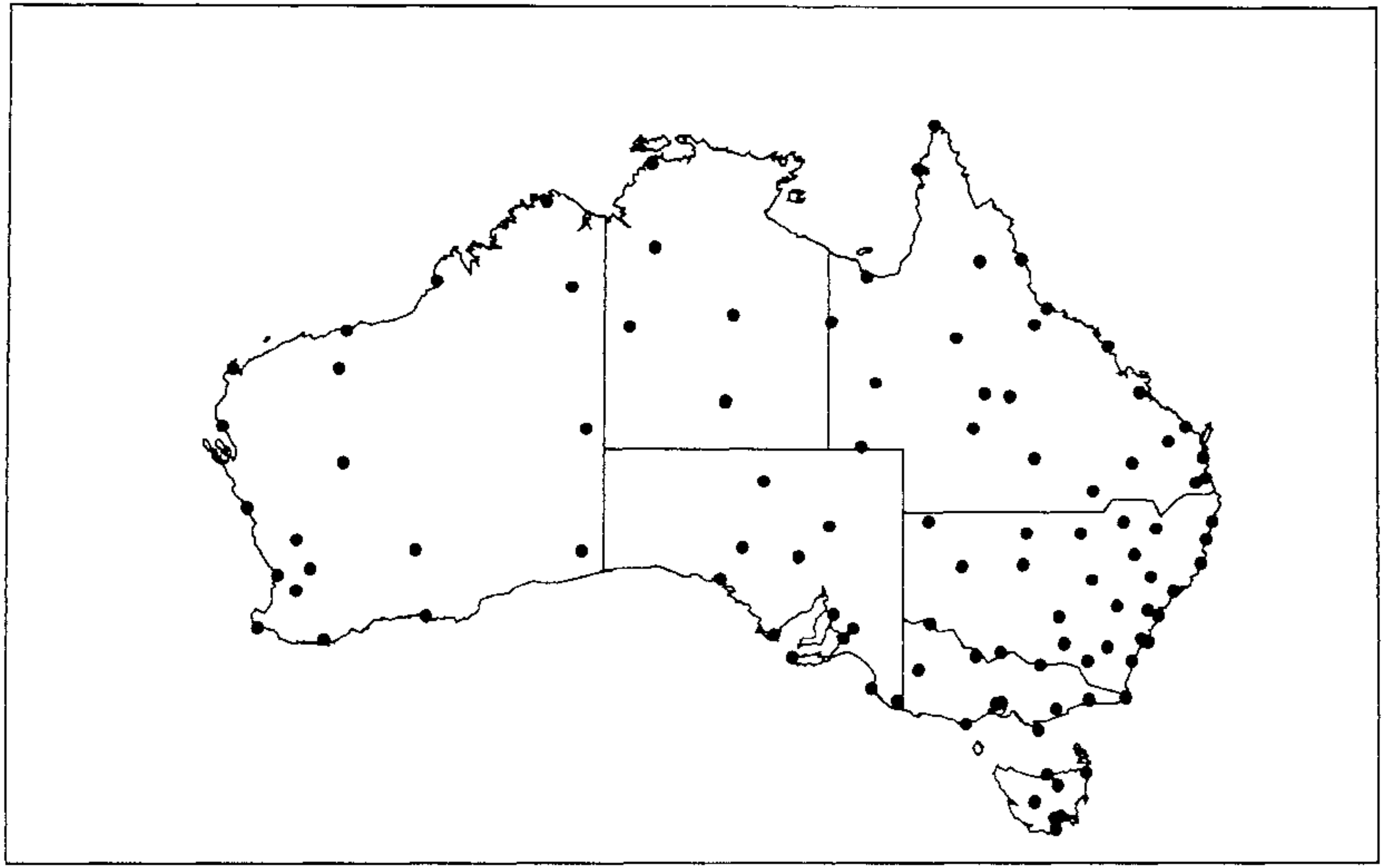
Stations from the Plummer/Jones networks: Thirty stations were included in either the Plummer or Jones networks which were not Reference Climate Stations. (Fifteen of these were in Queensland). These stations were examined to determine whether they would add useful information to the network, by substantially improving its geographical coverage, sampling a climatic type which was underrepresented in the Reference Climate Station network, or including a station identified by Torok as having a long, high-quality record. 15 stations were added on this basis. Barcaldine was also added, despite its apparent duplication of nearby Longreach (a Reference Climate Station), because of problems with Longreach prior to its 1966 conversion to a Meteorological Office.

Other stations to fill gaps: After the first two steps three substantial data-void areas remained; the eastern interior of Western Australia, the northern inland Northern Territory, and inland Tasmania. There were no stations available to fill the gaps in Western Australia. Victoria River Downs was chosen from the Northern Territory, despite concerns about its quality at times, as it was the only station in the region with continuous records since 1965. Two stations were chosen from inland Tasmania; Launceston Airport to represent the low-elevation areas, and Butlers Gorge to represent the high-elevation areas. Butlers Gorge closed in 1993, but the only currently open station in the region with 20 years or more of data, Lake St. Clair, was rated as being of very poor quality, prior to a 1988 move, by the Tasmania and Antarctica Regional Office of the Bureau of Meteorology (Shepherd, pers. comm.). The loss of three years of data at the end of the record is not a major problem for this study, but an alternative station will need to be found (or Butlers Gorge reopened) if this network is to be used for ongoing climate monitoring. The Reference Climate Station in the region, Liawenee, is 55 kilometres away, too far to be a realistic composite station in such a mountainous region.

A full listing of the stations chosen is given in Table 2.1a, and a map of their locations in Fig. 2.6. Further details of the stations, including opening and closing dates and the populations of any urban centres with which they are associated, are given in Table 2.1b.

The station network derived has good coverage of most of Australia during the principal period of interest in this study, between 1957 and 1996. There is a substantial data void over eastern Western Australia which is likely to remain for the foreseeable future, whilst some of the Northern Territory records used commence after 1957. The other significant shortcoming of the data set as it has been defined here is the limited amount of high-quality data from high elevations (above 500 metres in Tasmania and 1000 metres elsewhere), with only Cabramurra (which opened in 1962) and Butlers Gorge (which closed in 1993) available for use. The network, as it stands, is suitable for ongoing climate monitoring. Should it prove feasible to extend the data set backwards in time with the digitisation of additional pre-1957 data, it may be necessary to reassess the station

Fig. 2.6. Locations of final set of 103 stations used in this study



Station number	Station name	Latitude (deg S)	Longitude (deg E)	Altitude (m)	Station category	Station networks
1021	Kalumburu	14.17	126.38	23	R	R
2012	Halls Creek AMO	18.14	127.40	422	A (ST)	R, J, P, T*
3003	Broome AMO	17.56	122.14	7	A (LT)	R, J, P, T*
4032	Port Hedland AMO	20.22	118.38	9	A (LT)	R, J, P, T*
5007	Learmonth AMO	22.14	114.05	5	R	R
5026	Wittenoom PO	22.14	118.20	463	R	R, P
6011	Carnarvon AMO	24.53	113.40	4	A (ST)	R, J, T*
7045	Meekatharra AMO	26.37	118.32	517	A (ST)	R, J, P, T*
8039	Dalwallinu PO	30.17	116.40	335	R	R, P
8051	Geraldton AMO	28.47	114.41	33	A (LT)	R, P
9021	Perth Airport	31.56	115.56	20	A (U)	
9518	Cape Leeuwin	34.22	115.08	14	R	R, J, T
9500	Albany Town	35.01	117.52	18	LT	R, T*
9741	Albany AMO	34.56	117.48	68	A (LT)	R, T*
9541	Esperance PO	33.51	121.53	4	ST	R, P, T*
9789	Esperance MO	33.50	121.53	25	A (ST)	R, P, T*
10035	Cunderdin PO	31.39	117.14	236	R	R, P
10648	Wandering	32.40	116.40	280	R	R, P, T
11004	Forrest AMO	30.50	128.07	156	R	R, J, P
11052	Forrest AWS	30.50	128.07	156	R	R, J, P
12038	Kalgoorlie AMO	30.47	121.27	365	A (LT)	R, J, P, T*
13017	Giles MO	25.02	128.17	598	R	R, P
14015	Darwin Airport	12.25	130.53	31	A (LT)	R, J, T*
14825	Victoria River Downs	16.24	131.01	82	R	
15087	Tennant Creek PO	19.37	134.11	377	ST	R
15135	Tennant Creek MO	19.38	134.11	375	A (ST)	R
15548	Rabbit Flat	20.11	130.01	340	R	R
15590	Alice Springs MO	23.48	133.53	546	A (LT)	R, J, T*
16001	Woomera AMO	31.08	136.49	165	A (ST)	R, J, P
16044	Tarcoola	30.42	134.35	119	R	R
16098	Tarcoola (new site)	30.42	134.35	123	R	R
17031	Marree PO	29.39	138.03	50	R	R
17043	Oodnadatta AWS (formerly MO)	27.34	135.26	113	R	J
17114	Oodnadatta PS	27.32	135.26	120	R	J
18012	Ceduna AMO	32.08	133.42	15	A (ST)	R, J
18070	Port Lincoln PO	34.43	135.51	4	LT	T
21046	Snowtown PO	33.47	138.13	103	R	R, T
22801	Cape Borda	35.45	136.35	143	R	R, T
23000	Adelaide (W.Terrace)	34.56	138.35	40	U	J, T*
23090	Adelaide (Kent Town)	34.55	138.37	48	U	J, T*
23321	Nuriootpa	34.28	139.00	274	A (ST)	R, P
23373	Nuriootpa AWS	34.29	139.00	275	A (ST)	R, P
26021	Mount Gambier AMO	37.44	140.47	63	A (LT)	R, J, T*
26026	Robe PO	37.10	139.45	3	R	R, T
27022	Thursday Island MO	10.35	142.13	58	A (ST)	R, J, P, T*
27042	Weipa Composite	12.37	141.53	11	ST	R
27045	Weipa MO	12.40	141.55	20	A (ST)	R
28004	Palmerville	16.59	144.04	204	R	P, T
29004	Burketown PO	17.44	139.32	5	R	R, P, T
30045	Richmond (Qld.) PO	20.44	143.08	211	R	R, T
31011	Cairns AMO	16.53	145.45	3	A (LT)	R, J, T*

Table 2.1a. Final list of stations used in this study

Station number	Name	Latitude (deg S)	Longitude (deg E)	Altitude (m)	Station category	Station networks
32040	Townsville AMO	19.15	146.46	7	A (U)	R, J, P
33119	Mackay MO	21.07	149.13	30	A (LT)	R, J, P, T
34002	Charters Towers PO	20.04	146.16	310	ST	P, T*
34084	Charters Towers AP	20.02	146.16	291	A (ST)	P, T*
36007	Barcaldine PO	23.33	145.17	267	ST	P, T
36030	Longreach PO	23.27	144.15	191	ST	R, J, T
36031	Longreach AP	23.26	144.16	192	A (ST)	R, J, T
37010	Camooweal PO	19.55	138.07	233	R	T
38002	Birdsville PS	25.54	139.20	46	R	R
38003	Boulia PO	22.55	139.54	156	R	T
39015	Bundaberg PO	24.52	152.20	14	LT	P, T*
39128	Bundaberg AP	24.54	152.19	30	A (LT)	P, T*
39039	Gayndah PO	25.38	151.37	106	ST	T
39083	Rockhampton AMO	23.22	150.28	10	A (LT)	R, J, P, T*
40004	Amberley AMO	27.38	152.43	27	A (U)	R, J
40223	Brisbane AP	27.23	153.07	4	A (U)	J, T*
40264	Tewantin PO	26.23	153.02	8	LT	R, P
40908	Tewantin AWS	26.23	153.02	6	LT	R, P
42023	Miles PO	26.39	150.11	305	ST	R, T
43034	St. George PO	28.02	148.35	201	ST	R, P
43109	St. George AP	28.03	148.36	198	A (ST)	R, P
44021	Charleville AMO	26.25	146.16	303	A (ST)	R, J, P, T*
45017	Thargomindah PO	24.59	143.49	129	R	R, P
46037	Tibooburra PO	29.26	142.01	183	R	R, T
46043	Wilcannia PO	31.34	143.22	76	R	T
48013	Bourke PO	30.05	145.56	106	ST	T*
48239	Bourke AP	30.02	145.57	107	A (ST)	T*
48030	Cobar PO	31.30	145.48	250	ST	R, T*
48027	Cobar MO	31.29	145.49	221	A (ST)	R, T*
52026	Walgett PO	30.01	148.07	131	ST	P, T*
52088	Walgett AP	30.02	148.07	133	A (ST)	P, T*
53027	Moree PO	29.30	149.54	207	ST	R, T*
53048	Moree MO	29.29	149.50	212	A (ST)	R, T*
55024	Gunnedah Soil Cons	31.01	150.16	307	A (ST)	R, P
56017	Inverell PO	29.46	151.07	584	ST	R, T*
56242	Inverell (new site)	29.47	151.07	582	ST	R, T*
58012	Yamba	29.26	153.22	29	A (ST)	R, T
59040	Coffs Harbour MO	30.19	153.07	5	A (LT)	R
60026	Port Macquarie	31.26	152.55	7	LT	R, T
61078	Williamtown	32.47	151.50	9	R	R
61089	Scone Soil Cons	32.04	150.55	216	A (ST)	R, T*
63005	Bathurst ARS	33.26	149.34	713	A (LT)	R, T
65012	Dubbo	32.13	148.34	275	LT	T
66062	Sydney	33.52	151.12	39	U	J, T
67033	Richmond AMO	33.36	150.46	19	A (LT)	R, T*
67105	Richmond AWS	33.36	150.46	19	A (LT)	R, T*
68034	Jervis Bay	35.05	150.48	85	R	R, P, T
68076	Nowra RAN	34.57	150.32	109	A (LT)	R
69018	Moruya Heads	35.55	150.09	17	R	R, T
70014	Canberra AMO	35.18	149.11	571	A (U)	R
72091	Cabramurra	35.56	148.23	1475	R	R, P

Table 2.1a (cont.). Final list of stations used in this study

Station number	Name	Latitude (deg S)	Longitude (deg E)	Altitude (m)	Station category	Station networks
72150	Wagga Wagga AMO	35.10	147.27	212	A (LT)	R, T*
73054	Wyalong PO	33.55	147.14	245	R	R
74128	Deniliquin PO	35.33	144.56	93	ST	R, T
76031	Mildura AMO	34.14	142.05	51	A (LT)	R, T*
78031	Nhill	36.20	141.38	133	ST	R, P, T
80023	Kerang PO	35.44	143.55	78	ST	P, T
82039	Rutherglen Research	36.06	146.30	168	A (ST)	P, T*
84016	Gabo Island	37.34	149.55	15	R	T
84030	Orbost	37.41	148.27	41	ST	R
85072	East Sale AMO	38.06	147.08	5	A (LT)	R, T*
85096	Wilsons Promontory	39.08	146.25	89	R	R, J, T
86071	Melbourne	37.48	144.58	35	U	J, T
87031	Laverton AMO	37.52	144.44	18	A (U)	R, T*
90015	Cape Otway	38.51	143.31	82	R	R, P, T
91057	Low Head	41.03	146.47	28	R	R, T
91104	Launceston AP	41.34	147.12	170	A (LT)	J, T*
92045	Eddystone Point	40.59	148.20	13	R	R
94010	Cape Bruny	43.29	147.08	55	R	R
94198	Cape Bruny AWS	43.29	147.08	60	R	R
94029	Hobart	42.53	147.19	55	U	J, T
94069	Grove Research	42.59	147.04	60	R	R, P
96003	Butlers Gorge	42.16	146.16	666	R	

Table 2.1a (cont.). Final list of stations used in this study

Explanation of symbols used in table

	Symbol	Explanation
Site	AMO MO PO PS AP AWS ARS	Airport Meteorological Office Meteorological Office Post Office Police Station Airport Automatic Weather Station Agricultural Research Station
Station location	R ST LT U A (ST)	Rural site or in settlement with population less than 1,000 Small town (population 1,000 - 10,000) Large town (population 10,000 - 100,000) Major urban centre (population greater than 100,000) Airport or similar site (e.g. research farm) in vicinity of population centre. Symbol in parentheses indicates size of associated population centre. Airports not associated with a population centre > 1,000 (e.g. Forrest, Learmonth) are shown R. All populations are as of the 1996 Census.
Station networks	R J P T	Reference Climate Station Station network used by Jones et al. (1986c) Station network used by Plummer et al. (1999) Station with long record as identified by Torok (1996) (* - as composite)

Station number	Station name	Year open	First digital data	Year closed	Population of associated centre (Census)		
					1954	1976	1996
1021	Kalumburu	1942	1957				
2012	Halls Creek AMO*	1944	1944		370	767	1263
3003	Broome AMO*	1939	1939		1093	2920	11368
4032	Port Hedland AMO*	1948	1948		895	11144	12846
5007	Learmonth AMO	1975	1975				
5026	Wittenoom PO	1952	1958			962	
6011	Carnarvon AMO*	1945	1945		1453	5341	6357
7045	Meekatharra AMO*	1950	1950		1100	829	1270
8039	Dalwallinu PO	1956	1957			683	697
8051	Geraldton AMO*	1941	1941		8308	18773	25243
9021	Perth Airport	1944	1944		348596	731275	1096829
9518	Cape Leeuwin	1897	1957				
9500	Albany Town	1880	1950+	1965	8265	13696	20493
9741	Albany AMO	1965	1965		8265	13696	20493
9541	Esperance PO	1883	1957	1969	1087	5262	8647
9789	Esperance MO	1969	1969		1087	5262	8647
10035	Cunderdin PO	1950	1957			756	715
10648	Wandering	1902	1957				
11004	Forrest AMO	1946	1946	1995			
11052	Forrest AWS	1993	1993				
12038	Kalgoorlie AMO*	1939	1939		22834	19041	28087
13017	Giles MO	1956	1956				
14015	Darwin Airport*	1941	1941		8071	41374	70251
14825	Victoria River Downs	1965	1965				
15087	Tennant Creek PO	1926	1957	1970	959	2236	3856
15135	Tennant Creek MO	1969	1969		959	2236	3856
15548	Rabbit Flat	1969	1969				
15590	Alice Springs MO*	1941	1941		2785	14149	22488
16001	Woomera AMO	1949	1949			2958	1349
16044	Tarcoola	1922	1950+	1997			
16098	Tarcoola (new site)	1997	1997				
17031	Marree PO	1939	1957			334	
17043	Oodnadatta AWS (formerly MO)	1940	1940			229	
17114	Oodnadatta PS	1985	1985	1991		229	
18012	Ceduna AMO*	1939	1939		1953	2327	2599
18070	Port Lincoln PO	1922	1957		5871	10272	11678
21046	Snowtown PO	1925	1957			511	429
22801	Cape Borda	1925	1957				
23000	Adelaide (W. Terrace)	1887	1887	1979	483535	857196	978100
23090	Adelaide (Kent Town)	1977	1977		483535	857196	978100
23321	Nuriootpa	1952	1957		1465	2808	3486
23373	Nuriootpa AWS	1996	1996		1465	2808	3486
26021	Mt Gambier AMO*	1942	1942		10334	19292	22037
26026	Robe PO	1957	1957			490	816
27022	Thursday Island MO*	1950	1950	1993			
27042	Weipa composite	1959	1959	1994		2876	2200
27045	Weipa MO	1992	1992			2876	2200
28004	Palmerville	1907	1957				
29004	Burketown PO	1907	1957				220
30045	Richmond (Qld.) PO	1908	1957			881	733
31011	Cairns AMO*	1942	1942		21021	39305	92273

Table 2.1b. Stations used in study - opening and closing dates, city populations

Station number	Station name	Year open	First digital data	Year closed	Population of associated centre (Census)		
					1954	1976	1996
32040	Townsville AMO*	1940	1940		40485	78653	109914
33119	Mackay MO*	1959	1959		14764	31522	44880
34002	Charters Towers PO	1907	1957	1992	6960	7914	8893
34084	Charters Towers AP	1992	1992		6960	7914	8893
36007	Barcaldine PO	1913	1957+		1705	1443	1592
36030	Longreach PO	1907	1957	1973	3356	3354	3766
36031	Longreach AP	1966	1966		3356	3354	3766
37010	Camooweal PO	1907	1957	1997		322	258
38002	Birdsville PS	1954	1957				
38003	Boulia PO	1888	1949+			272	243
39015	Bundaberg PO	1907	1957	1990	19953	31189	41025
39128	Bundaberg AP	1959	1959x		19953	31189	41025
39039	Gayndah PO	1894	1957		1644	1643	1781
39083	Rockhampton AMO*	1939	1939		40676	50132	57770
40004	Amberley AMO	1941	1941		502353	892987	1291117
40223	Brisbane AP	1949	1949		502353	892987	1291117
40264	Tewantin PO	1949	1957+	1996	1766	5834	26053**
40908	Tewantin AWS	1996	1996		1766	5834	26053**
42023	Miles PO	1908	1957		1193	1367	1187
43034	St. George PO	1938	1957+	1997	1698	2095	2463
43109	St. George AP	1997	1997		1698	2095	2463
44021	Charleville AMO*	1942	1942		4517	3802	3327
45017	Thargomindah PO	1938	1957				215
46037	Tibooburra PO	1910	1921+			211	
46043	Wilcannia PO	1881	1957			1023	
48013	Bourke PO	1871	1957	1996	2642	3534	2775
48239	Bourke AP	1994	1994		2642	3534	2775
48030	Cobar PO	1890	1957	1965	2223	3339	4524
48027	Cobar MO	1962	1962		2223	3339	4524
52026	Walgett PO	1878	1957	1993	1348	2253	1970
52088	Walgett AP	1993	1993		1348	2253	1970
53027	Moree PO	1879	1879+	1966	5501	9359	9270
53048	Moree MO	1964	1964		5501	9359	9270
55024	Gunnedah Soil Cons*	1948	1959+		5129	8689	8315
56017	Inverell PO	1907	1957	1997	7517	9432	9378
56242	Inverell (new site)	1995	1995		7517	9432	9378
58012	Yamba	1877	1921+			1649	4721
59040	Coffs Harbour MO*	1943	1943		6214	12197	22177
60026	Port Macquarie	1907	1921+		4423	13362	33709
61078	Williamtown	1942	1942				
61089	Scone Soil Cons*	1952	1959+		3351	3424	3468
63005	Bathurst ARS*	1909	1909+		16090	18589	26029
65012	Dubbo	1871	1957		12025	20149	30102
66062	Sydney	1859	1859		1863217	2765040	3276207
67033	Richmond AMO*	1939	1939	1994	9867	13340	21317
67105	Richmond AWS	1994	1994		9867	13340	21317
68034	Jervis Bay	1907	1921+				
68076	Nowra	1955	1955		5981	15496	23823
69018	Moruya Heads	1876	1921+				
70014	Canberra AMO*	1939	1939		35584#	213055#	324932#
72091	Cabramurra	1962	1962				203
72150	Wagga Wagga AMO*	1942	1942		19243	32984	42848
73054	Wyalong PO	1950	1959+				
74128	Deniliquin PO	1858	1949+		4705	6865	7816

Table 2.1b (cont.). Stations used in study - opening and closing dates, city populations

Station number	Station name	Year open	First digital data	Year closed	Population of associated centre (Census)		
					1954	1976	1996
76031	Mildura AMO*	1946	1946		10971	14417	24142
78031	Nhill	1897	1951		2208	2124	1890
80023	Kerang PO	1903	1957+		3326	4022	3883
82039	Rutherglen Research	1913	1957+		1912	1325	1904
84016	Gabo Island	1877	1957				
84030	Orbost	1938	1957		2215	2789	2150
85072	East Sale AMO*	1945	1945		6536	12111	13366
85096	Wilsons Promontory	1877	1890+				
86071	Melbourne	1855	1855		1524062	2479225	2865329
87031	Laverton AMO*	1943	1943		1524062	2479225	2865329
90015	Cape Otway	1865	1957				
91057	Low Head	1895	1957				
91104	Launceston AP	1939	1939		49310	63386	67701
92045	Eddystone Point	1957	1957				
94010	Cape Bruny	1924	1957				
94198	Cape Bruny AWS	1997	1997				
94029	Hobart	1881	1944		95223	131524	126118
94069	Grove Research	1952	1957				
96003	Butlers Gorge	1944	1957	1993			

Table 2.1b (cont.). Stations used in study - opening and closing dates, city populations

Symbols used in the table:

- * Another station in the area (usually without digital daily records) exists and could potentially be used as a composite to extend the data back in time.
- \+ Includes data digitised manually as part of this and other projects that is not available through regular Bureau channels.
- x Bundaberg Airport has data for 1959-71 and 1990 onwards. The 1959-71 data is used for comparison purposes only.
- ** Combined population of Tewantin-Noosa.
- \# Combined population of Canberra-Queanbeyan.

Dates given under 'year open' are the earliest year for which monthly temperature data is available in the Bureau digital archives. Some data exists from prior to this date at a number of stations (notably Robe). There are breaks in the data at some stations. All stations without a closure date listed are currently open.

network (possibly using additional stations with data from 1908 or earlier to supplement the numerous Meteorological Office sites that opened between 1939 and 1950), and the coverage of central Australia will be more limited than it is with the present network.

Chapter 3

Some systematic issues influencing quality of daily temperature data in Australia

3.1. Introduction

Climate data are subject to numerous systematic inhomogeneities. These inhomogeneities, which are elaborated on in Chapter 4, include station moves, instrument changes, changes in site condition and local land use and changes in observation practices. A crucial aspect of the development of any high-quality temperature data set is the manner in which data are adjusted to remove these inhomogeneities from the climate record. This is a particular challenge in the case of daily data. A new technique for the adjustment of daily data is presented in section 3.2.

Two issues which have the potential to affect temperature records in a systematic manner are changes in the time of observation, and the use of accumulated data after a missed observation. These are discussed in sections 3.3 and 3.4 respectively.

3.2. Methods of producing composite daily temperature data sets from inhomogeneous data

Standard procedures for adjustments of mean temperatures in order to remove non-climatic inhomogeneities have relied on the implicit assumption that, if two neighbouring stations have homogeneous records over some period of time, the difference in daily maximum (or minimum) temperature between them will be a constant for any day in a given month of the year. This implies that the difference in monthly means will be constant for that month from year to year. This assumption is inherent in works such as Barger and Nyhan (1960), Karl and Williams (1987), Torok (1996), Torok and Nicholls (1996), and has been built into software systems such as the THOMAS system used in Slovakia and Switzerland (Begert et al., 1998) and the MASH system developed in Hungary (Szentimrey, 1998), which has been widely used in the development of indices of extreme climate events (e.g. Manton et al., 2001). In one of the few attempts to produce homogenised series of extreme event frequencies, in Austria (Auer et al., 1998), uniform monthly adjustments were applied to daily data. It appears to originate from work by Mitchell (1961), who established that there was no relationship between the difference in mean monthly temperature for February between two sites at Blue Hill, Massachusetts (one on the summit, one at the base) and the actual temperature at one of the sites. Since that time, refinements of methods for removing inhomogeneities (e.g. Karl and Williams, 1987) have concentrated on the accurate determination of the point in a record at which an inhomogeneity exists, and the selection of the most appropriate neighbouring station(s) for use in adjustment.

A different approach was adopted in a very recent paper by Allen and DeGaetano (2000), who were investigating inhomogeneities in time series of the number of days per year above or below given thresholds. They initially used metadata to identify potential inhomogeneities (although they note that the use of metadata is not fundamental to their technique, and that statistical techniques could be used instead), compiled a difference series involving the 25th and 75th percentiles of the number of days per year above/below their chosen threshold at the candidate station and a weighted sum of neighbouring stations, and tested for changes in those difference series. They then 'adjusted' the time series by an iterative process involving the changing of their thresholds on one side of the identified inhomogeneity, until no significant change in the adjusted difference series could be identified.

It is, however, well documented that local influences on climate, such as the intensity of urban heat islands (Bernhofer, 1984; Morris and Simmonds, 2000; Morris et al., 2001) and the influence of cold-air drainage (Kalma et al, 1992) are not constants, but are dependent on factors such as wind speed and direction and cloud amount. At a site such as Blue Hill in winter, where the dominant influence on temperature is non-periodic air mass advection, these are not major factors and the assumption that temperature is independent of, say, wind speed is not unrealistic. This results in any discrepancies in the temperature differences being distributed randomly in the record and not creating a bias. However, at many sites, and in particular, in much of inland

Australia, the dominant influence on minimum temperatures is radiational cooling and thus there will be a tendency for light winds to be associated with low temperatures (Kalma et al, 1992). This is observed at Armidale (Burr, pers. comm.), one of the sites considered further in this section, where the difference in minimum temperature between the town centre site used in this study and a second site approximately 2 km to the east (which has been the Bureau of Meteorology's official site in Armidale since June 1997 but has been operating unofficially since 1981), in the outer part of the town, has a mean value of 1.5 to 2°C, but can increase to 4°C on cold, clear nights. Thompson (1973b) also found that the temperature difference between a hilltop and valley site in the Armidale area varied depending on the circulation type over the region. It is also known (e.g. Gall et al., 1992) that the difference in temperature between a poorly-ventilated instrument and a well-ventilated one will reach its maximum under sunny conditions in summer, suggesting that the temperature difference between them would increase with increasing temperature. The assumption that the temperature difference between any two nearby sites is always constant must therefore be questioned.

This section proposes alternative methods for constructing composite daily temperature records where that assumption breaks down, using four station pairs in south-eastern Australia. While this is only a small part of the globe, the results obtained are potentially of wide general applicability.

3.2.1. Methods and station selection

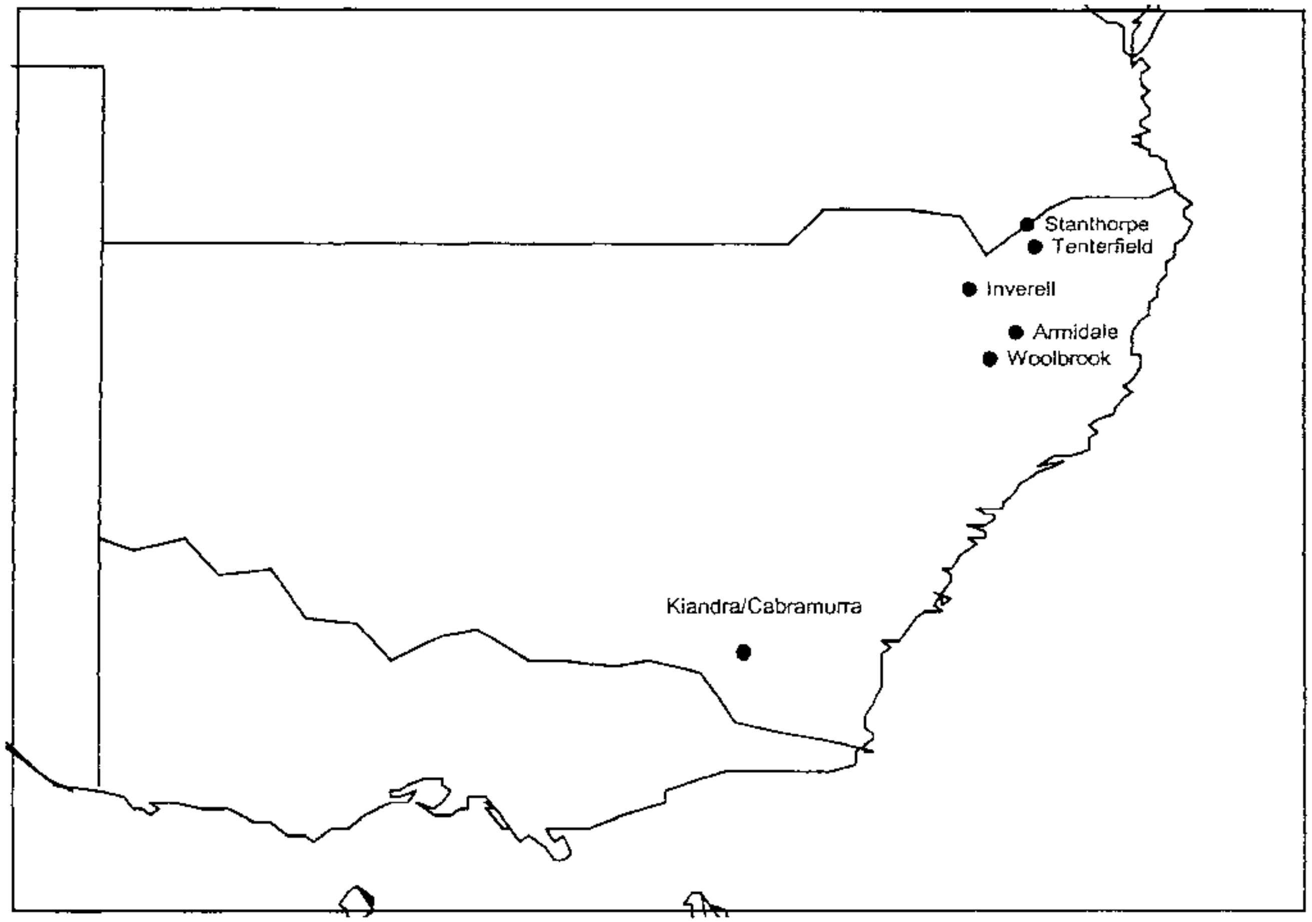
Fig. 3.1 shows the location of the stations used in this section, with Table 3.1 giving details of the sites. Station pairs were selected with the intention of illustrating the varying influences on temperature at contrasting sites. The dominant contrast at these sites is topography and exposure. While, ideally, a pair would have been investigated in order to show the effect of an urban and non-urban site, to achieve this it would be necessary to choose an urban centre in a flat region (to remove any effects of topography) away from the coast (to remove the influence of exposure to the ocean). There are few centres of this type in Australia with populations in excess of 10,000, and none of those that exist (e.g. Dubbo, Wagga Wagga) have a pair of stations, one urban and the other non-urban, with a reasonable period of overlap. Stanthorpe and Tenterfield, a pair of sites with very similar characteristics, may be regarded as a 'control' pair which illustrates conditions at stations which do not show significant contrast. (This is important in the development of methods for the adjustment of data, as such methods must perform well in the case of *all* discontinuities of a record, not just those which involve a major change in topography and/or exposure). The choice of station pairs within south-eastern Australia was constrained primarily by the limited number of neighbouring sites available with a reasonable length of overlapping record. Those pairs chosen had an overlapping record of between 13 and 28 years.

The relationship between the temperature characteristics of the two sites in each pair was examined, with the aim of determining an appropriate method for use in extrapolating records at one site to records at the other. This is quite a common situation if an attempt is being made to ensure records at an old site are consistent with those at a new site (or vice versa), because a relationship between temperatures at two sites during a period of overlap can be used to estimate temperatures at one site from records taken at the other during periods when records are only available from one site. This can also be (and is in Chapter 4) extended to the comparison of records from two sites with little or no overlap with those at a third site as a method of constructing a composite record for the pair. Ideally, to optimise the accuracy of such a comparison, the period of common record should be as long as possible, providing the records of the two sites are each reasonably homogeneous during that period. In practice, the period of overlapping record associated with a station move is usually much less than 13 years, but the conclusions drawn should still be applicable to shorter records, albeit with a higher level of uncertainty.

For the duration of common record for each station pair, values were obtained at each site (subject to the conditions below) for:

(i) all daily maxima or minima for a given month of the year;
(ii) monthly mean maxima or minima for a given month for each year;
(iii) annual mean maxima or minima for each year.

Fig. 3.1. Location of stations used for development of methods used for construction of composite records



Station name	Latitude (°S)	Longitude (°E)	Altitude (m)	Years of common record	Distance between sites (km)	Location and exposure
Inverell PO Inverell SC	29.78 29.78	151.11 151.08	603.5 707.1	28	2	Vacant lot on valley floor in town centre On ridge on western edge of town
Kiandra Cabramurra	35.88 35.93	148.50 148.38	1395.4 1475.0	13	12	On slope just above valley floor, on east side of range Near top of west-facing scarp. Very exposed to prevailing westerly winds
Armidale Woolbrook	30.52 30.97	151.65 151.35	979.9 917.1	23	56	Town centre; buildings and car parks nearby; on gentle slope Valley floor in small village
Stanthorpe Tenterfield	28.65 29.05	151.93 152.02	792.2 862.6	28	44	Both sites on gentle slopes in town centres

Table 3.1. Site details for station pairs used in section 3.2.

For simplicity, these are referred to henceforth as daily, monthly, and annual 'data objects' respectively.

Days on which data were available for one site only were not considered for inclusion in data objects (or the calculations of means) at the other. If fewer than 10 days in any month had data available at both sites, the means for that month, and hence that year, were regarded as missing.

If we consider two data objects for a pair stations of the form (x_1, x_2, ...) and (y_1, y_2,...), the ordered pairs (x_1, y_1), (x_2, y_2), ... were plotted, and a linear regression equation:

$$y = a + bx$$

was fitted to the data points, using standard least-squares techniques.

3.2.2. Relationships between temperatures at paired sites

In this section, the null hypothesis that there is no relationship between the temperature difference between the paired sites and the temperature at one of those sites is tested. This is equivalent to stating that b=1 in the regression equation above. A relationship between the temperatures, rather than between the temperature difference between the sites and the temperature at one sites, is used to avoid any bias that could arise from the choice of one or other of the paired sites as the 'base' against which the temperature difference between the sites is compared. The tests of significance used are also based on the relationship between the temperatures at the paired sites.

Tables 3.2 and 3.3 indicate months in which b departs from 1 at given levels of significance. The relationships shown for daily, monthly, and yearly data objects, respectively, in these tables are further illustrated by Figs. 3.2 and 3.3. In order to make departures from the assumption of a constant difference more visually apparent, one of the axes in each of these graphs is the temperature difference between the two sites rather than the temperature at the second site.

Table 3.2 shows a highly significant departure of the coefficient b from 1 for daily minima in all months at three of the four station pairs: Inverell, Kiandra-Cabramurra and Armidale-Woolbrook. There is also a significant departure for daily maxima in most autumn and winter months at each of these pairs except Kiandra-Cabramurra. There is much less evidence of a relationship in either case at the 'control' pair of Stanthorpe-Tenterfield.

Table 3.3 indicates that a significant departure also exists for monthly mean minima in most months at three of the pairs: Inverell, Kiandra-Cabramurra and Armidale-Woolbrook. These are the three pairs where the sites contrast substantially in local topography. Except at Armidale-Woolbrook, significant departures also exist for annual mean minima.

3.2.3. Comparison of percentile points in overlapping temperature records

The use of regression relationships indicates the presence of a statistically significant dependence of temperature difference between sites on the temperature at one site for some of the station pairs used in this study. It does not necessarily follow from this that the relationship is linear.

Fig. 3.4, showing the frequency distribution of July minimum temperatures at the two Inverell sites, and Fig. 3.5, giving specific points in these frequency distributions, illustrate possible non-linearities in such relationships. Assuming that there is no systematic difference in rank order of temperature between the two sites, the expected difference in temperature between the sites is approximately constant for the coldest 65 percent of nights; it is only in the upper 35 percent of the frequency distribution that the difference decreases.

Month	Station pair							
	Inverell		Kiandra-Cabramurra		Stanthorpe-Tenterfield		Armidale-Woolbrook	
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
January		1		1			5	1
February	5	1		1		5		1
March	5	1		1				1
April		1		1		5	5	1
May	1	1		1		1	1	1
June	1	1		1			1	
July	5	1		1			1	1
August	5	1		1		5	1	1
September		1		1				1
October		1		1		5		1
November		1		1				1
December		1		1				1

Table 3.2. Statistical significance of departures from unity in the slope of the regression line relating data at each station pair; daily maximum and minimum temperatures. '1' and '5' denote a departure from unity in the slope of the regression line, b, significant at the 1 per cent or 5 per cent levels respectively. A blank entry denotes no departure significant at the 5% level.

Month	Station pair							
	Inverell		Kiandra-Cabramurra		Stanthorpe-Tenterfield		Armidale-Woolbrook	
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
January		5		1				5
February	1							
March		1		5				5
April		5					5	
May		1		1				
June		1		1				5
July		1		1				
August		1						1
September		5						
October								
November		1						
December		1						1
Annual		1		1				

Table 3.3. Statistical significance of departures from unity in the slope of the regression line relating data at each station pair; monthly and annual mean maximum and minimum temperatures. The usage of '1' and '5' in the table is as for Table 3.2.

Fig. 3.2. Relationship between July daily minimum temperatures at Inverell PO and Inverell SC

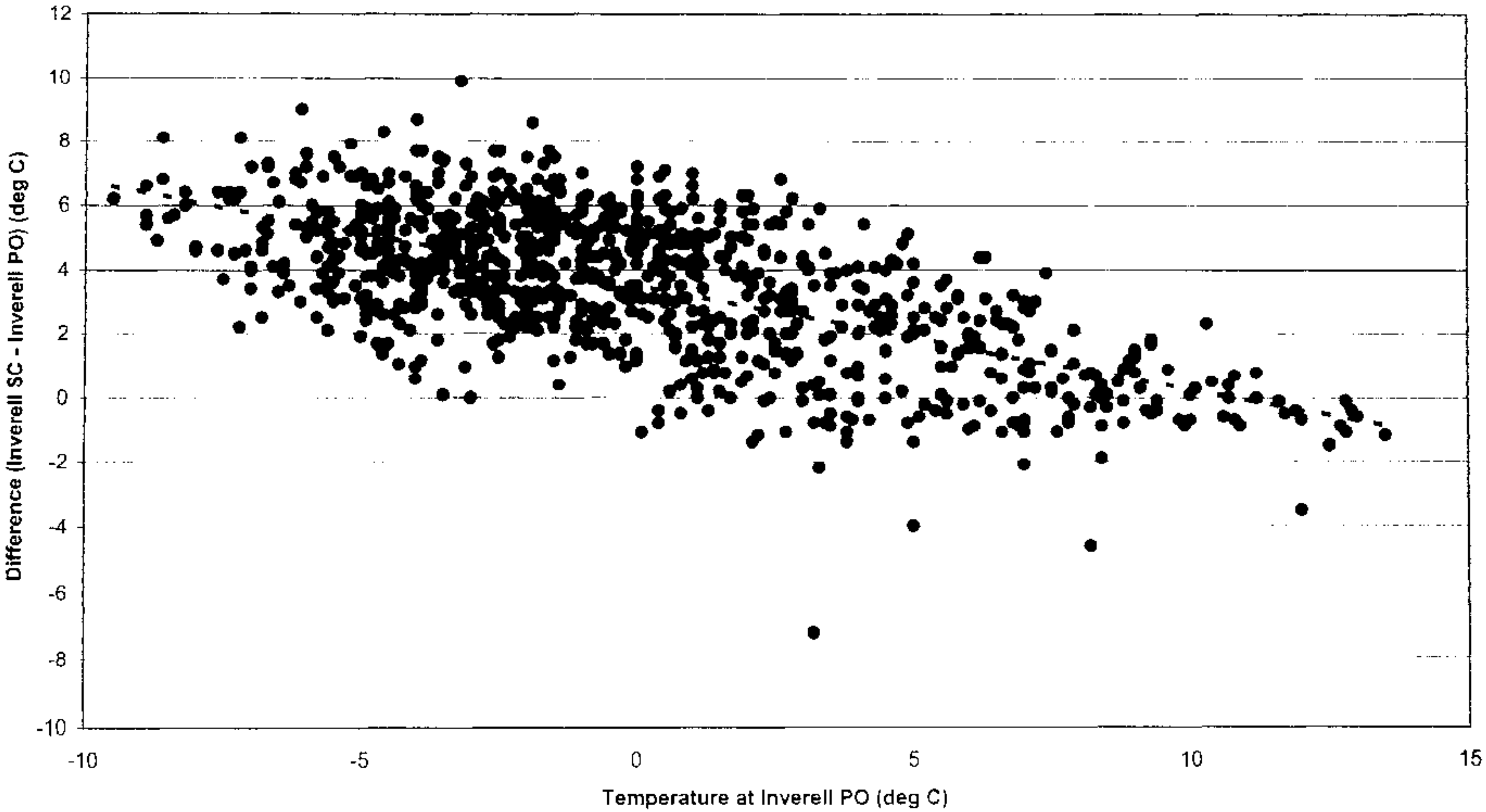


Fig. 3.3a. Relationship between June monthly mean minimum temperatures at Inverell PO and Inverell SC

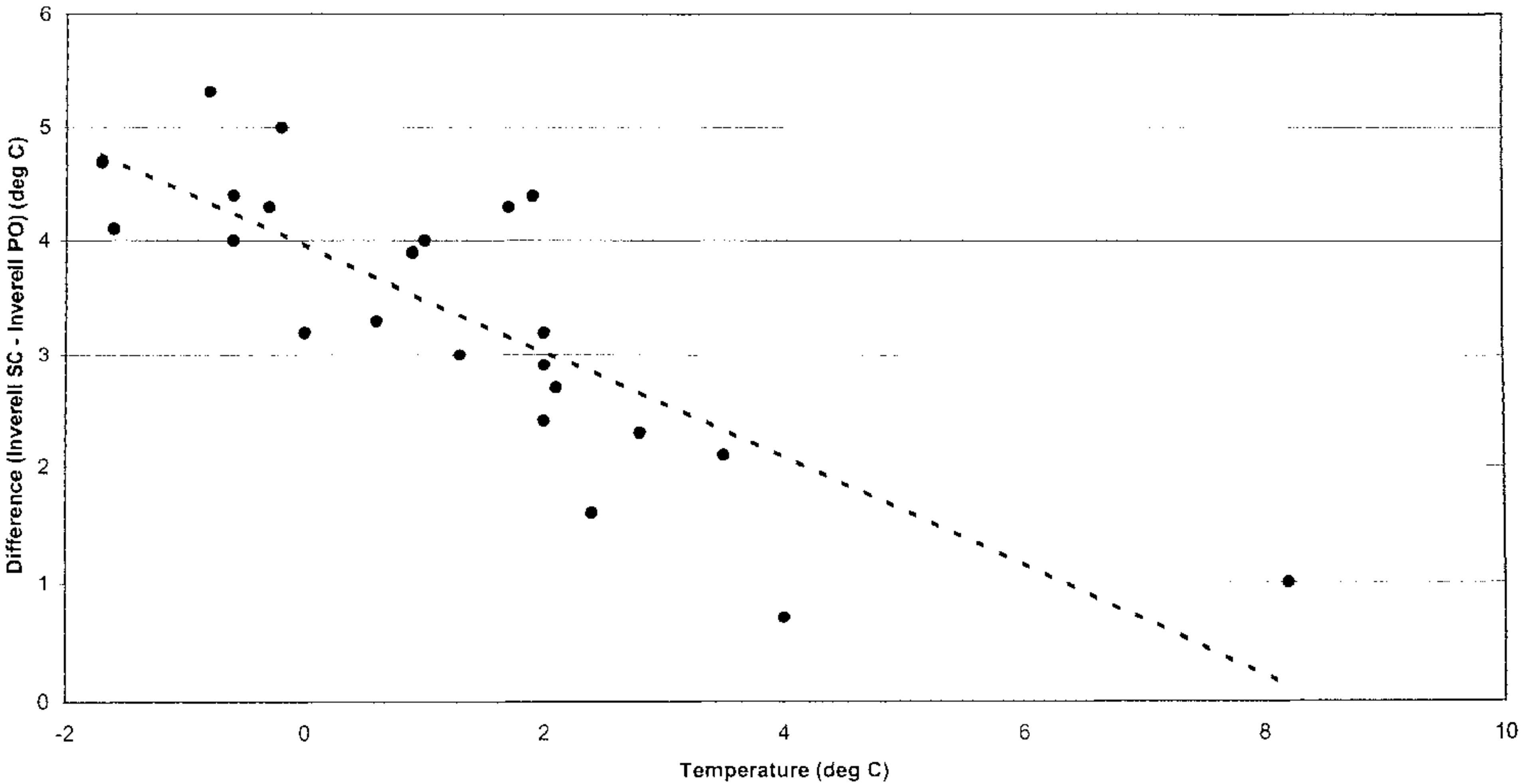


Fig. 3.3b. Relationship between mean annual minima at Inverell PO and Inverell SC

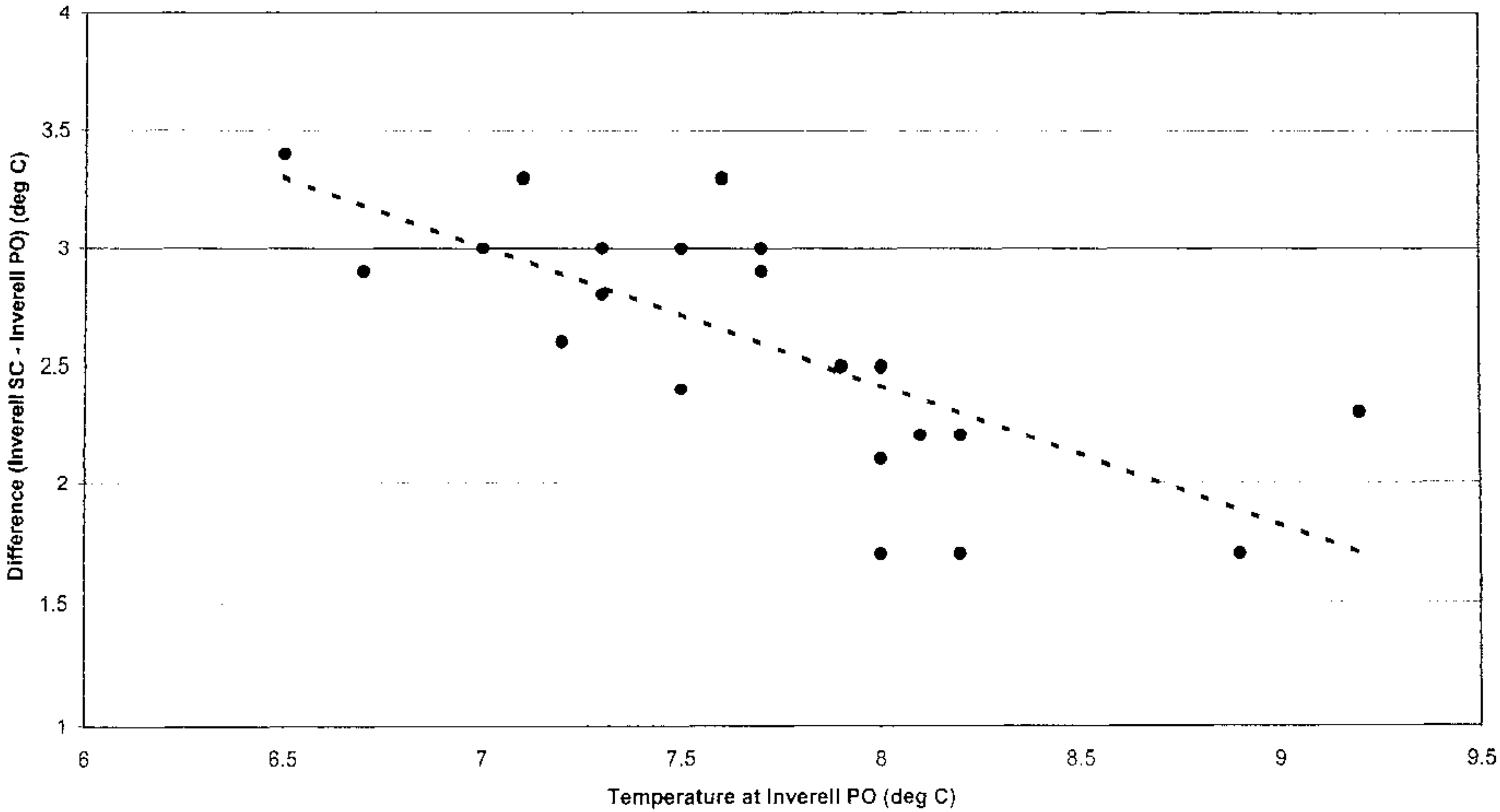


Fig. 3.4. Frequency distributions of July daily minimum temperatures at Inverell PO and Inverell SC

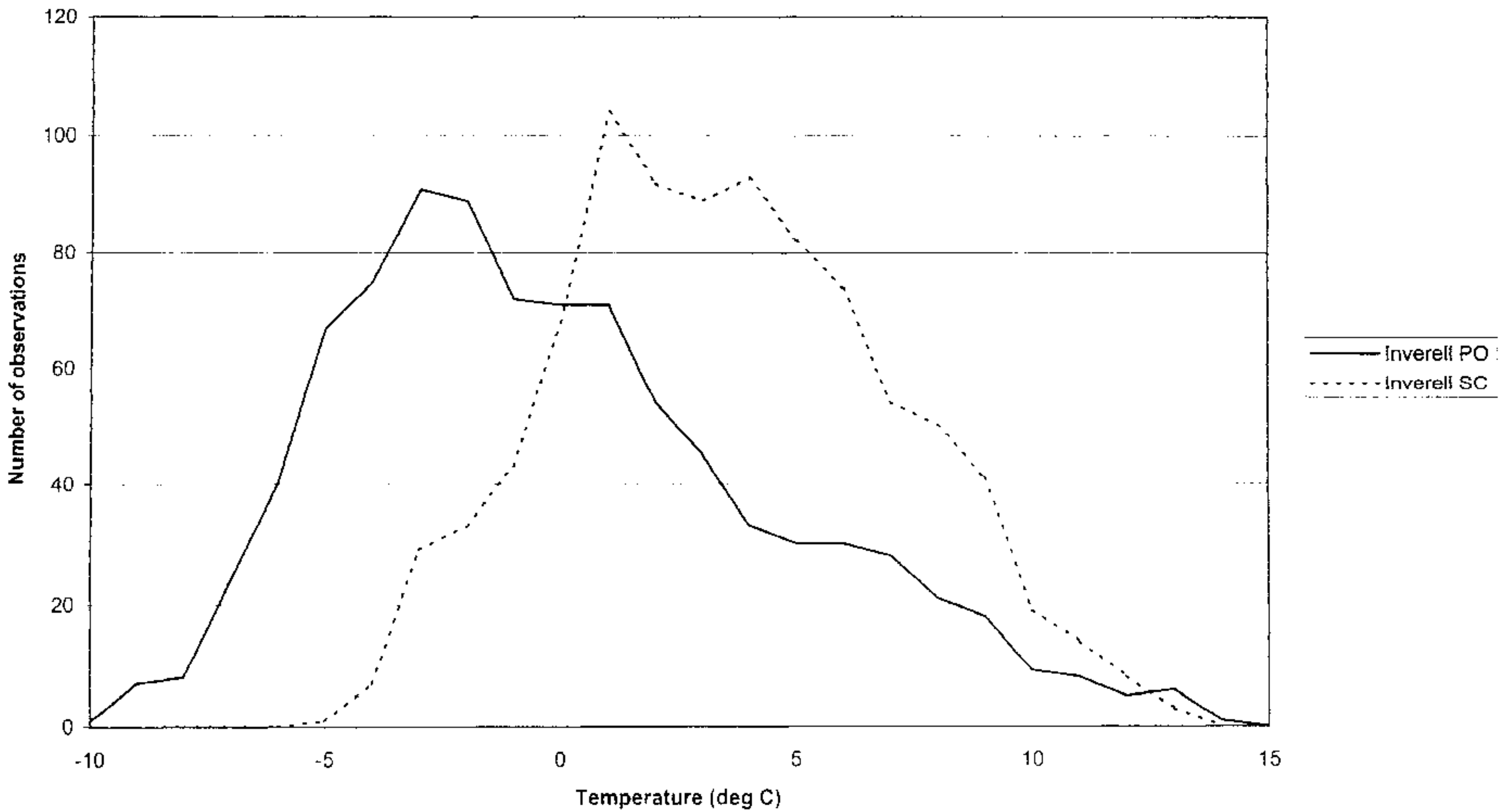
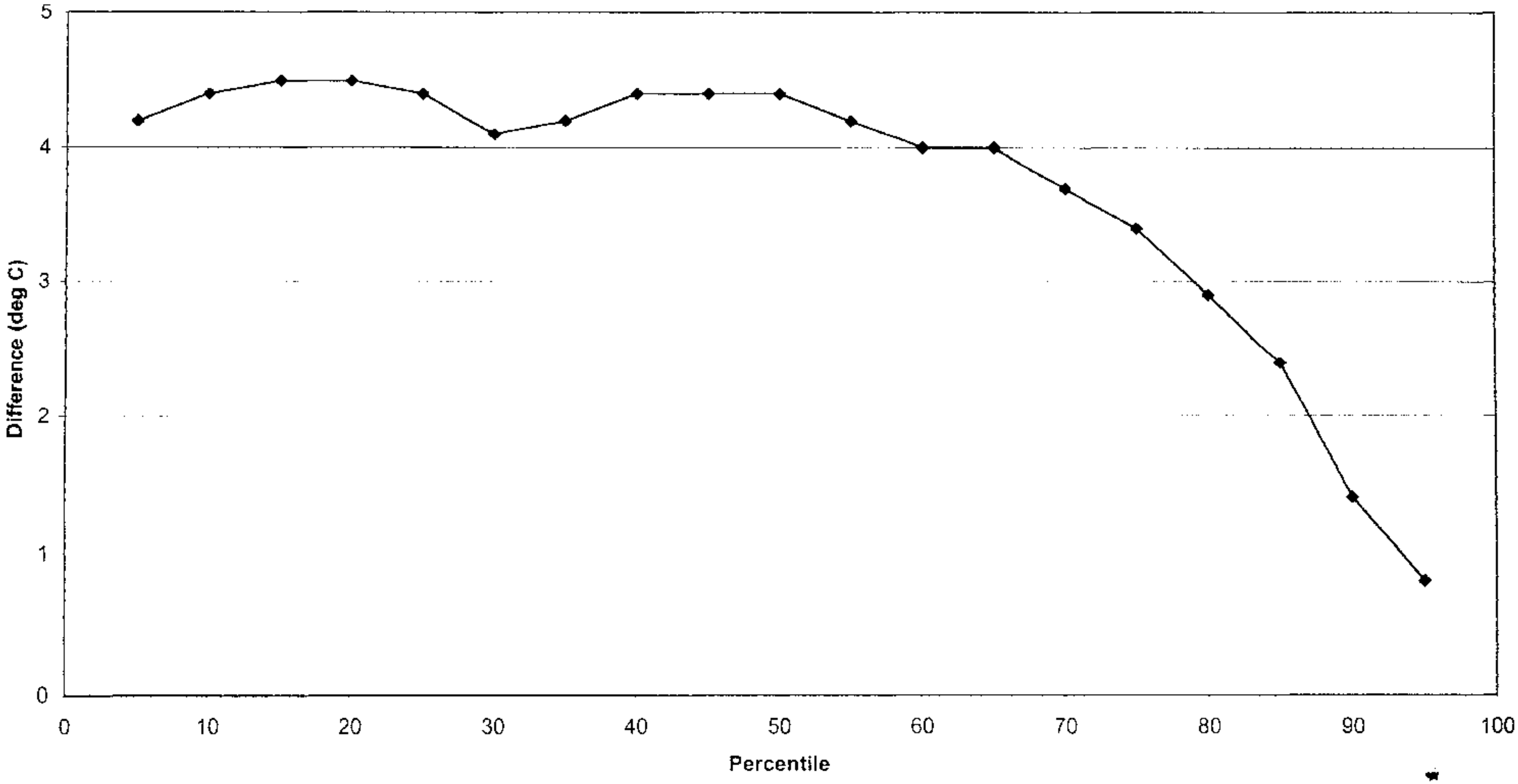


Fig. 3.5. Difference between percentile points of frequency distributions of July daily minimum temperatures at Inverell PO and Soil Conservation Research Station



3.2.4. Possible techniques for the interpolation of temperature records

As a result of the relationships found above between temperatures at adjoining sites, three techniques were considered for the interpolation of records. In each case, the full period of available common record for a given station pair was used as a base for calculating the parameters used in the interpolation, in which a synthetic series of daily maxima and minima at one station was created using data from the other in the pair.

(a) <u>The 'traditional' constant-difference approach</u>

The difference in maximum (or minimum) temperature between the sites on each day was taken as the difference between the mean monthly maxima (or minima) at the two sites for the month concerned during the period of overlap.

(b) <u>The 'regression' method</u>

The coefficients and equation generated in section 3.2.1 were used to estimate temperatures at one site using those at the other.

(c) <u>Frequency distribution matching</u>

The 5 through to 95 percentile points (at 5 percentile intervals) for daily maxima and minima for each month at each site, using data from the period of overlap, were calculated. These points were denoted 'matching points'. To create a synthetic series, the position of each day's temperature at the first site in the appropriate frequency distribution was found, and the temperature difference between the sites estimated using the formula:

$$T_2 - T_1 = T_{1,i} + \frac{(T_{2,(i+5)} - T_{2,i})(T_1 - T_{1,i})}{(T_{1,(i+5)} - T_{1,i})}$$

where T_2 denotes the estimated temperature at the second site

T_1 the actual temperature at the first site

$T_{1,i}$ the nearest matching point below T_1 in the frequency distribution of temperature at the first site (the i-th percentile)

$T_{2,i}$ the i-th percentile point in the frequency distribution at the second site

Where T_1 is below the 5 percentile or above the 95 percentile level, the temperature difference between the sites was taken as $(T_{2,5} - T_{1,5})$ or $(T_{2,95} - T_{1,95})$ respectively. An alternative would be to use the highest or lowest temperature on record as matching points, but this would be very sensitive to individual, and possibly erroneous, outlying observations.

T_2 was then found using the difference found above and the known value of T_1.

3.2.5. An evaluation of the techniques for composite record development

A number of indicators were chosen to assess the accuracy with which the procedures considered simulated the actual temperature record. These were chosen to reflect possible features that may be of interest in the investigation of a temperature record: the accuracy of the record as a whole, the frequency of temperatures above or below a certain level (e.g. the frequency of frost), and the highest and lowest temperature in the record.

Firstly, each of the three synthetic series was compared with the actual record for that site, and a root-mean-square error (E_{rms}) calculated for each month, using:

$$E_{rms} = \sqrt{\sum_{i=1}^{n} \frac{(T_i - P_i)^2}{n}}$$

where T_i represents the actual maximum or minimum temperature (or mean maximum or minimum in the appropriate tables)

P_i the modelled maximum or minimum temperature

n the number of observations considered.

Results of this procedure are given in Tables 3.4a, 3.4b and 3.4c.

Tables 3.5 and 3.6 show the estimated frequency and magnitude of extreme events using the three procedures. The need for a separate consideration of extreme events is illustrated by Fig. 3.5, which shows the non-linearity of the relationship between winter minimum temperatures at the two Inverell sites. This shows that, although assuming a constant temperature difference will lead to an underestimate of the temperature difference on the coldest nights, attempting to represent the difference by a linear relationship will lead to an overestimate of the difference. In the case of Inverell, Table 3.5 shows that procedure B underestimates the frequency of minima below 0°C at the Soil Conservation Research Station.

Tables 3.4a, 3.4b, 3.4c, 3.5 and 3.6 indicate that, for two of the site pairs (Stanthorpe-Tenterfield and Armidale-Woolbrook) the difference between the outcomes of procedures A, B and C, regardless of the indicator of accuracy chosen, is minimal. These two pairs of sites are those with the weakest relationships between temperature difference and temperature, as indicated by Tables 3.2 and 3.3. Where there is no evidence of any relationship, as at Stanthorpe-Tenterfield, the results of the three procedures converge, as expected. If there is no relationship at all, the slope of the regression line in procedure B will be 1.0 and procedures A and B will therefore be equivalent; similarly, the difference between the various pairs of percentile points in procedure C will be constant. It may be noted at this point that, by definition, the parameters of the regression line in procedure B are chosen in order to minimise the value of E_{rms}, and hence the value of E_{rms} for procedure A is an upper bound for that found by using procedure B.

Month	Station name											
	Inverell SC			Cabramurra			Tenterfield			Woolbrook		
	Procedure			Procedure			Procedure			Procedure		
	A	B	C	A	B	C	A	B	C	A	B	C
January	1.76	1.19	1.26	3.74	3.26	3.72	1.60	1.60	1.65	2.16	2.16	2.22
February	1.66	1.07	1.10	3.91	3.47	4.04	1.61	1.59	1.67	1.83	1.83	1.90
March	1.92	1.35	1.37	4.16	3.41	3.90	1.68	1.67	1.77	2.29	2.28	2.41
April	1.86	1.32	1.34	4.43	3.06	3.72	1.91	1.88	1.97	2.56	2.55	2.66
May	2.16	1.65	1.64	4.19	2.98	3.47	1.88	1.80	1.88	2.57	2.56	2.66
June	2.34	1.71	1.73	3.73	2.15	2.48	1.95	1.92	1.97	2.28	2.26	2.34
July	2.27	1.71	1.74	4.32	1.94	2.45	2.07	2.04	2.06	2.35	2.30	2.36
August	2.15	1.62	1.64	3.40	2.18	2.28	2.00	1.96	2.00	2.31	2.31	2.39
September	2.24	1.72	1.75	3.01	2.42	2.71	2.00	1.97	2.02	2.33	2.33	2.43
October	2.31	1.73	1.77	3.52	3.17	3.60	1.85	1.82	1.88	2.27	2.26	2.37
November	2.20	1.65	1.71	3.33	3.72	3.76	1.64	1.63	1.67	2.27	2.27	2.38
December	2.13	1.51	1.61	3.51	3.21	3.57	1.76	1.76	1.84	2.41	2.41	2.50

Table 3.4a. Values of E_{rms} (°C) for stations for each month: daily minimum temperature

At the other two site pairs (the Inverell sites and Kiandra-Cabramurra), procedures B and C provide substantial improvements over procedure A on all indicators given in nearly all months when used for minimum temperatures. These are the two pairs with strong relationships between temperature differences and temperatures for both daily and monthly mean temperatures, and relatively little scatter of points about a line of best-fit. They are also the two pairs with the greatest potential influence of topographic contrasts on microclimate.

In these two cases, procedures B and C provide substantial improvements on procedure A on all indicators, but their performance relative to each other depends on the performance indicator chosen. This reflects, in part, biases in the performance indicators. A regression procedure aims specifically to minimise the value of E_{rms}, the only constraint being that the relationship must be linear. It is therefore not surprising that procedure B produces consistently lower values of E_{rms} than procedure C, but the differences are small in most cases: only for minima at Kiandra-Cabramurra does the difference exceed 6 percent in any month.

Table 3.5, conversely, indicates that differences in the expected frequency of low temperatures derived from procedures B and C are quite dramatic at Inverell and Kiandra-Cabramurra. At both locations, procedure B underestimates the expected frequency of low temperatures at the second site by a margin comparable to the overestimate arising from procedure A. Procedure C, on the other hand, performs well - a reflection of its basis in the comparison of frequency distributions of temperature at the paired sites. This, not surprisingly, leads to good performance on indicators that relate to the expected frequency of temperatures above or below a certain level.

In order to quantify the extent to which the indicated performance of procedure C was attributable to the use of the frequency distributions for the full period as a basis, the procedure was repeated for the two Inverell sites, but using only part of the overlapping data as the set for the derivation of the frequency distributions used in matching data from the two stations. This was done four times, each using a separate set of overlap data comprising 150 pairs of observations for each month (approximately 5 years of data, depending on month lengths and the distribution of

Month	Station name											
	Inverell SC			Cabramurra			Tenterfield			Woolbrook		
	Procedure			Procedure			Procedure			Procedure		
	A	B	C	A	B	C	A	B	C	A	B	C
January	0.85	0.82	0.86	1.38	1.34	1.39	1.58	1.58	1.62	1.89	1.81	1.86
February	0.89	0.85	0.87	1.36	1.36	1.39	1.41	1.41	1.44	1.74	1.58	1.63
March	0.92	0.88	0.90	1.32	1.29	1.32	1.42	1.42	1.45	1.88	1.67	1.72
April	0.80	0.78	0.79	1.41	1.39	1.42	1.36	1.36	1.40	1.65	1.55	1.61
May	0.85	0.78	0.80	1.17	1.12	1.18	1.41	1.41	1.44	1.65	1.64	1.70
June	0.87	0.80	0.81	1.33	1.30	1.35	1.39	1.38	1.40	1.70	1.70	1.75
July	0.74	0.69	0.70	1.12	1.08	1.11	1.26	1.25	1.27	1.49	1.49	1.53
August	0.88	0.84	0.84	1.31	1.25	1.31	1.25	1.25	1.28	1.43	1.42	1.47
September	0.85	0.82	0.81	1.41	1.37	1.43	1.21	1.21	1.22	1.44	1.42	1.45
October	0.78	0.75	0.76	1.55	1.51	1.58	1.43	1.43	1.44	1.56	1.49	1.54
November	1.07	1.06	1.07	1.24	1.24	1.25	1.49	1.49	1.52	1.64	1.55	1.55
December	0.93	0.90	0.91	1.33	1.33	1.34	1.45	1.45	1.50	1.68	1.61	1.62

Table 3.4b. Values of E_{rms} (°C) for stations for each month: daily maximum temperature

Station name	Minimum temperatures			Maximum temperatures		
	Daily	Monthly	Annual	Daily	Monthly	Annual
Inverell SC	0.356	0.337	0.322	0.352	0.337	0.329
Cabramurra	0.339	0.316	0.305	0.126	0.115	0.118
Tenterfield	0.269	0.261	0.265	0.410	0.403	0.409
Woolbrook	0.344	0.327	0.350	0.360	0.342	0.352

Table 3.4c. Values of E_{rms} (°C) for annual mean temperatures estimated by performing procedure B (regression) on daily, monthly mean, and annual mean temperatures

Station name	Actual frequency of event (%)	Frequency of event (%) predicted by procedure		
		A	B	C
Inverell SC	2.6	4.3	1.3	2.7
Cabramurra	7.6	11.5	2.5	8.0
Tenterfield	12.5	13.8	13.0	13.6
Woolbrook	23.5	23.2	23.0	23.8

Table 3.5. Frequency of nights with temperature below 0°C (-3°C at Cabramurra) in the period of overlap for each site pair: actual and estimated by the three interpolation procedures described in the text

Station name	Highest on record				Lowest on record			
	Actual	Estimated by procedure			Actual	Estimated by procedure		
		A	B	C		A	B	C
Inverell SC	38.5	37.9	37.4	38.0	-5.1	-5.8	-2.8	-5.3
Cabramurra	31.9	32.0	31.5	32.3	-11.2	-15.4	-6.8	-11.3
Tenterfield	37.5	37.3	37.2	38.4	-9.9	-9.6	-8.9	-9.9
Woolbrook	37.0	37.1	35.2	36.8	-12.8	-11.4	-12.5	-12.9

Table 3.6. Highest and lowest temperatures (°C) during period of overlap; actual and estimated by the procedures outlined in the text

missing data through the year), in order to more closely simulate the usual situation, where the overlap data available is a subset of the period of record at the site whose records are being used in the interpolation.

Table 3.7 shows the results of applying the performance indicators used in Tables 3.5 and 3.6 to the synthetic data series generated using subsets of the full data set as the basis set. Calculation of the mean of the four trials, which produces estimated extreme temperatures and frequency of minima below 0°C close to the actual values, provides no evidence of any systematic bias in procedure C. Furthermore, although there is some variation depending on the basis sample chosen, for minimum temperature at Inverell the absolute minimum using the second basis set was the only parameter that was less accurately predicted using this method than it was by procedures A or B.

3.2.6. Explanation and implications of relationships between temperatures at paired sites

Conventional procedures, as described in the introduction to section 3.2, for developing composite temperature records implicitly assume that the nature of the frequency distribution of temperature at the new site is the same as that at the old. Some difficulties posed by that assumption are illustrated in Figs. 3.4 and 3.5. At Inverell, the variability of winter minimum temperature is greater at the Post Office site, as illustrated by the standard deviation of July minima, which is 4.4°C there and only 3.5°C at the Soil Conservation Research Station. Furthermore, the frequency distribution of minimum temperature displays greater positive skew at the Post Office. These factors combine to render the temperature difference between the sites strongly dependent on temperature at one site.

This also has implications for the expected frequency and magnitude of extreme events. It has been demonstrated (Katz and Brown, 1992) that the frequency of extreme events is influenced by the variability of temperature at a site as well as the mean temperature, an aspect which is discussed in much more detail in Chapter 6. Any discontinuity in the variability of temperature in a record will hence cause a discontinuity in the frequency of extreme events, even if the mean temperature remains unchanged.

A similar effect is visible at Kiandra-Cabramurra. The assumption of a constant difference is particularly unjustified at these sites; the estimated absolute minimum at Cabramurra using such a procedure is 4.2°C too low (Table 3.6).

Differences in the nature of the frequency distribution of temperature between two neighbouring sites may arise from the presence of an additional influence on temperature over and above its usual day-to-day variability. Examples of such influences are the presence or absence of an urban heat island, cold air drainage under clear, calm conditions, or moderating ocean influences. The first two particularly affect daily minimum temperatures. The results suggest that stations which contrast strongly in local topography will also tend to have strongly contrasting frequency distributions.

The station pair with the weakest relationships between temperature difference and temperature, and hence the one where the alternative techniques discussed here produce results comparable to conventional procedures, is Stanthorpe-Tenterfield. Because it was chosen as a 'control' pair with similar site characteristics, the similar frequency distribution characteristics are to be expected.

Similar relationships between temperature difference and temperature exist for mean monthly and annual temperature as for daily temperatures, but are, in general, somewhat weaker (Tables 3.2 and 3.3). This is not an unexpected result, because at the sites with the strongest relationships (Inverell and Kiandra-Cabramurra), an anomalously cold month could be expected to contain an anomalously large number of cold nights, which could be expected to have an above-normal temperature difference between the sites. The difference in mean temperature between the sites could therefore be expected to be greater than normal. The reverse applies for anomalously warm months. The relationships are damped by the presence of some mild days in cold months (or vice versa), acting counter to the overall trend for the month. This accounts for the generally lower level of significance exhibited by the

Basis period	Percentage of days below 0°C	Highest temperature on record (°C)	Lowest temperature on record (°C)
1st	4.0	37.8	-4.9
2nd	1.6	38.0	-6.3
3rd	2.3	38.2	-3.9
4th	2.8	37.7	-5.3
Mean over all basis periods	2.7	37.9	-5.1
Value predicted by procedure A	4.3	37.9	-5.8
Value predicted by procedure B	1.3	37.4	-2.8
Actual values	2.6	38.5	-5.1

Table 3.7. Indicators of accuracy of simulation of temperature record at Inverell Soil Conservation Research Station using frequency distribution mapping (procedure C) with parts of the record as a basis, as discussed in text

relationships between monthly and annual mean temperatures at the paired sites and the mean temperature differences at those timescales.

Table 3.4c indicates that, despite this lower level of significance, performing the regression procedure on monthly or annual mean temperatures generally produces slightly more accurate estimates of annual mean temperature than performing the same procedure on daily temperatures. The differences are relatively small and may be influenced by the previously discussed biases involved in using the value of E_{rms} as an indicator of the accuracy of a regression model.

3.2.7. Summary

In this section, it is demonstrated that, at some sites, particularly those where topography has a substantial impact upon the temperature regime, a temperature-dependent technique for extrapolating temperature extremes at one site to a second site is of value. There are certain localities where the temperature difference between two paired sites cannot be assumed to be constant in all conditions. Assumption of a constant difference may lead to a bias in the predicted variability of temperature at the sites, and a consequent bias in the predicted frequency of extreme events, given the previously discussed influence of variability on the frequency of extreme temperature events. This may have important consequences in the determination of long-term trends of extreme event frequency to be used in such applications as the investigation of global or regional climate change.

At some pairs of sites, where there is little evidence of any relationship between the temperature difference between the sites and the temperature at either site (e.g. Stanthorpe and Tenterfield), such techniques do not offer substantial improvements over the conventional constant-difference method. There is, however, no evidence that they perform any worse, and these cases therefore do not provide any justification for avoiding the use of these new approaches.

The two alternative techniques examined in this study both have certain advantages, which vary according to context. If the accurate simulation of the temperature regime as a whole is the only consideration, the regression technique may be the most appropriate, but the frequency-distribution method performs substantially better in any consideration of extreme events, while performing only marginally worse than the regression technique in term of errors over the record as a whole.

3.3. Time of observation bias in Australian temperature records

The time at which daily maximum and minimum temperature observations are taken has long been known as a potential influence on mean maximum and minimum temperatures. As long ago as the late nineteenth century, Ellis (1890) had investigated the difference in mean maximum and minimum temperatures arising from a change from an observation day ending at 0900 LST to one ending at 0000 LST.

The influence of observation time arises from the situation whereby the time of observation is close enough to the time at which the maximum (or minimum) of the diurnal cycle of temperature occurs that high maxima (or low minima) are double-counted against two separate observation days.

The problem of time of observation bias has received the greatest attention in the United States. In that country, the only stations which have a nationally uniform observation time are first-order stations (such as major city airports), which use an observation day ending at 0000 LST. Other stations use an observation day ending at a time of the observer's choice, with the most common times being around 0700 LST and 1700 LST. This leads to spatial discontinuities in reported temperatures, a problem first pointed out by Donnel (1912), and can also lead to artificial discontinuities in the climate record at a site if the observation time changes, as is quite common with a change of observer. Karl et al. (1986) point out that stations in the United States which have maintained an unchanged observation time throughout their history are rare, and furthermore, that there has been a systematic shift in observation times over the period of the climate record: in 1931, 14% of American stations used an observation day ending in the morning and 79% one ending in the afternoon, but by 1984 these proportions were 42% and 47% respectively.

There have been numerous attempts to quantify the bias in mean maximum and minimum temperatures arising from changes in observation times. Ellis (1890) found that, over a four-year period at Greenwich, England, annual mean minimum temperatures were 0.20°C higher using an observation day ending at 0900 LST than one ending at 0000 LST, with the difference reaching 0.6°C in September, and annual mean maximum temperatures were 0.08°C higher for the 0900 observation day. There have been numerous American studies, including those of Donnel (1912), Nichols (1934), Rumbaugh (1934), Mitchell (1958), Baker (1975), Schaal and Dale (1977), Blackburn (1983) and Karl et al. (1986). These found biases of varying magnitudes over the United States, with Karl et al. (1986) finding a difference between monthly mean temperatures for days ending at 1700 and 0700 LST which reached 2°C locally in winter and spring in Texas and Oklahoma. Mitchell (1958) also pointed out that the time of observation bias was very sensitive to small changes in observation time near sunrise, with the bias changing by up to 0.4°C for every hour of change in observation time. There has also been work carried out outside the United States, with Nordli (1998) finding a bias of up to 1.5°C in mean minimum temperature at some stations arising from changes in observation times for minimum temperature in Norway in 1894 and 1938.

Most of the American studies have estimated the time of observation bias using 'maximum' and 'minimum' temperatures derived from the highest and lowest of 24 hourly observations. While such a process underestimates the true daily maximum and overestimates the true minimum, with Karl et al.(1986) finding differences of 0.39°C and 0.47°C respectively for Bismarck, North Dakota, they also found that the impact of using 24 hourly measurements, as opposed to true daily maxima and minima, on the estimated time of observation bias was negligible (0.03°C). A different approach was adopted by Schaal and Dale (1977), who used reports of six-hourly minimum and maximum temperatures from Indianapolis to generate series of daily maximum and minimum temperatures for days ending at differing observation times, while Nichols (1934) estimated maxima and minima for different periods using thermograph records.

3.3.1. The Australian situation

At present, the standard observation day for daily maximum and minimum temperatures in Australia is the 24 hours ending at 0900 LST. This has been in effect since 1964, with two minor exceptions:

1. Some automatic stations report two sets of maximum and minimum temperatures: one for the standard observation day ending at 0900 LST, plus a maximum for the 24 hours ending at 1200 UTC and a minimum for the 24 hours ending at 0000 UTC. As the 0900 observations are the first to be received, they are overwritten in the Bureau of Meteorology's database by the 0000/1200 UTC observations (Wong, pers. comm..)

2. Tasmania adopted daylight saving time in the summer in 1967-68, but still used standard time (DST - 1 hour) for observations until 1971-72. In 1972-73 this was changed to 0900 daylight savings time, in line with other parts of Australia which introduced daylight saving time in that year (Bureau of Meteorology, 1988).

In effect, the introduction of daylight saving time in 1972-73 in Victoria, New South Wales, South Australia and the ACT was a shift of the observation day by one hour (to 0800 LST). Queensland and Western Australia have adopted daylight saving time briefly in the past but neither do so at present.

It has been proposed to change the observation day to one ending at either 2100 UTC or 0000 UTC in order to fall into line with WMO standard hours (Bureau of Meteorology internal circular 45/1077), but this proposal has been postponed indefinitely.

Prior to 1964, a variety of observation times were used, depending on the status of the station. It is simplest to consider 'first-order' stations (in general, those staffed by Bureau of Meteorology personnel) and second- and third-order stations (otherwise known as co-operative stations) separately.

(a) <u>First-order stations</u>

'First-order' stations recorded maximum and minimum temperatures on a 'corrected midnight-midnight' basis between 1931 and 1963 (Linforth, 1995). In practice, the maximum thermometer was reset at 0900 LST, and the minimum thermometer at 1500 LST.

Three-hourly temperature data for a number of stations suggest that, in most cases, the minimum thermometer was read at 0900 or 1500 before resetting. It was then read again at 0000. The lower of these two readings would be taken as the minimum temperature for the day. This will, in effect, be the minimum temperature for the 33 hours ending at 0000.

At some stations, the second reading of the minimum thermometer at 0000 did not take place; instead, if any three-hourly observation between 1500 and 0000 was lower than the minimum for the period ending at 0900 or 1500, that observation would be taken as the minimum for the day. (This substitution may have been done at the data processing stage). This method will produce the same result as re-reading the minimum thermometer at 0000 if the temperature falls smoothly through the evening (in which case the minimum temperature for the nine hours between 1500 and 0000 would be the temperature at 0000), but not if there are fluctuations.

For maximum temperature, adjusting to an 0000-0000 observation day was a problem, as the maximum thermometer was reset at 0900 LST and there was no way of determining the maximum for the period between 0000 and 0900, unless the highest temperature during that period exceeded the highest recorded on the previous day - there is no analogue for maxima to the reading of a minimum thermometer at 0000 without resetting. As a result, the 0000-0000 maximum temperature was usually calculated by taking the highest of the maximum temperature for the 15 hours between 0900 and 0000 (measured by reading the maximum thermometer without resetting) and the observations at 0000, 0300 and 0600. In a situation analogous to that for minima, this procedure will give the 'true' 0000-0000 maximum if either the maximum temperature occurs after 0900 (the usual situation) or if the temperature falls smoothly from its level at 0000, leaving the 0000 temperature as the highest of the 24 hours. It will fail to do so if the temperature fluctuates between 0000 and 0900, or if the 24-hour maximum occurs after sunrise but before 0900 (something that could arise, for example, from the passage of a cold front just before 0900, particularly on the coast in summer).

Although most stations operating this procedure were staffed by Bureau of Meteorology personnel, it was still not unknown for errors to occur in the adjustment procedure. An example of this is the minimum of 26.0°C (the equal highest on record there) at Canberra on 6 November 1946. This appears to be a valid overnight minimum from three-hourly temperatures, but the temperature had fallen to 19.3°C by 2100 that evening, so the 0000-0000 minimum should have been no greater than that. (It had also been 19.2°C at 0900 the previous morning, so the observation is not a valid 0900-0900 minimum either).

Some stations only adopted the 0000-0000 observation day for minimum temperatures, and continued to use an 0900-0900 day for maxima. A comparison of three-hourly temperatures with recorded maximum and minimum temperatures suggests that this was the case for stations in South Australia and the Northern Territory.

(b) Second- and third-order stations

These stations followed a variety of different procedures before the 1964 standardisation of the observation day as the 24 hours ending at 0900.

Bureau of Meteorology (1925) states that maximum and minimum thermometers should be reset at 2100 if observations were made at that time, or at 0900 otherwise. It was noted of the 2100 observations that "unless this is done regularly it is preferable to adhere to the morning setting". Few second- and third-order stations, with the occasional exception of coastal lighthouses, did take observations at 2100, so in practice most stations following this instruction would use a 0900 reset time, in line with current practice.

A later set of observation instructions (Bureau of Meteorology, 1954) states that the maximum thermometer should be read and reset at 0900, with the proviso that if the maximum was "close" to the temperature at the time of reading, it should be ignored and replaced by the maximum for the 6 hours ending 1500 on the previous day. The minimum thermometer was to be read at 0900. It was to be reset at 1500 on the previous day if observations were made then, or 0900 otherwise. This would give a minimum for either the 18 or 24 hours ending at 0900, depending on how many observations per day the station took.

No record was available of when the observation instructions changed, but it seems reasonable to surmise that the change might have coincided with the change to an observation day ending at 0000 at the first-order sites in 1931.

A consequence of these instructions is that the time period over which maximum and minimum temperatures were taken at second- and third-order sites depended on the number of observations per day that that station took. Unfortunately, given the very limited amount of digital data available prior to 1957 on the daily or three-hourly timescale, it is generally not possible to determine which observation day was used at a particular station without examining original manuscript records (and sometime not even with them). This makes an estimation of the impacts of observation time changes on areally-averaged mean temperatures extremely difficult.

3.3.2. Methods of estimating the time of observation bias at Australian stations

As mentioned earlier, the American studies of time of observation bias used either hourly temperatures or, in the case of Schaal and Dale (1977), maximum and minimum temperatures for 6-hour periods. Neither of these types of data are readily available for Australian stations. In general, Australian synoptic stations report three-hourly at best, which is inadequate for the estimation of the daily maximum and minimum temperature on a day from the fixed-hour observations. In contrast, American first-order stations report hourly. Automatic stations report more frequently than this, but these are only archived in the form of METAR reports, which are stored in a cumbersome format (Lellyett, pers. comm.) and only extend back for a few years at best. Some stations, especially in the state capital cities, have taken hourly observations at times, but these are not available in digital form. It is expected that higher-resolution data from automatic stations will be routinely archived in the near future (Plummer, pers.comm.) which will assist greatly in future studies.

Furthermore, unlike the situation in the United States, where a maximum and minimum temperature is taken at some stations for each of the four 6-hour periods in a given day, the only part-day maximum or minimum temperature observation routinely made in Australia is the maximum for the six hours between 0900 and 1500 LST, and these are not archived digitally.

This forced a number of alternative methods to be used for the evaluation of the time of observation bias.

(a) Parallel data from different observation days

Ideally, the best way to compare the maximum and minimum temperatures recorded using different observation days would be to compare parallel data from the same station at the same time, but using different observation times. There are two sites in Australia where this is feasible: Adelaide and Melbourne.

At the (now-closed) West Terrace site in Adelaide, parallel observations, using observation days of 24 hours ending at 0000 and 0900, were made for the nine years 1967-1975. At Melbourne, there is no direct overlap of the two observation days, but observations of minimum temperatures for the 18-hour period from 1500 to 0900 have been carried out since at least 1958, and these may be compared with 24-hour minima for observation days ending at 0900 from 1964 onwards, and at 0000 prior to that date. As these data were not digitised, only the 1958-63 (for the 0000 observation day) and 1989-96 (for the 0900 observation day) periods were used in the comparison.

(b) Use of hourly data to estimate impact of methods of calculating "corrected midnight-midnight" maximum and minimum

At Adelaide (Kent Town), hourly temperature data were available for the period between 1990 and 1996, along with the time of occurrence, to the nearest five minutes, of the maximum temperature for the 24 hours ending at 0000 and the minimum for the 15 hours between 1800 and 0900. These were used to estimate the impact of the difference between the true maxima and minima for the 24 hours ending at 0000, as measured between 1967 and 1975, and the approximations to them, described in 3.4.1 (a), that were in common use prior to 1964.

This was done as follows:

Maximum temperature

On days when the maximum temperature for the 24 hours ending at 0000 was recorded before 0900, the difference between that maximum and the highest of the four observations at 0000, 0300, 0600 and 0900 was determined.

Minimum temperature

For each day, the lowest of the 25 hourly observations between 0000 on one day and 0000 on the next, inclusive, was found. The differences between this lowest hourly temperature and the minimum for the 15 hours between 1800 and 0900 were calculated for each day. Days on which the 1800-0900 minimum occurred before 0000 (i.e. the 1800-0900 minimum would be lower than the 0000-0000 minimum) were then compared with days when it occurred after 0000.

By setting

$m_1 =$ mean difference between 1800-0900 minimum and lowest hourly temperature on days when 1800-0900 minimum recorded after 0000

$m_2 =$ mean difference between 1800-0900 minimum and lowest hourly temperature on days when 1800-0900 minimum recorded before 0000

$(m_2 - m_1)$ will then be an estimate of the bias arising from taking a minimum temperature for the 30 hours ending at 0000, compared with the 24 hours ending at 0000. This will not be the same as the bias arising from using the 33 hours ending at 0000 (which was the usual pre-1964 practice), but the 30- and 33-hour minima will only differ on days when the daily minimum temperature is recorded between 1500 and 1800, an extremely rare event in temperate latitudes.

The hourly data at Adelaide were also used to estimate the impact of daylight saving, by identifying days when the lowest of the 25 hourly observations between 0900 on one day and 0900 on the next was at 0900 on the first day, and days where the highest of the 25 hourly observations between 1000 and 1000 was at 1000 on the second day.

(c) Use of three-hourly data to identify days on which maxima or minima differ between observation days ending at 0000 and 0900

A number of stations have reasonably complete three-hourly data available in digital form. While three-hourly data are not sufficient to quantify maximum and minimum temperatures, it does allow an attempt to be made to identify days when the maximum (or minimum) temperature for an observation day ending at 0900 differs from that for an observation day ending at 0000.

The following criteria were used to identify such days. Note that these will not identify all days when the two observations will differ, nor will all days identified actually have differing observations. However, the nature of the criteria is such that exceptions should be relatively minor (that is, all days where the difference is large should be detected) and thus have little impact on mean biases. To examine the efficiency of the scheme, it was also applied to the period with parallel observations at 0000 and 0900 in Adelaide, to compare the number of differences it identified with the number that actually occurred.

Maximum for day ending at 0900 > maximum for day ending at 0000

Temperature at reset time (0900 following day) within 0.5°C of the maximum for the day ending at 0900.

Maximum for day ending at 0900 < maximum for day ending at 0000

At least one out of the 0000, 0300 and 0600 temperature observations greater than the highest of the observations made at 1200 or later that day.

Minimum for day ending at 0900 > minimum for day ending at 0000

At least one of the three-hourly observations at 1200 or later lower than the lowest of the observations made at 0000, 0300, 0600 or 0900 that day.

Minimum for day ending at 0900 < minimum for day ending at 0000

Temperature at reset time the previous day (0900) within 0.5°C of the 24-hour minimum temperature.

While the number of days on which the maximum and minimum temperatures for days ending at 0900 differ from those for a day ending at 0000 will not necessarily indicate the magnitude of the difference in temperature on those days, this procedure still gives a guide to the relative probability of the maxima and minima for days ending at 0900 being higher or lower than those recorded at 0000.

(d) Relationship of three-hourly observations to mean minimum temperatures

Another method of investigating, indirectly, the areal extent of the time-of-observation bias is to examine three-hourly temperature data and the mean interdiurnal temperature change to estimate the likelihood of days on which minimum temperatures will differ between observation days ending at 0000 and 0900. If we let $T_{a/h,x}$ be the minimum temperature for an observation day of h hours ending at time a on day x, and $t_{a,x}$ the temperature at time a on day x, then a necessary condition , on a day when the diurnal rise and fall of temperature is monotonic between the highest and lowest points of the diurnal cycle, for:

$$T_{0000/24,\,x} < T_{0900/24,\,x}$$

is:

$$(T_{0900/24,\,x} - \mathrm{T}_{0900/24,\,(x+1)}) > (t_{0000,\,x} - T_{0900/24,\,(x+1)})$$

Conversely, for:

$$T_{0000/24,\,x} > T_{0900/24,\,x}$$

we require:

$$(T_{0900/9,\,(x+1)} - T_{0900/24,\,x}) > (t_{0900,\,x} - T_{0900/24,\,x})$$

It follows from this that the probability of both events occurring will be enhanced by an increase in the mean interdiurnal change in minimum temperature. Furthermore, the probability of the minimum being greater for an observation day ending at 0900 than at 0000 will be enhanced by a decrease in the difference between the mean 0000 temperature and the mean minimum, while the probability of the minimum being greater for an observation day ending at 0000 will be enhanced by a decrease in the difference between the mean 0900 temperature and the mean minimum. It thus follows that an increase in the mean interdiurnal change in minimum temperature will tend to lead to an increased time-of-observation bias, while a mean 0900 temperature substantially greater than the mean 0000 temperature will promote the likelihood of a negative bias for an observation day ending at 0000; conversely, a positive bias is more likely if the mean 0000 temperature is greater than the mean 0900 temperature.

Therefore, the mean temperatures at 0000 and 0900, the mean minimum temperature (for an observation day ending at 0900) and the mean interdiurnal change in minimum temperature were calculated, to provide an indirect method of estimating the time-of-observation bias over a wide area.

3.3.3. Estimates of time of observation bias for Australian stations

The mean maximum and minimum temperatures at Adelaide between 1967 and 1975, using observation days ending at 0900 and 0000, are shown in Table 3.8.

It may be seen that the mean minimum temperature for an observation day ending at 0000 is lower than that for a day ending at 0900 in all months of the year, with an annual mean difference of 0.29°C. The difference is greatest in the summer half-year, reaching 0.42°C in February. The results also show that the impact of using a minimum temperature for the 30 hours ending at 0000, rather than the 24 hours ending at 0000, is minimal.

The impact on mean maximum temperature at Adelaide is much smaller, with an observation day ending at 0000 having the higher maximum temperatures by 0.05°C. Only in summer does the difference exceed 0.1°C. In addition, the impact of using the three-hourly observations at 0000, 0300, 0600 and 0900 to approximate the maximum temperature for the 9 hours between 0000 and 0900 was found to be minimal. At Adelaide, there was a mean of 5.6 days per year in the 1990-96 period on which the maximum temperature for the 24 hours ending at 0000 occurred before 0900. On 2.3 of these days the maximum was recorded at 0000, and on the other 3.3 days the mean difference between the maximum temperature and the highest three-hourly observation was 1.1°C, leading to an overall bias in the annual mean maximum temperature of -0.01°C.

The hourly data for Adelaide revealed, in addition, that the impact of the introduction of daylight saving in summer was minimal, with a decrease of 0.03°C in the mean annual minimum temperature and no change for maxima. The findings of Mitchell (1958) that the magnitude of the time of observation bias was most sensitive to small changes in observation times near sunrise are of relevance here, as the time change takes place in summer and, even with daylight saving, the observation time is always at least 90 minutes after sunrise.

Table 3.9 shows the differences at Melbourne between minimum temperatures for the 18 hours between 1500 and 0900 and the minima for the 24 hours ending at 0000 or 0900. Comparisons of the two 24-hour minima with the 1500-0900 minimum imply that, as at Adelaide, the minimum temperatures for the 24-hour period ending at 0000 are lower than those for the 24 hours ending at 0900, with a mean annual bias of 0.31°C. Like Adelaide, the smallest bias is in winter; unlike Adelaide, the largest biases are in spring, autumn and early winter rather than summer, peaking at 0.47°C in June and November.

The Adelaide data were also used to estimate the impact of a time of observation change on the frequency distribution of minimum temperature, using the techniques developed in section 3.2. The difference between temperatures recorded on the two observation days occurs chiefly in the upper part of the frequency distribution, with the 80 percentile February minimum temperature being 1.1°C higher for an observation day ending at 0900 than one ending at 0000.

Table 3.10 shows the number of days per year indicated, under the procedures described in section 3.3.2, as having the potential for the maxima (or minima) to be different for observation days ending at 0000 and 0900. This reinforces the result from Adelaide and Melbourne that it is far more common for the daily minima to differ between an 0000 and 0900 observation day than for the maxima to do so, suggesting that the result from those two stations that time of observation bias chiefly affects minimum temperature may hold more generally in Australia. Furthermore, at ten of the eleven stations, the results suggest that it is more common for a daily

Month	Temperature difference ($T_{0000/24}$ - $T_{0900/24}$) (°C)		Difference in minima ($T_{0000/30}$ - $T_{0000/24}$) (°C)	Overall difference in minima ($T_{0000/30}$ - $T_{0900/24}$) (°C)
	Maximum	Minimum		
January	0.15	-0.30	-0.02	-0.32
February	0.10	-0.42	-0.01	-0.43
March	0.06	-0.37	-0.02	-0.39
April	0.03	-0.24	-0.06	-0.30
May	0.03	-0.17	-0.09	-0.26
June	-0.03	-0.09	-0.08	-0.17
July	0.00	-0.10	-0.09	-0.19
August	0.02	-0.13	-0.10	-0.23
September	0.10	-0.30	-0.07	-0.37
October	0.01	-0.36	-0.05	-0.41
November	0.02	-0.39	-0.06	-0.45
December	0.12	-0.39	-0.03	-0.42
Annual mean	0.05	-0.29	-0.06	-0.35

Table 3.8. Difference in temperature between differing observation days at Adelaide (West Terrace), 1967-1975

Month	Mean difference (°C) for minimum temperature (24-hour minimum - $T_{0900/18}$) for day ending		Implied difference (°C) ($T_{0000/24}$ - $T_{0900/24}$)
	0000	0900	
January	-0.51	-0.28	-0.23
February	-0.55	-0.30	-0.25
March	-0.42	-0.19	-0.23
April	-0.62	-0.24	-0.38
May	-0.74	-0.41	-0.33
June	-0.90	-0.43	-0.47
July	-0.49	-0.41	-0.08
August	-0.45	-0.30	-0.15
September	-0.48	-0.16	-0.32
October	-0.52	-0.11	-0.41
November	-0.64	-0.17	-0.47
December	-0.48	-0.15	-0.33
Annual mean	-0.57	-0.26	-0.31

Table 3.9. Differences between overnight and 24-hour minimum temperatures at Melbourne, for 24-hour days ending at 0000 (1958-1963) and 0900 (1989-1996)

Station and period of record	Mean annual number of days flagged as type:			
	Maximum		Minimum	
	$T_{0900/24} > T_{0000/24}$	$T_{0900/24} < T_{0000/24}$	$T_{0900/24} > T_{0000/24}$	$T_{0900/24} < T_{0000/24}$
Adelaide (West Terrace) (1967-75)	22.4	22.1	79.5	37.1
Canberra (1951-94)	5.7	6.3	80.6	29.0
Charleville (1953-95)	1.9	4.1	35.0	6.1
Darwin Airport (1960-95)	3.8	2.7	34.8	14.2
Esperance MO (1969-95)	28.8	11.0	110.5	16.5
Halls Creek (1945-95)	1.7	0.9	24.9	3.0
Hobart (1972-95)	12.6	14.1	76.0	57.0
Melbourne (1955-95)	7.6	16.3	83.6	75.4
Perth Airport (1949-95)	2.2	6.6	86.0	18.8
Port Hedland (1948-95)	9.5	1.6	42.0	1.8
Woomera (1953-95)	1.1	3.7	16.0	19.8

Table 3.10. Mean annual number of days flagged as having potential differences between $T_{0000/24}$ and $T_{0900/24}$, using procedure described in section 3.4.2c.

	Mean annual number of days	
	Estimated by flagging procedure	Actual
Maximum, $T_{0900/24} > T_{0000/24}$	22.4	14.1
Maximum, $T_{0900/24} < T_{0000/24}$	22.1	18.9
Minimum, $T_{0900/24} > T_{0000/24}$	79.5	52.1
Minimum, $T_{0900/24} < T_{0000/24}$	37.1	12.6

Table 3.11. Comparison of number of days identified by flagging procedure in section 3.4.2c and days with actual differences between $T_{0000/24}$ and $T_{0900/24}$ at Adelaide (West Terrace), 1967-75.

minimum to be lower for a day ending at 0000 than that ending at 0900 than the reverse, which in turn suggests that an observation day ending at 0000 will result in lower mean minima than one ending at 0900 at these stations, although this conclusion must be drawn with caution because the flagging procedure gives no indication of the magnitude of the likely differences on a given day, only their existence. Again, this is a result which is consistent with the results obtained at Melbourne and Adelaide.

Table 3.11 shows the efficiency of the flagging procedure in detecting days when maximum or minimum temperatures for a day ending at 0000 differ from those for a day ending at 0900. These results suggest that the flagging procedure over-estimates the frequency of differences, with the over-estimate being greatest for the frequency of lower minima and higher maxima for observation days ending at 0900. This reinforces the suggestion from Table 3.10 that using an observation day ending at 0000 will lead to a negative bias in the mean minimum temperature, relative to an 0900 observation day.

Table 3.12 gives the mean differences between 0000, 0900 and minimum temperatures for a number of stations, as well as the mean interdiurnal change in minimum temperature, for January and July. The mean 0900 temperature is higher than the mean 0000 temperature at most of the sites in both months, with the exceptions being Woomera in both months, and Hobart and Melbourne in winter. The difference is particularly marked at two of the three tropical sites, Port Hedland and Halls Creek, as well as at Esperance. In the latter case, this may be a consequence of Esperance's easterly location within its time zone and its consequent early sunrise, especially in summer. Conversely, at Melbourne and Hobart in winter, and at Darwin (which displays a small difference all year), sunrise is relatively late. The mean interdiurnal change in minimum temperature is least in the tropics in all seasons, and greatest about the southern coasts in summer, and the eastern inland in winter.

3.3.4. Implications of the results

The examination of data from Melbourne and Adelaide suggests that the 1964 change in observation practice at those stations, from an observation day ending at 0000 to one ending at 0900, resulted in an artificial increase in mean annual minimum temperatures of 0.3° to 0.4°C, but no significant increase in mean annual maximum temperatures. The frequency of high minimum temperatures shows a particularly strong change. This, in turn, implies an artificial increase in the variability of minimum temperature. Variability of temperature is an important factor in the likelihood of extreme events, as is discussed in more detail in later chapters and in Katz and Brown (1992), and the likelihood of extreme high minimum temperatures is an important factor in human health and mortality (Karl and Knight, 1997), particularly at a site such as Adelaide, which occasionally experiences daily minimum temperatures in excess of 30°C.

The question arises as to how representative the Melbourne and Adelaide results are of Australia as a whole. The results from Table 3.10 suggest that days on which daily minimum temperatures are affected by a change in observation time are most frequent near the southern coast, and least frequent in the tropics. However, these results also suggest that, at the southern coastal sites, the large number of days when the minimum temperature for a day ending at 0000 is lower than that for a day ending at 0900 is partially offset by the larger number of days when it is higher. It is entirely possible that the magnitude of the temperature bias at Port Hedland, where total number of days affected by a change in observation time is smaller but days when the minimum temperature for a day ending at 0000 is higher than that at 0900 are very rare, may be similar to that at the southern stations, but no data exist to test this proposition objectively. Nevertheless, the 0000 and 0900 temperatures and the interdiurnal temperature changes outlined in Table 3.12 suggest that it is most probable that the time of observation bias is greatest in southern Australia, and consequently that the Adelaide and Melbourne results are at the high end of the range which is likely to exist over Australia as a whole.

Station name	January				July			
	Mean difference (°C) (t_{0900} - $T_{0900/24}$)	Mean difference (°C) (t_{0000} - $T_{0900/24}$)	Mean interdiurnal change in minimum temperature (°C)	Time of sunrise (LST)	Mean difference (°C) (t_{0900} - $T_{0900/24}$)	Mean difference (°C) (t_{0000} - $T_{0900/24}$)	Mean interdiurnal change in minimum temperature (°C)	Time of sunrise (LST)
Adelaide (Kent Town)	4.5	3.2	2.8	0618*	2.8	2.2	2.2	0721
Canberra	4.8	3.8	2.5	0604*	3.8	3.3	2.7	0710
Charleville	5.9	3.9	2.0	0536+	6.2	4.3	2.6	0702
Darwin AP	3.1	2.2	1.5	0632	3.4	2.8	1.1	0709
Esperance MO	5.9	1.8	2.4	0457+	3.2	2.1	2.0	0655
Halls Creek	6.1	3.0	1.7	0506+	7.9	4.1	1.7	0601
Hobart	3.6	2.1	2.1	0551*	2.0	2.4	1.9	0737
Melbourne	3.2	3.2	2.4	0615*	1.8	2.3	2.0	0733
Perth AP	6.8	3.8	2.4	0526+	3.4	2.6	2.1	0715
Port Hedland	6.4	2.2	1.3	0538+	8.2	3.0	1.9	0641
Woomera	4.1	5.0	2.6	0634*	3.4	3.6	1.9	0719

* Daylight saving in use throughout period: time shown is daylight saving time.
+ Daylight saving in use for a short part of the period: time shown is standard time.

Table 3.12. Difference between mean temperatures at 0000 and 0900 and mean 24-hour minimum temperature ($T_{0900/24}$), mean interdiurnal change in minimum temperature, and local time of sunrise for the 15th of each month, for period 1972-1996 (1977-1996 at Adelaide)

When historical data are being examined, the extent of the influence of the time of observation bias will also be affected by the number of stations that were actually using an observation day ending at 0000 prior to 1964. As noted in section 3.3.1., the observation day ending at 0000 was only used at first-order stations, and not all of them followed the procedure rigorously. Many of the co-operative stations, which form the bulk of the Australian temperature station network, used, in effect, a minimum temperature for the 18 hours ending at 0900. The results from Melbourne in Table 3.9 suggest that the positive bias from using an 18-hour minimum ending at 0900, at that site at least, is of comparable magnitude to the negative bias from using a 24-hour minimum ending at 0000. It follows from this that the impact on long-term temperature trends at a particular stations could be significant, but, when averaged spatially, the opposite biases will tend to cancel each other out to some extent. A regional bias could still arise, as first-order stations tended to be more concentrated in coastal areas than co-operative stations were, especially before the opening of a large number of airport meteorological offices during the Second World War.

The implications of the proposal to change the observation time in eastern Australia to 2100 UTC (0700 LST in winter, 0800 in summer in those states which observe daylight saving) are also worthy of examination. Mitchell (1958) has already noted that the mean temperature is particularly sensitive to observation time changes around sunrise, and 2100 UTC is within 30 minutes of sunrise in winter in much of eastern Australia. In the worst-case scenario, where one assumes that the time of observation coincides with the time of minimum temperature, on any day when the overnight minimum temperature on one day is higher than it has been the previous day, the 24-hour minimum on that day will be biased downwards by the difference between the overnight minimum temperatures on the two days, as the cooler first day is effectively counted twice.

As such a situation would be expected to arise on 50% of days, the expected difference between the overnight minimum and 24-hour minimum would be half the mean interdiurnal temperature change as shown in Table 3.12. Combining this with the difference between the mean overnight and 24-hour minima (Table 3.9), the interdiurnal temperature change in some areas approaches 3°C, suggesting that the potential exists for a bias in the vicinty of -1°C in minimum temperatures in some areas if a change to an observation day ending at 2100 UTC takes place.

3.4. Biases arising from the use of accumulated data

Ideally, all data sets used in a study would be complete. In practice, there is no long-term station in Australia that has no missing days in its record, and hence it is necessary to consider the implications of missing data for the overall temperature record.

Missing data can take one of two forms:

1. An observation is missed.
2. An observation is taken but is found to be faulty, or is not communicated (in the case of an automatic station where there is no manual record to act as a back-up).

Missing data of the second type should not affect the overall temperature record, as long as there is no systematic bias in the type of days on which observations are missed. This may not be the case if observations are more likely to be missed under extreme conditions, although it seems reasonable to surmise that communications failures or the like are more likely to happen in extreme rainfall or wind than they are in extreme temperatures. (Robinson (1990) noted a potential for data loss during extreme conditions at automatic stations, due to power outages). A tendency towards missing data occurring under particular temperature conditions could also result from missing weekend data, as a number of authors, such as Simmonds and Kaval (1986) and Simmonds and Keay (1997), have found a relationship between temperature and day of the week. In such cases the deletion of a particular day of the week on a consistent basis could lead to a bias in mean temperatures.

The first type of missing data, which is by far the more common, is of more concern. If the observation is missed then the thermometers are not reset, and hence the maximum and minimum temperatures which are recorded when the thermometers are eventually read are the minimum and maximum temperatures for the previous 48 hours (or 72 or more if two or more days are missed), rather than 24. These accumulated temperatures will thus be the highest maximum and lowest minimum temperature on any of the days since the last observation was made, resulting in a positive bias for maximum temperature and a negative bias for minimum temperature.

The greatest frequency of accumulated data occurs when a station consistently makes observations for a period for only 6 or 5 days per week (with Sunday, or less commonly both Saturday and Sunday) being missed. It was quite common prior to about 1960 for stations (especially post offices) to miss Sunday observations for many years at a time. More recently, some stations, such as Robe and Bathurst, have missed all weekend observations for periods of several months or years. Revfiem (1990) argued that the absence of weekend data need not bias mean values unduly providing appropriate adjustments were made, but did not consider the case of extreme values.

Data accumulated over more than one day have been treated inconsistently in the Bureau of Meteorology's database. Prior to 1966, accumulated temperature data were not flagged at all. Between 1966 and 1992, a flag of '1' was used for accumulated data regardless of the number of days over which the temperatures were accumulated. Since 1992 the flag has been the number of days over which the temperature was accumulated. In all cases, monthly mean temperatures have been calculated including the accumulated values, resulting in an upward bias in mean maximum temperatures and a downward bias in mean minimum temperatures. (It is worth noting, however, that a site making no weekend observations will go close to the minimum number of observations required for the calculation of monthly means, and may fall below it in months with several public holidays, such as December or April, or other missing data).

The only way to place all data on a consistent footing is to delete all data which may be accumulated, that is, all data that follow one or more days of missing data. As this will also delete data from days following missed days of type 1, it will lead to some valid data being deleted. This was the practice followed in the main part of this study.

3.4.1. Quantification of biases arising from use of accumulated temperatures

There are two feasible approaches to the investigation of accumulated temperatures.

1. Use a reasonably complete data set and delete data for each Sunday (or Saturday and Sunday), adjusting maxima and minima on Monday to be the equivalent of accumulated data for 48 or 72 hours.
2. Examine a data set with a substantial amount of accumulated data and investigate whether there is any significant difference between the temperatures recorded on days with accumulated temperatures and temperatures on other days.

Both approaches were used in this section.

The results of the first approach are given in Tables 3.13 and 3.14. All available Bureau-operated sites were used in this part of the study (these being chosen because of their generally small amount of missing data). If only Sunday observations are missing and the Monday temperature is accumulated over 48 hours, this results in a bias of between +0.1° and 0.3°C for maximum temperature and between -0.1 and -0.3°C for minimum temperature at most stations, although the bias for maximum temperature reaches +0.43°C at Ceduna in January. The bias is least in the tropics, especially near the coasts, and greatest near southern coasts for maxima and in the southern inland for minima. The bias for maximum temperature shows a marked peak at most stations in spring and summer, and, for minimum temperature, a less pronounced peak in winter and spring. As the biases for maximum and minimum temperature are of opposite sign, there will be a particularly marked bias for the mean diurnal temperature range, reaching +0.73°C at Ceduna in October.

The biases arising from removing all weekend observations and accumulating Monday temperatures over 72 hours, as would be expected, have a similar spatial and seasonal distribution to those arising from the absence of Sunday observations only, but are of approximately double the magnitude. The bias for spring and summer maxima exceeds +0.6°C at a number of southern stations and reaches +0.92°C at

Station name	Bias (°C)											
	January			April			July			October		
	Maximum	Minimum	DTR	Maximum	Minimum	DTR	Maximum	Minimum	DTR	Maximum	Minimum	DTR
Halls Creek	0.16	-0.10	0.26	0.07	-0.07	0.14	0.10	-0.16	0.26	0.07	-0.15	0.22
Broome	0.13	-0.13	0.29	0.09	-0.08	0.17	0.13	-0.16	0.29	0.14	-0.13	0.27
Port Hedland	0.16	-0.12	0.28	0.10	-0.09	0.19	0.12	-0.18	0.30	0.19	-0.14	0.33
Learmonth	0.14	-0.07	0.21	0.13	-0.08	0.21	0.10	-0.16	0.26	0.22	-0.12	0.34
Carnarvon	0.23	-0.10	0.33	0.16	-0.13	0.29	0.12	-0.13	0.25	0.15	-0.16	0.31
Meekatharra	0.14	-0.21	0.35	0.20	-0.14	0.34	0.18	-0.13	0.31	0.21	-0.23	0.44
Geraldton	0.32	-0.21	0.53	0.20	-0.17	0.37	0.13	-0.13	0.26	0.22	-0.24	0.46
Perth Airport	0.29	-0.21	0.50	0.18	-0.18	0.36	0.14	-0.18	0.32	0.23	-0.22	0.45
Albany	0.30	-0.22	0.52	0.24	-0.19	0.43	0.15	-0.20	0.35	0.15	-0.24	0.39
Esperance	0.39	-0.21	0.60	0.31	-0.17	0.48	0.19	-0.17	0.36	0.26	-0.23	0.49
Forrest	0.38	-0.17	0.55	0.30	-0.20	0.50	0.20	-0.20	0.40	0.31	-0.35	0.66
Kalgoorlie	0.29	-0.22	0.51	0.27	-0.15	0.42	0.20	-0.22	0.42	0.29	-0.25	0.54
Giles	0.15	-0.13	0.28	0.20	-0.11	0.31	0.18	-0.17	0.35	0.20	-0.30	0.50
Darwin Airport	0.10	-0.12	0.22	0.07	-0.08	0.15	0.08	-0.11	0.19	0.09	-0.09	0.18
Alice Springs	0.13	-0.22	0.35	0.18	-0.17	0.35	0.21	-0.20	0.41	0.30	-0.25	0.55
Woomera	0.26	-0.19	0.45	0.22	-0.14	0.36	0.17	-0.15	0.32	0.31	-0.24	0.55
Ceduna	0.43	-0.22	0.65	0.28	-0.29	0.57	0.18	-0.22	0.40	0.39	-0.34	0.73
Adelaide RO	0.32	-0.25	0.57	0.23	-0.24	0.47	0.13	-0.17	0.30	0.38	-0.25	0.63
Mount Gambier	0.36	-0.27	0.63	0.21	-0.21	0.42	0.11	-0.19	0.30	0.28	-0.22	0.50
Thursday Island	0.09	-0.04	0.13	0.08	-0.02	0.10	0.04	-0.07	0.11	0.03	-0.05	0.08
Cairns	0.10	-0.07	0.17	0.11	-0.07	0.18	0.09	-0.13	0.22	0.07	-0.12	0.19
Townsville	0.10	-0.07	0.17	0.09	-0.09	0.18	0.10	-0.19	0.29	0.06	-0.13	0.19
Mackay MO	0.08	-0.12	0.20	0.07	-0.08	0.15	0.12	-0.18	0.30	0.06	-0.13	0.19
Longreach	0.09	-0.15	0.24	0.10	-0.15	0.25	0.17	-0.19	0.36	0.22	-0.17	0.39
Rockhampton	0.14	-0.09	0.23	0.11	-0.11	0.22	0.17	-0.22	0.39	0.13	-0.16	0.29
Amberley	0.16	-0.12	0.28	0.12	-0.12	0.24	0.13	-0.23	0.36	0.23	-0.21	0.44
Brisbane AP	0.11	-0.09	0.20	0.11	-0.08	0.19	0.12	-0.15	0.27	0.17	-0.14	0.31
Charleville	0.16	-0.16	0.32	0.14	-0.21	0.35	0.16	-0.22	0.38	0.22	-0.21	0.43

Table 3.13. Biases in mean maximum and minimum temperature and diurnal temperature range if Sunday observations missing

Table 3.13 (cont.). Biases in mean maximum and minimum temperature and diurnal temperature range if Sunday observations missing

Station name	Bias (°C)											
	January			April			July			October		
	Maximum	Minimum	DTR	Maximum	Minimum	DTR	Maximum	Minimum	DTR	Maximum	Minimum	DTR
Cobar	0.21	-0.22	0.43	0.14	-0.20	0.34	0.16	-0.15	0.31	0.32	-0.17	0.49
Moree	0.18	-0.15	0.33	0.11	-0.21	0.32	0.18	-0.23	0.41	0.28	-0.22	0.50
Coffs Harbour	0.14	-0.12	0.26	0.15	-0.17	0.32	0.12	-0.22	0.34	0.21	-0.19	0.40
Williamtown	0.26	-0.16	0.42	0.19	-0.18	0.37	0.18	-0.19	0.37	0.29	-0.22	0.51
Sydney RO	0.24	-0.12	0.36	0.18	-0.11	0.29	0.14	-0.12	0.26	0.25	-0.16	0.41
Richmond	0.26	-0.20	0.46	0.22	-0.19	0.41	0.15	-0.21	0.36	0.30	-0.22	0.52
Nowra	0.24	-0.18	0.42	0.22	-0.17	0.39	0.11	-0.15	0.26	0.33	-0.21	0.54
Canberra AP	0.24	-0.21	0.45	0.18	-0.17	0.35	0.15	-0.21	0.36	0.20	-0.27	0.47
Wagga Wagga	0.26	-0.25	0.51	0.15	-0.22	0.37	0.16	-0.16	0.32	0.22	-0.24	0.46
Mildura	0.29	-0.21	0.50	0.24	-0.18	0.42	0.15	-0.16	0.31	0.30	-0.24	0.54
Sale	0.31	-0.19	0.50	0.22	-0.20	0.42	0.14	-0.21	0.35	0.29	-0.22	0.51
Melbourne RO	0.40	-0.19	0.59	0.23	-0.18	0.41	0.14	-0.17	0.31	0.30	-0.24	0.54
Laverton	0.36	-0.21	0.57	0.23	-0.25	0.48	0.11	-0.19	0.30	0.32	-0.22	0.54
Launceston AP	0.21	-0.26	0.47	0.20	-0.23	0.43	0.11	-0.23	0.34	0.17	-0.21	0.38
Hobart RO	0.27	-0.20	0.47	0.25	-0.20	0.45	0.13	-0.18	0.31	0.30	-0.17	0.47

Station name	Bias (°C)											
	January			April			July			October		
	Maximum	Minimum	DTR	Maximum	Minimum	DTR	Maximum	Minimum	DTR	Maximum	Minimum	DTR
Halls Creek	0.27	-0.19	0.46	0.13	-0.19	0.32	0.20	-0.31	0.51	0.17	-0.30	0.47
Broome	0.26	-0.24	0.50	0.20	-0.16	0.36	0.25	-0.30	0.55	0.35	-0.22	0.57
Port Hedland	0.34	-0.25	0.59	0.22	-0.16	0.38	0.18	-0.34	0.52	0.43	-0.27	0.70
Learmonth	0.27	-0.17	0.44	0.25	-0.20	0.45	0.18	-0.31	0.49	0.40	-0.28	0.68
Carnarvon	0.51	-0.18	0.69	0.36	-0.23	0.59	0.25	-0.24	0.49	0.35	-0.32	0.67
Meekatharra	0.29	-0.40	0.69	0.41	-0.25	0.66	0.36	-0.24	0.60	0.41	-0.48	0.89
Geraldton	0.67	-0.35	1.02	0.46	-0.35	0.81	0.24	-0.28	0.52	0.43	-0.46	0.89
Perth Airport	0.61	-0.38	0.99	0.47	-0.38	0.85	0.27	-0.34	0.61	0.44	-0.42	0.86
Albany	0.67	-0.41	1.08	0.46	-0.39	0.85	0.30	-0.38	0.68	0.36	-0.44	0.80
Esperance	0.89	-0.39	1.28	0.63	-0.37	1.00	0.38	-0.34	0.72	0.62	-0.42	1.04
Forrest	0.74	-0.35	1.09	0.65	-0.37	1.02	0.39	-0.38	0.77	0.71	-0.62	1.33
Kalgoorlie	0.62	-0.40	1.02	0.56	-0.31	0.87	0.38	-0.42	0.80	0.62	-0.49	1.11
Giles	0.29	-0.30	0.59	0.37	-0.22	0.59	0.32	-0.31	0.63	0.49	-0.54	1.03
Darwin Airport	0.20	-0.22	0.42	0.16	-0.15	0.31	0.16	-0.21	0.37	0.16	-0.17	0.33
Alice Springs	0.25	-0.48	0.73	0.36	-0.36	0.72	0.41	-0.41	0.82	0.64	-0.52	1.16
Woomera	0.47	-0.42	0.89	0.41	-0.33	0.74	0.31	-0.30	0.61	0.75	-0.41	1.16
Ceduna	0.90	-0.54	1.44	0.59	-0.54	1.13	0.36	-0.39	0.75	0.92	-0.63	1.55
Adelaide RO	0.63	-0.51	1.14	0.42	-0.33	0.75	0.23	-0.33	0.56	0.90	-0.40	1.30
Mount Gambier	0.76	-0.49	1.25	0.45	-0.41	0.86	0.21	-0.39	0.60	0.61	-0.40	1.01
Thursday Island	0.30	-0.08	0.38	0.14	-0.06	0.20	0.08	-0.11	0.19	0.07	-0.11	0.18
Cairns	0.20	-0.15	0.35	0.19	-0.14	0.33	0.18	-0.27	0.45	0.12	-0.24	0.36
Townsville	0.19	-0.15	0.34	0.16	-0.18	0.34	0.20	-0.41	0.61	0.13	-0.29	0.42
Mackay MO	0.17	-0.21	0.38	0.15	-0.20	0.35	0.23	-0.35	0.58	0.13	-0.27	0.40
Longreach	0.26	-0.27	0.53	0.20	-0.28	0.48	0.35	-0.31	0.66	0.41	-0.37	0.78
Rockhampton	0.27	-0.19	0.46	0.22	-0.19	0.41	0.30	-0.43	0.73	0.26	-0.34	0.60
Amberley	0.34	-0.26	0.60	0.22	-0.23	0.45	0.23	-0.38	0.61	0.41	-0.44	0.85
Brisbane AP	0.23	-0.19	0.42	0.20	-0.14	0.34	0.20	-0.28	0.48	0.29	-0.31	0.60
Charleville	0.35	-0.30	0.65	0.29	-0.37	0.66	0.30	-0.45	0.75	0.46	-0.46	0.92

Table 3.14. Biases in mean maximum and minimum temperature and diurnal temperature range if Saturday and Sunday observations missing

Table 3.14 (cont.). Biases in mean maximum and minimum temperature and diurnal temperature range if Saturday and Sunday observations missing

Station name	Bias (°C)											
	January			April			July			October		
	Maximum	Minimum	DTR	Maximum	Minimum	DTR	Maximum	Minimum	DTR	Maximum	Minimum	DTR
Cobar	0.44	-0.47	0.91	0.27	-0.41	0.68	0.30	-0.32	0.62	0.66	-0.33	0.99
Moree	0.40	-0.36	0.76	0.21	-0.39	0.60	0.34	-0.40	0.74	0.52	-0.48	1.00
Coffs Harbour	0.29	-0.28	0.57	0.29	-0.28	0.57	0.24	-0.38	0.62	0.38	-0.43	0.81
Williamtown	0.56	-0.31	0.87	0.40	-0.31	0.71	0.29	-0.32	0.61	0.56	-0.47	1.03
Sydney RO	0.48	-0.25	0.73	0.39	-0.21	0.60	0.27	-0.23	0.50	0.50	-0.32	0.82
Richmond	0.55	-0.37	0.92	0.43	-0.37	0.80	0.27	-0.35	0.62	0.58	-0.49	1.07
Nowra	0.47	-0.36	0.83	0.49	-0.33	0.82	0.22	-0.27	0.49	0.61	-0.40	1.01
Canberra AP	0.50	-0.42	0.92	0.37	-0.39	0.76	0.26	-0.40	0.66	0.41	-0.51	0.92
Wagga Wagga	0.49	-0.51	1.00	0.31	-0.40	0.71	0.29	-0.34	0.63	0.47	-0.46	0.93
Mildura	0.62	-0.42	1.04	0.46	-0.39	0.85	0.30	-0.34	0.64	0.69	-0.43	1.12
Sale	0.67	-0.42	1.09	0.45	-0.40	0.85	0.27	-0.34	0.61	0.61	-0.46	1.07
Melbourne	0.86	-0.37	1.23	0.48	-0.35	0.83	0.27	-0.32	0.59	0.64	-0.43	1.07
Laverton	0.77	-0.40	1.17	0.41	-0.45	0.86	0.23	-0.36	0.59	0.68	-0.38	1.06
Launceston AP	0.39	-0.46	0.85	0.34	-0.44	0.78	0.22	-0.38	0.60	0.36	-0.44	0.80
Hobart RO	0.59	-0.40	0.99	0.49	-0.37	0.86	0.27	-0.31	0.58	0.59	-0.33	0.92

Ceduna in October, while for minima the same station has an October bias of -0.63°C, leading to a bias of +1.55°C for the mean diurnal temperature range.

In the second approach, data from two stations with missing Sunday data were examined. The stations used were Wyalong (1959-64) and Tewantin (1957-61). These stations were chosen during these periods because they were missing all Sunday observations but few other observations. Table 3.15 shows a comparison between observations on the day after missing data at these stations (mostly Mondays) and all other days. On the assumption that one observation in six is accumulated, the estimated bias in mean maximum and minimum temperatures will be one-sixth of the mean difference between the two types of observations. Given this, the estimated bias at Tewantin is +0.14°C for annual mean maxima and -0.23°C for annual mean minima, while at Wyalong the values are +0.19°C and -0.13°C respectively. These results are of similar magnitude to those shown in Table 3.13 for stations in comparable regions (coastal southern Queensland and inland New South Wales).

3.4.2. Implications of the use of accumulated data

The greatest impact of the use of accumulated data is on the diurnal temperature range, as the upward bias in maximum temperature and the downward bias in minimum temperature are added to each other. (Conversely, when mean temperatures are calculated the biases counteract each other). This is of particular potential importance for a number of reasons. Firstly, one of the more pronounced trends in global temperature that has been found in a number of studies is a reduction in the mean diurnal temperature range (e.g. Easterling et al., 1997), and Torok (1996) found a decrease of 0.48°C in the mean Australian diurnal temperature range since 1910. Secondly, the biases found in this section, when applied to maximum and minimum temperatures separately, are at or near the lower limit of the magnitude of discontinuity detectable by the techniques used in this study (being mostly in the order of 0.1°C to 0.3°C when one day per week is missing), yet, when they are combined, the resultant bias is between 0.2°C and 0.6°C at most stations.

The mean monthly maximum and minimum temperatures in the Bureau of Meteorology's database are, as mentioned earlier, calculated with accumulated data included. The task of identification of months with accumulated data is made more difficult by the fact that the number of days with observations is not available in the database prior to 1957 at most stations, and hence periods of the record when weekend data are missing at a station can only be identified by examining the daily manuscript records from that station. One possible solution for the identification of such periods could be to carry out the tests used in Chapter 4 for the detection of inhomogeneities on the diurnal temperature range as well as maximum and minimum temperature.

In the worst-case scenario, in which all data at the start of the record were missing Sunday observations and none at the end were, the artificial trend in the diurnal temperature range would be of comparable magnitude to the trend observed by Torok (1996). In practice, it is unlikely that this would be the case, as not all stations would have missed Sunday observations. The pre-1957 manuscript data that has been obtained suggests that missing Sunday data were most common between about 1920 and 1960, with fewer missed days before and after, and that the observation were mostly missed at post offices and similar sites; lighthouses and similar sites, which make up a large part of the coastal observing network, rarely missed days. The impact of accumulated data on the observed trend in mean diurnal temperature range over Australia as a whole is worthy of further investigation, although it is outside the direct scope of this thesis.

3.5. Summary

Three systematic issues affecting the development of homogeneous, high-quality data sets have been addressed in this chapter. These serve as a precursor to the development of the data set in Chapter 4. The potential dependence of the magnitude of temperature discontinuities upon the position of a day in the frequency distribution of temperature, as described in section 3.2, is particularly crucial in the development of a homogeneous time series of extreme events. In Chapter 4, the methods developed in section 3.2 are applied to the development of a comprehensive data set.

Month	Station name			
	Wyalong		Tewantin	
	Maximum	Minimum	Maximum	Minimum
January	+0.26	-0.76	+0.68	-0.92
February	+1.15	-2.20	+0.41	-0.66
March	+0.78	+0.29	-0.09	-1.60
April	+1.52	-0.86	+0.98	-0.06
May	+0.58	-0.56	+0.80	-1.39
June	+0.72	-1.18	+0.08	-2.34
July	+0.79	-0.07	+1.32	-1.21
August	+1.16	-0.44	+0.14	-1.87
September	+0.58	-1.27	+0.98	-1.07
October	+1.42	-0.28	+2.31	-2.16
November	+1.74	-1.54	+0.69	-2.07
December	+2.97	-0.31	+1.62	-1.17
Annual	+1.14	-0.76	+0.83	-1.38

Table 3.15. Mean temperature difference (°C) between days following missing data and all other observations for Wyalong (1959-64) and Tewantin (1957-61)

Chapter 4

The Development of a High-Quality Daily Temperature Data Set for Australia

4.1. Introduction to the problem of developing high-quality daily temperature data

The development of high-quality temperature data sets, as noted in Chapter 1, is a problem which has received considerable attention in recent years. The major works in this field in Australia have been those of Torok (1996) and Torok and Nicholls (1996). Their work has been focused on data at the annual timescale. This has also been the case with much of the work undertaken outside Australia. There has been some attention given to data at the seasonal or monthly timescale, but this has involved similar methods to those used for homogenisation of annual data.

The development of daily temperature time series involves a more complex set of problems than those involved in developing annual or seasonal series. Daily time series are much more susceptible to short-term gross errors than are monthly or annual means. A 5°C error in a single maximum or minimum temperature will have a minimal impact on a monthly, seasonal or annual mean, but it may be critical when extreme temperature events are being examined. Furthermore, as was discussed in section 3.2, the methods used to homogenise annual or seasonal mean temperatures once a discontinuity is identified may not be appropriate for the homogenisation of daily maximum and minimum temperatures, as they generally take no account of possible changes in the variability of temperature, only in its mean.

The inherent problems in developing high-quality daily temperature data sets may be divided into two categories: long-term systematic inhomogeneities and short-term errors.

4.1.1. Long-term systematic inhomogeneities

The following are examples from an extensive list of potential systematic inhomogeneities which are discussed by Torok (1996). A more detailed description of these factors may be found there.

Station moves: These are relatively common throughout the period of record. In particular, many stations have moved from town centres to airports, as urban sites have become built up and aviation has become an important user of meteorological information. This process was most frequent during the 1940's and 1950's, but is continuing to the present day. Of the stations used in this study, Charters Towers, St. George, Walgett and Bourke all moved to airports between 1992 and the end of the data set in 1996.

There is also a long-term Bureau policy to reduce the number of observations at post offices, at which many stations are located. Stations located on private land are susceptible to moves when properties change hands or observers cease making observations for any reason.

Small-scale relocations of instruments within the same general area are also quite common. These may have a significant impact on observed temperatures if the characteristics of the new site are different (see below).

Station relocations are a particularly significant issue in locations where there are strong local temperature gradients, such as near coasts or in hilly terrain.

Instrument changes: The Stevenson Screen has been a standard throughout Australia for most of the 20th century. Prior to the formation of the Commonwealth Bureau of Meteorology in 1908, a wide variety of screens were in use, making comparisons difficult, both in time and space. While this is a real problem in attempting to extend the Australian climate record back into the 19th century, the limited availability of digitised daily data means that a very limited amount of pre-1908 data has been used in this study.

A more recent change has been the move to automatic weather stations. The Bureau is installing approximately 35 automatic weather stations per year, some in new sites and some in place of existing sites. Where automatic stations have been installed in place of manual sites, there has often been a period of dual observations maintained at the two sites. Four of the stations in this study were automated (Forrest, Cape Otway, Tewantin and Oodnadatta) prior to the end of this study in December 1996, all of them since late 1994. At present, this affects only a small proportion of stations for a very short part of their record, but the process has continued since 1996 and it is likely that the majority of stations in this data set will be using automated observations by 2005. The majority of alpine temperature observations are already automated.

Poorly maintained equipment (such as a screen becoming discoloured, rather than white as per specifications) could also have an impact on observed temperatures.

Changes in site environment: Even where the location of a site has remained unchanged, the local environment around a site may change. Common causes of this include building around instrument sites, or growth (or removal) of vegetation in the vicinity of instruments. Building around instrument sites has been particularly common at rural post office sites, which are often located in town centres. This includes the construction of asphalt car parks adjacent to sites (Armidale and Glen Innes are examples of this).

The issue of urbanisation as an influence on the climate record is a separate issue. It is well-established that urban centres are likely to experience warmer minimum temperatures than surrounding rural areas (the so-called "urban heat island"), with the magnitude of the urban heat island being a function of the town or city's population (e.g. Karl et al., 1988). For the purposes of a study such as this, any change in the magnitude of the urban heat island over time is of greater importance than the existence of an urban heat island *per se*. Thus, for those stations for which daily records are only available for the period since 1957 (as is the case for the majority of stations used in this study), the stations of greatest concern are those located in or near the centres of towns that have seen significant growth between 1957 and the present.

A population of 10,000 has often been taken as the lower limit for significant urbanisation effects, although noticeable urban heat islands have been found in much smaller centres (Torok et al., 2001). The following stations used in this study can be considered to have been affected by urbanisation:

1. In major city: Sydney, Melbourne, Adelaide (both sites), Hobart.
2. Away from centre of major city but within general metropolitan area: Laverton, Richmond (NSW), Perth Airport, Brisbane Airport, Darwin Airport.
3. In or near centre of country town with population exceeding 10,000: Dubbo, Port Lincoln, Tewantin, Port Macquarie.
4. Has moved from centre of town with population exceeding 10,000 to airport during period of record used in study: Albany, Bundaberg.

A categorisation of all station locations may be found in Table 2.1a.

It should be noted at this point that the existence of an artificial temperature trend due to urbanisation at an individual station does not exclude it from consideration in this study; rather, it is an aid to interpretation of observed trends at those stations. It is, however, invalid to interpret observed trends at an urban station as being representative of conditions over a broader region.

Changes in observation practices: The principal problems here arise from changes in the time of observation, and changes in the frequency of missed observations (for example, taking/not taking Sunday observations). These were both discussed at some length in Chapter 3.

The Bureau of Meteorology adopted the Celsius scale of temperature measurement on September 1, 1972. While a discontinuity in the relationship between mean maximum temperatures and annual rainfall over Australia has been observed around this time (Nicholls et al., 1996a), there is no evidence that the change in units (and the consequent change of thermometers) was responsible for that discontinuity.

Observers are instructed to make observations to the nearest 0.1 degree Celsius, and prior to metrication were instructed to make observations to the nearest 0.1 degree Fahrenheit. In practice, as the figures in Tables 4.1a, 4.1b and 4.1c demonstrate, many observers, prior to 1972, observed temperatures only to the nearest whole degree. This practice has become less common since 1972, although there continues to be a bias towards observations ending in .0, something that has also been noted outside Australia (Nese, 1994; Petrovic, 1998). In addition, at present, maximum and minimum temperatures from some automatic weather stations are only archived to the nearest whole degree, as a result of limitations in the codes used for transmission (Wong, pers. comm.).

While mistakes, and failure to observe standards of observation, by observers can result in long-term systematic biases, they more commonly result in short-term errors and are dealt with in that section.

4.1.2. Short-term errors

These are errors that affect observations either on a single day or over a period of a few weeks or months. Unless they are especially large, such errors will not have a substantial effect on mean annual temperatures, but they may be critical in an examination of extremes.

Errors of this type include:

Observer errors: Observer errors recorded include the misreading of thermometers by 5 or 10 degrees, reading the wrong end of the index for maximum and minimum thermometers, failing to reset the thermometers each day, or recording some other climate element (such as the temperature at 0900 or the grass minimum temperature) as the maximum or minimum temperature. These errors were usually isolated, but occasionally persist over a longer period (e.g. Thargomindah in January-February 1963), possibly at times when the regular observer was absent.

Clerical errors: Data received by the Bureau and entered into its computer system were normally keyed twice, until the introduction of improved data management and quality control software in 1994, to minimise the risk of typographical errors in processing (Hutchinson, pers. comm..). Nevertheless, processing errors still occurred, especially as the legibility of the handwriting of some observers leaves something to be desired.

Defective instruments: It was not unknown for an instrument to develop a fault, but for some time to elapse between the fault's occurrence and the removal or replacement of the defective instrument. The observed temperatures would therefore be suspect in the intervening period. Torok (1996) notes that the minimum thermometer was particularly vulnerable to faults, and was also less readily replaced than maximum thermometers were. There are, accordingly, more breaks in the minimum temperature record than there are for maximum temperature, especially in remote areas.

4.2. Techniques of development of high-quality temperature data sets

The technique used to develop high-quality sets of daily temperature data consisted of three principal steps. These steps were:

1. A first pass of detection of single-day errors, in order to remove obvious errors from the data sets prior to any attempts to detect long-term inhomogeneities.
2. The identification of, and adjustment for, inhomogeneities in the long-term data sets after gross errors had been removed.
3. Spatial analysis of the adjusted temperature data in order to identify stations whose data differ substantially from those of its neighbouring stations.

At this point, it is important to note the distinction between rejected and flagged data. Data may be rejected immediately if it violates a condition which must hold (e.g. maximum $\geq$ minimum). Data which are identified by some of the tests outlined below (e.g. for differing by more than a set amount from its neighbours) are flagged for further examination. This may lead to its ultimate deletion but does not necessarily do so.

Station name	% of °C temps ending in .0	% of °F temps ending in .0	Station name	% of °C temps ending in .0	% of °F temps ending in .0	Station name	% of °C temps ending in .0	% of °F temps ending in .0	Station name	% of °C temps ending in .0	% of °F temps ending in .0
Kalumburu	16.1	44.2	Marree	10.9	46.9	Amberley	12.4	28.9	Cabramurra	17.5	55.7
Halls Creek	13.4	36.6	Oodnadatta AWS	13.1	26.6	Brisbane AP	12.8	29.3	Wagga Wagga	13.7	28.0
Broome	12.2	32.2	Oodnadatta PS	34.3		Tewantin PO	17.9	48.0	Wyalong	20.3	79.0
Port Hedland	11.8	27.7	Ceduna	14.9	30.6	Tewantin AWS	10.4		Deniliquin PO	10.5	63.8
Learmonth	12.2		Port Lincoln	21.0	63.2	Thargomindah	32.5	78.9	Mildura AMO	15.0	30.5
Wittenoom	13.7	61.6	Snowtown	16.8	63.9	Tibooburra	16.5	87.9	Nhill	28.2	68.1
Carnarvon	13.6	29.5	Adelaide (WT)	15.3	20.4	Wilcannia	21.0	99.7	Kerang	21.0	58.3
Meekatharra	12.0	31.2	Adelaide (KT)	13.3		Bourke PO	31.7	95.6	Rutherglen	26.6	77.6
Dalwallinu	25.2	58.3	Nuriootpa	17.4	28.2	Bourke AP	11.8		Gabo Island	23.7	82.4
Geraldton	14.1	30.4	Mount Gambier	13.7	26.0	Cobar PO		93.1	Orbost	13.8	52.9
Perth Airport	11.6	27.0	Robe	25.1	61.8	Cobar MO	12.1	28.6	East Sale	12.9	30.8
Cape Leeuwin	25.4	78.5	Thursday Island	13.2	23.8	Walgett PO	24.4	82.2	Wilsons Prom	23.3	92.2
Albany Town		51.5	Weipa comp	17.9	58.0	Walgett AP	24.8		Melbourne	12.5	26.9
Albany AMO	12.5	36.2	Weipa MO	14.4		Moree PO		94.7	Laverton	16.0	29.5
Esperance PO		76.2	Palmerville	53.5	96.5	Moree MO	11.7	25.7	Cape Otway	28.3	84.6
Esperance MO	13.8	26.7	Burketown	21.9	86.2	Gunnedah	11.3	30.3	Low Head	41.1	87.5
Cunderdin	21.2	42.6	Richmond (Qld.)	26.3	65.7	Inverell PO	16.3	62.6	Launceston AP	15.3	32.5
Wandering	22.4	53.5	Cairns	13.8	26.4	Inverell (new)	10.7		Eddystone Point	29.6	87.4
Forrest AMO	13.4	27.5	Townsville	12.7	26.3	Yamba	23.9	78.1	Cape Bruny	24.0	89.6
Forrest AWS	29.4		Mackay	13.1	26.8	Coffs Harbour	12.9	27.1	Hobart	13.7	28.5
Kalgoorlie	12.6	30.8	Charters T. PO	20.0	62.5	Port Macquarie	30.4	77.2	Grove	14.6	39.9
Giles	12.4	28.3	Charters T. AP	17.2		Williamtown	14.3	32.8	Butlers Gorge	41.0	76.9
Darwin Airport	13.0	26.2	Barcaldine	16.5	32.7	Scone Soil Cons	15.5	29.3	Willis Island	13.8	26.5
Victoria River	24.4	44.1	Longreach AP	14.9	32.0	Bathurst ARS	24.2	61.5	Cocos Island	13.7	29.9
Downs			Camooweal	23.2	60.9	Dubbo	15.1	74.7	Norfolk Island	14.3	31.3
Tennant Ck PO		26.1	Birdsville	26.0	93.0	Sydney	11.2	25.2	Lord Howe (old)	14.0	30.5
Tennant Ck MO	13.4	69.6	Boulia	26.4	70.9	Richmond AMO	14.1	31.5	Lord Howe	11.7	
Rabbit Flat	18.9	27.3	Bundaberg PO	20.2	63.7	Richmond AWS	10.9		Davis	43.3	85.6
Alice Springs	12.3	29.1	Bundaberg AP	17.5	31.4	Jervis Bay	25.2	92.3	Mawson	31.8	75.8
Woomera	13.9	28.4	Gayndah	19.2	31.5	Nowra RAN	12.2	28.4	Macquarie Island	12.6	83.0
Tarcoola	17.0	75.4	Rockhampton	14.2	28.4	Moruya Heads	27.3	68.1	Casey	29.4	74.8
						Canberra	13.6	28.1	Casey (new)	10.5	

Table 4.1a. Frequency of recorded temperatures ending in .0 for Celsius (post-1972) and Fahrenheit (pre-1972)

Year	Frequency of temp. ending in .0	% over-representation of temps. ending in .01	Year	Frequency of temp. ending in .0	% over-representation of temps. ending in .01	Year	Frequency of temp. ending in .0	% over-representation of temps. ending in .01
1957	0.575	219	1971	0.418	132	1985	0.173	73
1958	0.588	227	1972	*	*	1986	0.172	72
1959	0.608	238	1973	0.200	100	1987	0.165	65
1960	0.600	233	1974	0.203	103	1988	0.165	65
1961	0.574	219	1975	0.210	110	1989	0.162	62
1962	0.563	213	1976	0.202	102	1990	0.161	61
1963	0.518	188	1977	0.209	109	1991	0.155	55
1964	0.502	179	1978	0.218	118	1992	0.155	55
1965	0.506	181	1979	0.222	122	1993	0.157	57
1966	0.482	168	1980	0.222	122	1994	0.199	99
1967	0.449	149	1981	0.218	118	1995	0.187	87
1968	0.426	137	1982	0.190	90	1996	0.164	64
1969	0.401	123	1983	0.181	81	1997	0.167	67
1970	0.406	126	1984	0.177	77	1998	0.204	104+

* Changeover from Fahrenheit to Celsius took place in 1972.
+ One month's data only.

Table 4.1b. Frequency of temperatures ending in .0, by year

Last digit of recorded temperature	% frequency
.0	18.5
.1	7.2
.2	10.0
.3	7.6
.4	9.7
.5	13.0
.6	10.0
.7	8.6
.8	8.6
.9	6.6

Table 4.1c. Frequency of final digit of recorded temperatures (°C) over 1973-97 period

4.2.1. First pass of detection of short-term errors

4.2.1.1. Detection of gross errors

This section consisted of a test to detect gross errors in the data. It is a logical necessity that the maximum temperature on any given day is greater than the minimum temperature on that day, as the following relationship must hold for observations taken at 0900 (as observations generally are in Australia):

Maximum temperature for day beginning at 0900 ≥ temperature at 0900 ≥ minimum temperature for day ending at 0900

Furthermore, as the minimum temperature for a given day and the maximum temperature for the previous day are both measured for the 24 hours ending at 0900, the relationship

Minimum temperature on given day ≤ maximum temperature on previous day.

This relationship is only valid where maximum and minimum temperatures are taken over a 24-hour period ending at the same time, so it may not apply to data which are not taken over the post-1964 standard of a 24-hour day ending at 0900 local time. This includes the automatic weather station data where the minimum and maximum temperatures are taken at different times (see section 3.3).

Data may also be checked against known extremes for the station, a reasonable range for the region concerned, or some other extreme parameters. While any data that do not fall within an extreme range should be detected by the more detailed tests described later in this section, the rejection of such data at an early stage reduces the number of flagged days which need to be examined individually at that stage, reducing the time necessary for processing.

The data for each station were checked for validity of the maximum and minimum temperature relationships, and against reasonable limits for the region concerned. Data which failed these checks (and were known to have been taken using the standard 0900 observation time) were rejected. If the maximum-minimum temperature conditions were violated, both were rejected unless there was firm evidence, e.g. from fixed-hour observations, that one was correct. Accumulated data, as discussed in section 3.4, were also rejected at this stage. Data were assumed to be accumulated if they followed one or more missing days, whether or not it was flagged as accumulated in the Bureau's database. As noted in section 3.4, the accumulation flag was not used prior to 1966.

4.2.1.2. Examining data for internal inconsistency

In addition to the maximum and minimum temperatures, all of the stations examined in this study take observations of the temperature at certain fixed hours. A few stations take observations eight times per day (at three-hour intervals), many take seven (missing either the 2100 or 0000 LST observation), and most take at least two, usually at 0900 and 1500 LST. A few stations take observations only at 0900 LST.

While all fixed-hour observations have been archived on computer since 1987, prior to that date most stations (with the exception of Meteorological and Regional Offices) only have 0900 and 1500 observations available on computer, even if other observations were taken.

All data were checked for consistency between the fixed-hour observations and the maximum and minimum temperatures, by checking that none of the fixed-hour observations for the period covered by the maximum and minimum temperatures fell outside the limits set by them. Any day on which any fixed-hour observation exceeded the maximum, or fell below the minimum, by 1°C or greater was flagged. All maxima or minima thus identified were rejected except in the following circumstances:

- it was clear that the fixed-hour observation was in error rather than the maximum or minimum temperature. This can be checked by comparison with neighbouring stations or, at stations with three-hourly observations, the observations preceding and following the one in question.

- some post-1964 data violated this condition solely by virtue of the 0900 temperature from the previous day falling below the minimum, or the 0900 temperature exceeding the previous day's maximum (suggesting that the maximum or minimum temperatures were not taken over the full 24 hours). In such cases the minimum was assumed to be equal to the 0900 temperature from the previous day, or the maximum equal to the 0900 temperature from the following day, as applicable.

While this technique is useful for removing some incorrect observations from the data set, it has a number of limitations. If a maximum temperature is too low, it is likely to be lower than the 1500 observation (at least) and is therefore likely to be detected by this test. However, maximum temperatures which are too high will not be detected by this test. The converse applies to minimum temperatures.

Furthermore, the power of this test is restricted by the limited number of fixed-hour observations available for many stations. While the 1500 temperature, which is readily available for most stations, is usually quite close to the true maximum temperature for the day, the 0900 temperature is often substantially higher (by up to 20°C in some cases) than the minimum temperature, which allows large errors to go undetected. The 0600 and 0300 temperatures are much better approximations of the minimum temperature, but these are only available in digital form for a relatively small number of stations, especially prior to 1987. In particular, the relatively common error of recording the 0900 temperature as the minimum will not be detected by this test if there are no 0300 or 0600 observations.

Finally, this test will not identify suspect maxima and minima on days where the fixed-hour observations are missing. It was noticeable, in examining data flagged as suspect by the spatial tests in sections 4.2.1.3 and 4.2.3, that a disproportionately high number of flagged days had one or more missing fixed-hour observations (again, recording the 0900 temperature as the minimum or the 1500 temperature as the maximum are common occurrences in such cases).

4.2.1.3. Comparison of data with neighbouring stations

In this part of the testing, data from each station were checked against a number of neighbouring stations. Ideally, stations chosen as neighbours for this part of the test would meet the following criteria:

- not more than 100 km from the candidate station
- at a similar elevation to the candidate station
- a similar temperature regime to the candidate station (ideally, with mean monthly maximum and minimum temperatures having a correlation of 0.9 or greater with those at the candidate station)
- continuous data for the period of record of the candidate station

In practice, very few stations in Australia have a reasonable number of neighbouring stations which satisfy all of the criteria, the exceptions being in inland south-eastern and south-western Australia, which are densely settled enough to support a relatively dense network of stations, but not close enough to the coast for strong temperature gradients to exist. For other stations, these criteria (distance, elevation, correlation of monthly temperatures, length of overlapping record) were used to choose the neighbouring stations used. At least four neighbours were sought for each station, but in some cases four reasonable neighbours could not be found, either because of the remoteness of the station from other stations (e.g. Kalumburu, Thursday Island, Giles) or because the station was in an environment dissimilar to those of other stations in the vicinity (e.g. Wilsons Promontory).

A full list of the neighbours used for each station in this part of the study is given in Appendix B.

Once the neighbouring stations were identified, the maximum and minimum temperatures at the candidate station on each day were checked against those at the neighbouring stations. If the temperature at the candidate station differed from that at all neighbouring stations by more than 4°C, the observation was flagged. This limit was extended to 5°C or 6°C at some stations (identified in Appendix B) in remote, coastal or high-elevation locations.

Data flagged by this procedure were subjected to more extensive checks to determine whether or not it should be rejected. These checks included:

- checks against fixed-hour observations (for example, comparing a suspiciously high maximum temperature with the 1500 temperature)
- checks against other stations in the region not used in the initial comparison (for example, stations with short records)
- checking for local weather conditions (such as rain or fog) which could result in anomalously low or high temperatures being recorded at a particular station

The decision as to whether or not to reject an observation is inevitably a subjective one. At some stations, large discrepancies with neighbouring stations can occur quite naturally. Fig. 4.1 shows the frequency distribution of differences of January maximum temperature between Robe and its nearest neighbour, Naracoorte. Where a station is known to have a distinct temperature regime, observations were less likely to be rejected. (Using Robe as an example again, a summer maximum temperature substantially lower than Naracoorte, which is much less exposed to the sea, would not arouse suspicion, but one substantially higher would). As an indication of the level at which flagged observations were rejected, a flagged maximum temperature which exceeded the 1500 temperature by more than 6°C would normally be rejected, unless there were reasons to believe that it was valid.

The dilemma in such a decision-making process is to set a level of rejection such that all erroneous observations are rejected while no valid observations are rejected. In practice it is impossible to achieve such a result, and it is therefore necessary to accept a certain level of error in order not to reject valid observations. Decisions on the rejection of data were made with this in mind.

This part of the quality control process is most effective in areas where there are several good neighbouring stations. It is least effective for stations with few good neighbouring stations - in general, remote stations and exposed coastal stations.

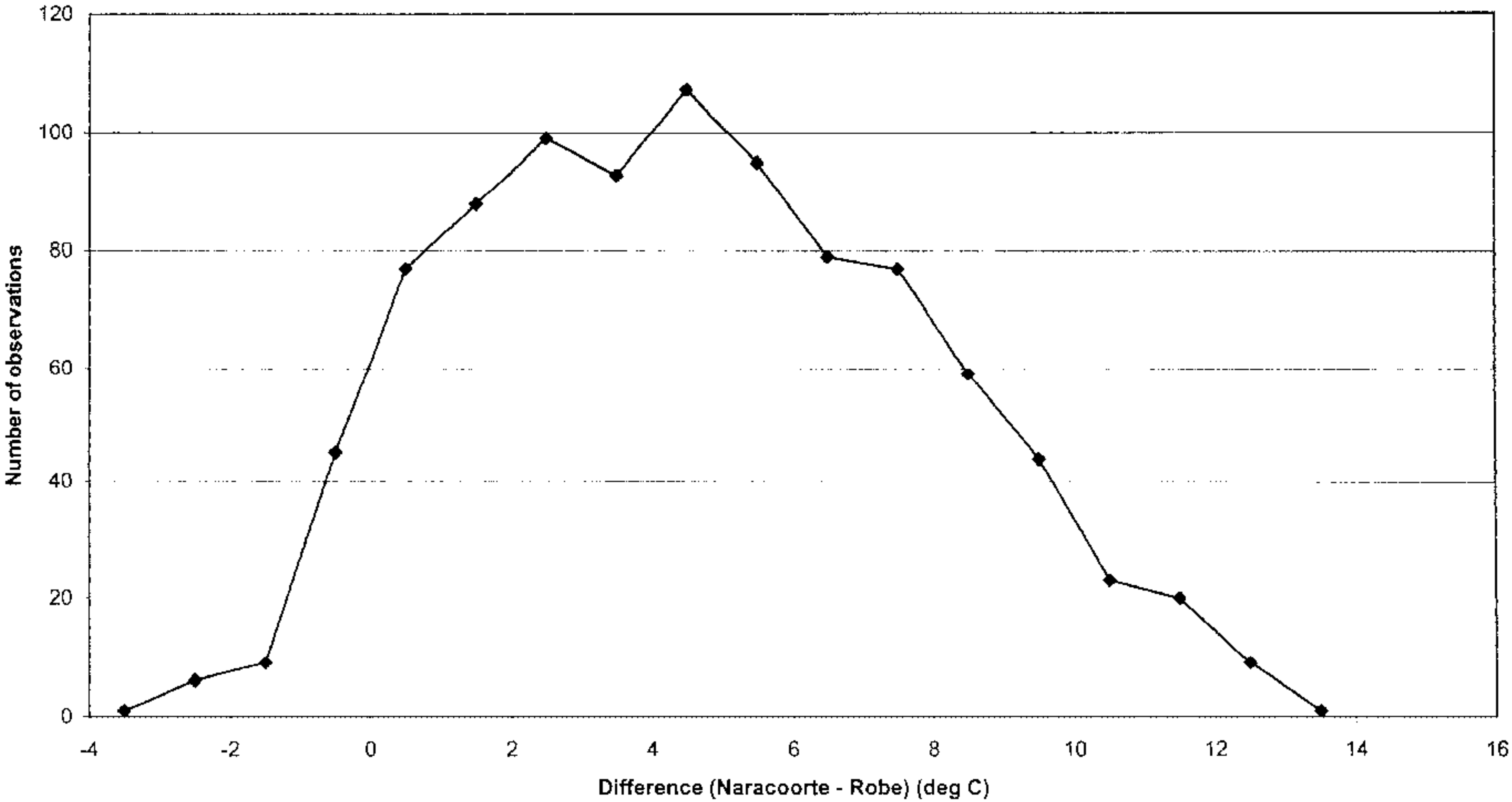
4.2.2. Long-term inhomogeneities

4.2.2.1. Identification of discontinuities in the record

As previously discussed in section 4.1.1, there are a number of factors that can result in discontinuities in a long-term climatic record, and considerable attention has been devoted to the problem of adjusting annual and seasonal means in order to reconstruct a homogeneous data set. The methods used in previous studies have, in general, involved the construction of a reference series of some kind to be compared with the data at the candidate station. The chief differences between the methods has been in the methods they use to construct the reference series, and the tests they use to identify inhomogeneities in the time series of temperature differences between the candidate station and the reference series.

This study differs somewhat from previous methods of adjusting climatic data for discontinuities, in that the adjustments are made to daily data, using the methods described in Chapter 3. The mean monthly data used in the compilation of a reference series for the identification of inhomogeneities are used only for the purpose of identifying inhomogeneities, and not to adjust for these inhomogeneities (except in a few cases early in the record where there were no neighbouring stations with digitised daily data). As such, a long-term non-climatic trend in the reference series (arising, for example, from urbanisation) is important only if its existence masks the existence of a specific inhomogeneity. This, in turn, means that it is possible to use all stations, whether urban or rural, which meet standards of adequate length of overlapping record and correlation with and distance from the candidate station in the compilation of a reference series.

Fig. 4.1. Frequency distribution of January daily maximum temperature differences between Naracoorte and Robe



4.2.2.1.1. Construction of a reference series

A candidate station for the reference series would, ideally, meet criteria along the same lines as those used in the selection of neighbouring stations in the tests in section 4.2.1.3, although the reduced spatial variability of monthly mean, as opposed to daily, temperatures results in a wider potential radius over which well-correlated comparison stations can be found. The criteria which would, ideally, be satisfied by a comparison station would be:

- near the candidate station
- have a similar temperature regime to the candidate station
- have a long and homogeneous record of its own

In order to allow comparison stations to be chosen objectively, these indicators may be (partially) quantified as follows:

- proximity: distance from the candidate station
- similar temperature regime: correlation of monthly temperature anomalies between candidate station and comparison station
- long record: number of months with data at both candidate and comparison station

There is no simple objective method of quantifying the homogeneity of records at comparison stations, without subjecting them to the same procedures as the candidate stations. In practice, as candidate stations have been chosen on the basis of having a potential high-quality record in the first place, the length and homogeneity of the record at comparison stations is likely to be less than that of the candidate station.

There are a total of 1587 stations in Australian with some maximum or minimum temperature data, although many of these have short records (some only a few months or years). This number makes it impracticable to assess the individual merits of each station as a comparison station subjectively, making objective criteria desirable.

There is no simple way of determining the homogeneity of the data at all of the comparison stations (as, at this point of the analysis, we have no homogeneous data sets with which to compare them). The use of a large number of neighbouring stations, however, will minimise the impact of an inhomogeneity at any one comparison station on the reference series, unless there is an inhomogeneity which affects a large number of stations simultaneously. Torok (1996) notes the introduction of the Stevenson Screen through much of Victoria in 1908 as one such inhomogeneity; however, very little of the data used in this study were from the pre-1908 period. The introduction of daylight saving is another possible large-scale inhomogeneity and was discussed further in section 3.3.

One method of minimising the impact of a discontinuity in a comparison station is to use a time series of month-to-month changes in temperature anomaly, rather than the anomalies themselves. This has the advantage of confining the impact of a discontinuity at a comparison station to a single data point (the month in which the discontinuity occurs), but, as discussed later, has disadvantages which outweigh this advantage when used for monthly data.

As potential comparison stations with long, continuous records are few and far between (and non-existent in many cases), there will be changes through time in the set of stations from which a reference series is compiled. Again, as long as there are a large number of comparison stations, one station entering or leaving the series should not affect the series greatly. A potential discontinuity arises if a large number of stations enter or leave the reference series simultaneously. As noted in Chapter 2, there are three occasions on which data commences or ceases from a large number of stations simultaneously: 1908, 1957 and 1965. The 1957-1964 break in data at many stations, especially in New South Wales, is of particular interest to this study. A spurious discontinuity in the reference series, if any arose from this cause, could have two effects: it could cause a spurious inhomogeneity to be identified at the candidate station in 1957 or 1965, or it could mask a genuine inhomogeneity around that time. The former is of limited relevance as, in such cases, the adjustment scheme in section 4.2.2 will produce a near-zero adjustment. The latter is of greater concern.

Torok (1996), who used a similar set of criteria for the choice of comparison stations, carried out a series of tests in which he computed a reference series using different values for the station selection criteria. While the method of compilation of his reference series differs from that used here, and therefore his findings should be applied to this study with some caution, he found that the choice of station selection criteria, while affecting the absolute value of the reference series, did not have any effect on the location of discontinuities, which is the matter of interest here.

The selection criteria eventually used in this study for comparison stations were:

- nominal distance between candidate and comparison station < 6 units
- correlation of monthly temperature anomalies between candidate and comparison station > 0.6
- at least 120 months (not necessarily continuous) of overlapping data between the candidate and comparison station

For the purpose of this section, the nominal distance, d, equates to the straight-line distance assuming the latitude-longitude grid to be a regular grid, and is calculated using the formula:

d^2 = (latitude of candidate - latitude of comparison)^2 + (longitude of candidate - longitude of comparison)^2

The nominal distance, rather than actual distance, is used in this section for computational simplicity.

This is not strictly equivalent to distance, as the distance between longitude points on such a grid decreases with increasing latitude, but is much simpler to handle computationally than is distance. 1° of longitude equates to 109 km at latitude 10°S and 79 km at latitude 45°S. 1° of latitude equates to 111 km everywhere. A value of $d = 6$

equates to between 530 and 670 km over mainland Australia, depending on latitude and direction. Note that a side-effect of this method of calculating distance is that, in northern Australia, comparison stations are considered from a slightly wider radius than they are in the south, which compensates in part for the north's lower station density.

As potential comparison stations had data covering differing periods, the monthly temperature anomalies for a station, as used for the calculation of correlations (r), were calculated with respect to means for all available years at that station, rather than using a standard normal (1961-90, for instance), which would have excluded stations with insufficient data in the 1961-90 period but more data in earlier years.

The next issue to resolve is how to combine the data from all of the comparison stations into a reference series. There are a number of methods of varying sophistication of achieving this. Desirable attributes of the combination scheme include:

- insensitive to outliers
- representative of conditions at the candidate station
- computationally simple

The most computationally simple scheme is an arithmetic mean of the temperature anomalies at all candidate stations. This, however, fails to meet the second desirable attribute, as a well-correlated station near the candidate station will have the same weight as a distant, poorly-correlated station (in as much as such are allowed by the selection criteria).

Torok (1996) uses the median of the interannual differences of temperature at each station in the reference series, and then uses these median differences to reconstruct a reference series. This was the first approach attempted in this study. One major difficulty with such an approach is that a sum of interannual differences is sensitive to small variations at the start of a record (when data are relatively scarce) and that small errors (for example, in rounding) can accumulate over the course of a record. Even at the annual timescale, the sensitivity is such that Torok found that a small change in the criteria for selecting comparison stations resulted in a 3.4°C change in the 1990 value of the reference series for minimum temperature at Mildura. This compounds considerably when monthly data are used, as the number of data points increases twelve-fold. It was found in trials that using re-summed interannual differences frequently resulted in cumulative anomalies in excess of 10°C by the end of the record. While this does not matter if the points of discontinuity are still apparent (as was the case in Torok's work for annual data), the existence of such an artificial trend is clearly not desirable in a reference series and the use of intermonthly differences was therefore not considered further.

Returning to the use of the temperature anomalies themselves in a reference series, the simplest methods for combining them are using a median or weighted mean. A median has the advantage that it is less sensitive to outliers than is a mean. Its disadvantage is that there is no simple way of weighting a median to give greater weight to nearby stations (or well-correlated stations) than more distant stations.

A weighted mean was ultimately used. This used the weighting function:

$w = (r \times (6-d))^2,\ r > 0.6,\ d < 6$

$w = 0,\ if\ r \leq 0.6$ or $d \geq 6$

The requirements for such a weighting function are that it give greatest weight to nearby stations which are well-correlated, but not to such an extent that a single station located very close to the candidate station would dominate the reference series (which would give excessive weight to any anomalous months or inhomogeneities at this station). To give an example of how the function behaves with increased distance from, and decreased correlation with, the candidate station, the weighting function, w, used has a maximum value of 36, while a station with a 0.8 correlation of mean monthly temperatures with the candidate station and at a distance $d = 3$ produces a w value of 5.76.

The resultant weighted mean temperature anomaly is given by:

$a = (\Sigma w_i a_i)/(\Sigma w_i)$, where a_i is the temperature anomaly for the month at station i and w_i is that station's weight.

4.2.2.1.2. Using the reference series to identify inhomogeneities

The first step in using the reference series to identify inhomogeneities is to produce a time series of the difference between the monthly values of the reference series and the monthly temperature anomalies at the candidate station. Discontinuities in this time series of temperature difference will indicate the location in time of potential inhomogeneities of temperature at the candidate station. It is important to note that the procedure followed in this section is used only to identify potential discontinuities, and that other procedures (which are described in section 4.2.2) are used to adjust the data for these potential discontinuities. As such, it is more important to identify all potential significant discontinuities than it is to exclude discontinuities which are not statistically significant.

There have been many statistical tests developed, as discussed in Chapter 1, both inside and outside the field of climatology, for the purpose of identifying discontinuities in time series. The test used for this section of the analysis was the two-phase regression model, based on that used by Solow (1987) and Easterling and Peterson (1995).

The two-phase regression model is carried out as follows:

A segment of the time series (initially, the whole series) is taken. Taking i and j as the starting and finishing points of the segment and d_k as the value of the difference time series in month k, for each point k between i and j, regression was used to fit separate linear relationships to each of the two parts of the segment between months i and k, and between $(k+1)$ and j. The two regression lines were not constrained to meet between points k and $(k+1)$ (as carried out by Easterling and Peterson, but not by Solow). A residual sum of squares was then calculated for the two relationships. The formula for this was:

$$RSS_{2,k} = \sum_{m=i}^{k} (d_m - (a_1 + b_1 m))^2 + \sum_{m=k+1}^{j} (d_m - (a_2 + b_2 m))^2$$

where	a_1 , a_2 , b_1, b_2	were the regression coefficients for the two relationships
	d_m	was the value of the difference series in month m

The value of k which minimised the value of $RSS_{2,k}$ was flagged as the value of a potential discontinuity, providing that k was between $(i+18)$ and $(j+18)$, that is, all flagged discontinuities were required to be at least 18 months apart. (This is to prevent a single anomalous month near the start or end of a record from being identified as a spurious inhomogeneity).

The significance of the two-phase fit was estimated using the likelihood ratio statistic

$$U = \frac{\dfrac{RSS_1 - RSS_2}{3}}{\dfrac{RSS_2}{n-4}}$$

from Solow (1987):

where	RSS_1	is the residual sum of squares for a single linear fit of the time series over the full interval
	RSS_2	is the minimum value of $RSS_{2,k}$ as determined above
	n	is the number of data points in the full interval

This test statistic is F-distributed with 3 and (n-4) degrees of freedom. The 99% significance level of such an F-distribution is 3.78 for $n = \infty$, increasing to 3.95 for n =120 (i.e. 10 years of data), 4.13 for n=60 and 4.72 for n=24, with the effective number of degrees of freedom (and hence the effective value of n) possibly being further reduced if the difference series is autocorrelated. It follows from this that all discontinuities significant at the 99% level must have a U-value of at least 3.78. For the purpose of identifying potential discontinuities, all discontinuities with a U-value greater than 3.78 were flagged, for computational simplicity, regardless of the value of n. This will result in some non-significant discontinuities being flagged, particularly where n is small. As discussed earlier in this section, this should not greatly affect the results, as the adjustments for such non-significant inhomogeneities will be small.

The procedure was then repeated for the two parts of the time series separated by the flagged discontinuity. This process was repeated for each segment until either:

(a) a segment contained no discontinuity significant at the 99% level
(b) the time period between the start and end of a segment was less than 36 months
or (c) there were fewer than 10 data points in a segment (this could happen in a segment which satisfied (b) if there were missing data.

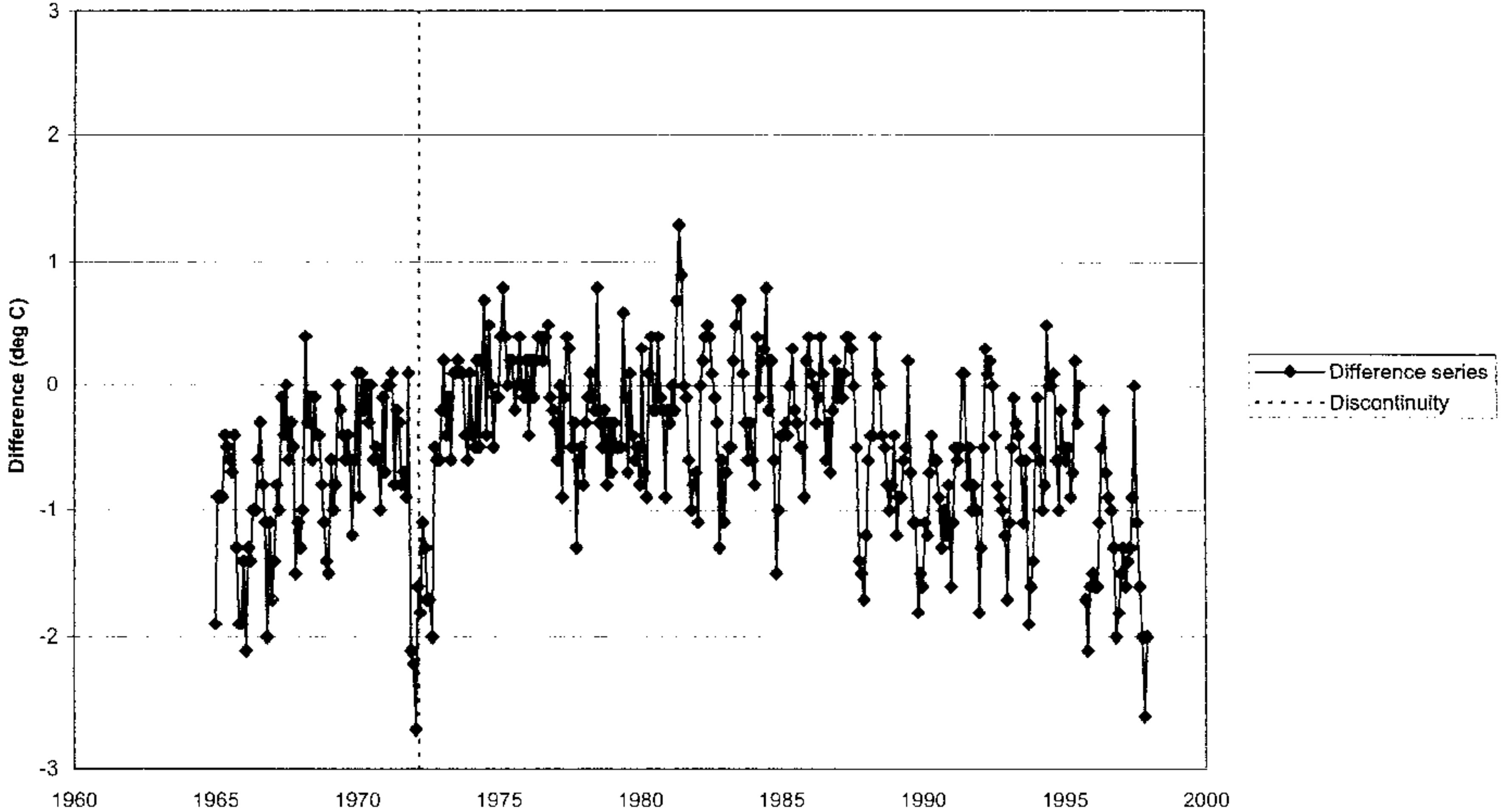
All significant discontinuities identified by this procedure were then checked against a graph of the difference series. Some of the 'discontinuities' were thus found to be a result of data 'spikes' lasting for a few months. In such cases the data for the months concerned were deleted and the 'discontinuity' ignored.

An example of a plot of the difference series for a station, and the discontinuities thus identified, is given in Fig. 4.2.

4.2.2.2. Adjustment for discontinuities

Once potential inhomogeneities in the monthly mean temperature time series are identified, the question arises of the most appropriate method of adjusting the data in order to produce a homogeneous series of daily temperature data. This was discussed at length in section 3.2. In brief, any adjustments based on monthly or annual mean temperature data may be inappropriate for daily data, as they implicitly assume that any

Fig. 4.2. Example of a temperature difference series - Bathurst ARS, minima



event at a station which leads to an inhomogeneity will result in the same change in temperature on a day, regardless of the conditions on that day. It is shown in section 3.2 that this is not a valid assumption, and thus applying adjustments based on mean monthly or annual temperatures will not necessarily result in the creation of a homogeneous daily time series.

The method of frequency distribution matching, as discussed in section 3.2, was used throughout (except where there were no adequate neighbouring daily data - these cases are discussed later). Its implementation was as follows:

(a) <u>When overlapping data exist</u>

This method was used where overlapping data exist on either side of the inhomogeneity - for example, where a composite is being created of two neighbouring sites and the first site did not close until some time after the second site opened. Examples of this include Moree (Post Office closed 1966, Met. Office opened 1964) and Longreach (Post Office closed 1973, Met. Office opened 1966).

For the period of overlapping records, the frequency distribution of maximum and minimum temperature for each of the 12 months was calculated for each of the two stations. The 5, 10, 15, ..., 95 percentile values were calculated from this distribution for each station in each month.

If we let these points be $T_{i,j,k}$, where i is the month, j the station and k the percentile level (for example, $T_{3,1,70}$ would be the 70th percentile of temperature at station 1 in March), then we can define the difference in the percentile values:

$$d_{i,k} = T_{i,j,k} - T_{i,j,k}, \text{ for } k = 5, 10, 15, ..., 95.$$

This was extended to all values of k by linear interpolation between the successive percentile difference points between k=5 and k=95, and by setting $d_{i,k} = d_{i,5}$ for k<5, and $d_{i,k} = d_{i,95}$ for k>95.

Once this set of difference points was calculated for a pair of stations, the older station's data were then adjusted to be consistent with that at the later station. This was done for each temperature at the older station, T_1, by finding its percentile level, m, in the frequency distribution of data for the overlapping period. In the cases where T_1 lies between $T_{i,1,5}$ and $T_{i,1,95}$, $d_{i,m}$ was found by linear interpolation between the values of $d_{i,k}$ and $d_{i,(k+5)}$ for a value of k (where k is a multiple of 5) such that the relationship $T_{i,1,k} \leq T_1 \leq T_{i,1,(k+5)}$ is satisfied,. Using this value of $d_{i,m}$, the adjusted temperature T_2 can then be found by using:

$$T_2 = T_1 + d_{i,m}$$

If T_1 lies outside the interval between $T_{i,1,5}$ and $T_{i,1,95}$, then the same equation may be defined using $d_{i,5}$ or $d_{i,95}$ as appropriate.

In the period when data only existed from the first station, T_2 was taken as the adjusted temperature. On days during the period of overlap when data existed from both stations, the adjusted temperature was taken as the mean of T_2 and the temperature at the second station.

(b) When overlapping data do not exist

This technique was used either where a discontinuity was identified in 4.2.2.1 without a change in station number, or where two separately numbered stations were being combined into a composite with little or no overlapping data between the two. In the case of a single-station discontinuity, the data from before and after the discontinuity were treated as if they were from two separate stations.

For each pair of stations, up to four neighbouring stations were identified with (preferably) at least five years of continuous data on either side of the change/discontinuity.

For a given temperature T_1 at the first (older) station, a 'nominal' temperature was calculated for each of the neighbouring stations, $T_{1,n}$, for $n = 1,2,3,4$. This was done using the same procedure as used in calculating T_2 in part (a). In these cases, the period of overlap used for calculating the overlapping frequency distributions was the 5 years ending on December 31 in the year prior to the discontinuity, unless these 5 years included another identified discontinuity, in which case only data after that second discontinuity were used. The 5-year period was used to maximise the amount of available comparison data whilst minimising the possibility of a discontinuity at the comparison station distorting the frequency distribution there, while the choice of December 31 as the end-point was aimed to minimise the possibility that data from after the point of discontinuity would be included in the comparison, should the actual discontinuity be a few months earlier than the position identified by the procedure in section 4.2.2.1.

Each of the nominal temperatures $T_{1,n}$ was then adjusted to be equivalent to a temperature at the second candidate station $T_{2,n}$, again using the same procedure, this time with the overlap period being the 5 years commencing on January 1 in the year following the discontinuity, or the period ending at the next identified discontinuity at the candidate station if that is within the 5-year period.

The final adjusted temperature, T_2, was then calculated as the mean of all of the values of $T_{1,n}$ for the various values of n.

(c) Adjustment using mean monthly values

In some cases, mostly in the period prior to 1957, discontinuities were identified using monthly temperature data by the procedure in section 4.2.2.1, but there were little or no digital daily data available from neighbouring stations for use in the procedures used in cases (a) and (b).

In these cases, it was necessary to adjust the daily temperature data using monthly data. As already discussed, this is not an ideal solution, as such adjustments will capture changes in mean temperature, but not its variability, but it is the best solution possible with the data available.

The mean of the difference series (defined in section 4.2.2.1) was found for each of the 12 months in the 5-year periods ending on 31 December of the year prior to the discontinuity, and commencing on 1 January on the year following it. The difference between these means was then calculated. Each of the daily temperatures prior to the discontinuity was then adjusted by the appropriate monthly difference for that month.

4.2.3. Spatial analysis of data for error detection

The final step in the creation of the high-quality daily temperature data set was an additional spatial analysis of the data. This was done by interpolating daily temperature anomalies at each station onto a 1 x 1 degree latitude-longitude grid, and examining plots of the gridded data for points where the data differed substantially from that at neighbouring grid points. On a plot of gridded data, this will appear as a 'bullseye'. This test is useful in examining days on which there are no data from the comparison stations used in 4.2.1.3, but the data still differ substantially from that at stations further afield.

The first step in this process was to create the series of daily temperature anomalies at each station. Anomalies were used in this process rather than the actual temperatures, in order to make use of more spatially coherent data and minimise the extent to which suspect data points were being masked by real temperature gradients, which can be very sharp near the coast and in regions with high local relief.

The adjusted data derived in 4.2.1 and 4.2.2 were used throughout. In order to prevent contamination from the analysed data by urbanisation, Sydney, Melbourne, Adelaide and Perth Airport were not included in the analysis. As all of these stations have digitised 3-hourly temperature data available for the full post-1957 period and are located in areas of high station density, it was assumed that any errors at these four stations would be detected by the methods used in 4.2.1. As many of the daily data series commenced in 1957, the gridded analysis was commenced in that year.

The maximum and minimum temperature anomalies were calculated using a smoothed mean for the day of the year in question. These smoothed means were calculated by calculating the mean maximum and minimum temperature for each day of the year for the 30-year period between 1961 and 1990. These daily means were then smoothed using an 11-day running mean.

The Barnes successive correction technique was used to interpolate the daily temperature anomalies at each station onto a regular grid. This technique is used for operational rainfall and temperature analyses in the Bureau of Meteorology. Major references for the technique include Koch et al. (1983), and Barnes (1994a, 1994b), while applications in the Australian context include those of Jones and Weymouth (1997), Mills et al. (1997) and Jones and Beard (1998).

The technique is discussed in more detail, and compared with other techniques for interpolating data onto grids, in Chapter 8. For the time being, it will suffice to describe the technique as it has been applied in this study.

Four passes, with varying length scales, of the successive correction technique were used. The a-th pass was defined by the equation:

$$T_a(i, j) = T_{(a-1)}(i, j) + \frac{\sum_{k=1}^{N} w(r)(T(k) - T_{(a-1)}(x(k), y(k)))}{\sum_{k=1}^{N} w(r)}$$

At each pass a, the value of the analysed temperature anomaly T at a grid point (i,j) is given by:

$$w(r) = \exp(\log_e (0.5) \frac{r_2}{\gamma D^2})$$

where $w(r)$ is a weighting function given by:

and	$T(k)$	is the temperature anomaly at station k
	N	is the total number of stations
	$T_a\,(x(k),\, y(k))$	is the analysed temperature at the co-ordinates (x,y) of station k on the a-th pass
	r	is the distance between station k and the grid point (i,j)
	γ	is a convergence value whose value is varied with each pass
	D	is a length scale parameter chosen such that $w(r) = 0.5$ when $\gamma = 1$

The parameters which can be varied, depending on the purpose of the analysis, are the first-guess field $T_0\,(i,j)$, the number of passes, the scale parameter D and the convergence parameter γ. In this analysis, climatology was used as the first-guess field and thus the temperature anomaly $T_0\,(i,j)$ was set to 0 for all i and j. Four passes were used with D = 500 km and γ = 1.00, 0.36, 0.04 and 0.04 for the four passes. This corresponds to an effective length scale (the distance r at which $w(r)$ = 0.5) of 500, 300, 100 and 100 km respectively.

The analysed value of T at each station, $T_a\,(x(k),\, y(k))$, was interpolated from the four surrounding grid points using an order 2 Lagrangian function.

In this analysis, $w(r)$ was set to 0 for all r > 1000 km in each of the passes, in order to prevent the possibility that a very remote station might influence an analysis point excessively if any data were missing in data-sparse areas (for example, if no observation was made at Giles the nearest stations that could be used on that day would be Alice Springs, Rabbit Flat (post-1969), Forrest and Meekatharra, and there would be some grid points which would be more than 500 km from the nearest station). This proved to be a largely unnecessary precaution as the most remote stations used, Giles and Alice Springs, both have a very low proportion of missing data.

The calculation of 40 years of gridded temperature data was computationally intensive - it took approximately 3 hours to run on the Bureau of Meteorology's NEC supercomputer.

Once the gridded data are generated, the next question is how to use them in order to identify erroneous data. As discussed earlier in section 4.2.1, it is not possible to use comparison techniques to be able to state positively that an observation is right or wrong; rather, the techniques presented are used to flag potential erroneous data for further examination.

There are two possible automated techniques for detecting erroneous data: cross-validation and examining the difference between the value at a certain grid point and those at grid points a given distance away, with differences above a certain level being flagged. Cross-validation is an approach often used with operational analyses and is the most objective method of flagging erroneous data. However, when 40 years of data are being examined, the computational requirements of re-analysing the data with each of the stations successively deleted becomes impracticably great (given the computer time required for a single analysis). Using some kind of difference criterion on the existing gridded set could be feasible, although one complication that would need to be resolved is that each station has a different 'footprint' of grid points that are influenced by an erroneous value at that station (for example, Fig. 4.3 shows the impact of an observation at Cunderdin, WA which was approximately 5°C too low), with the more remote stations influencing a larger area than those in denser parts of the observational network, and any flagging scheme would have to find some way of ensuring that the comparison gridpoints were outside that footprint.

In this study, each of the daily analyses was examined manually. This was a time-consuming task but did allow potential erroneous gridpoints to be readily identified. In general, areas where the temperature anomaly differed from that analysed in the wider region by more than 4°C were regarded as suspect and the station(s) within them had their data subject to further examination, along the lines of the procedures used in 4.2.1. Any data identified as erroneous after that step were deleted from the final data set.

4.3. Summary

In this chapter, a high-quality daily temperature data set has been defined. This data set will form the foundation of remaining analyses in this study, including the analysis of trends in the frequency of extreme events and the relationship between the frequency of extreme events and the El Niño-Southern Oscillation.

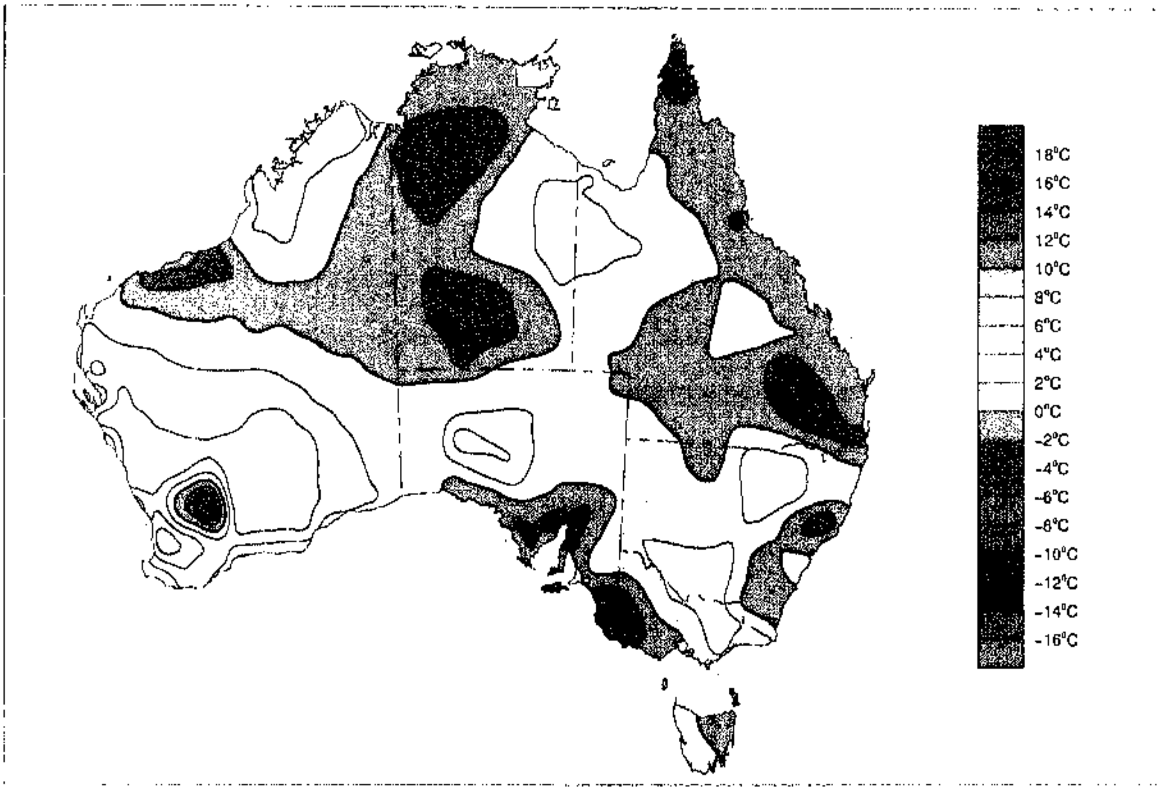


Fig. 4.3. The impact of erroneous observations on spatial temperature anomaly analyses

Chapter 5

The Australian record high temperature - fact or fiction?

5.1. Introduction

The temperature of 53.1°C recorded at Cloncurry on 16 January 1889 has been generally accepted as the highest temperature recorded in Australia. In more recent times Australia's hottest days have been recorded in other regions of the continent, giving rise to suspicions about the authenticity of the Cloncurry record. This temperature has not been approached since 1910, which is regarded as the earliest date for which one can have confidence in the full Australian climatological record, because of instrument changes, and the earliest date at which reasonable spatial coverage is available in Australia (Torok and Nicholls, 1996; Torok, 1996). In the post-1910 period, there have been only three observations of 50°C or greater, the highest being 50.7°C at Oodnadatta on 2 January 1960. If this reduction in the frequency, and change in the location, of extreme high temperatures is real, it represents a potentially significant change in the Australian climate over the last century, particularly in the light of substantial evidence that mean temperatures have warmed since 1910 (Torok and Nicholls, 1996).

Reasonably comprehensive national records of daily maximum and minimum temperature are available in digital form since 1957. Fig. 5.1 indicates the sites where temperatures in excess of 48°C have been recorded since then. These are concentrated in two regions, the central west of Western Australia and a belt extending north-east to south-west from the far south-west of Queensland and north-western New South Wales to the Nullarbor region of Western Australia and South Australia. The nearest station to Cloncurry to have reached 48°C since digital daily records are available is Birdsville, approximately 600 kilometres to the south.

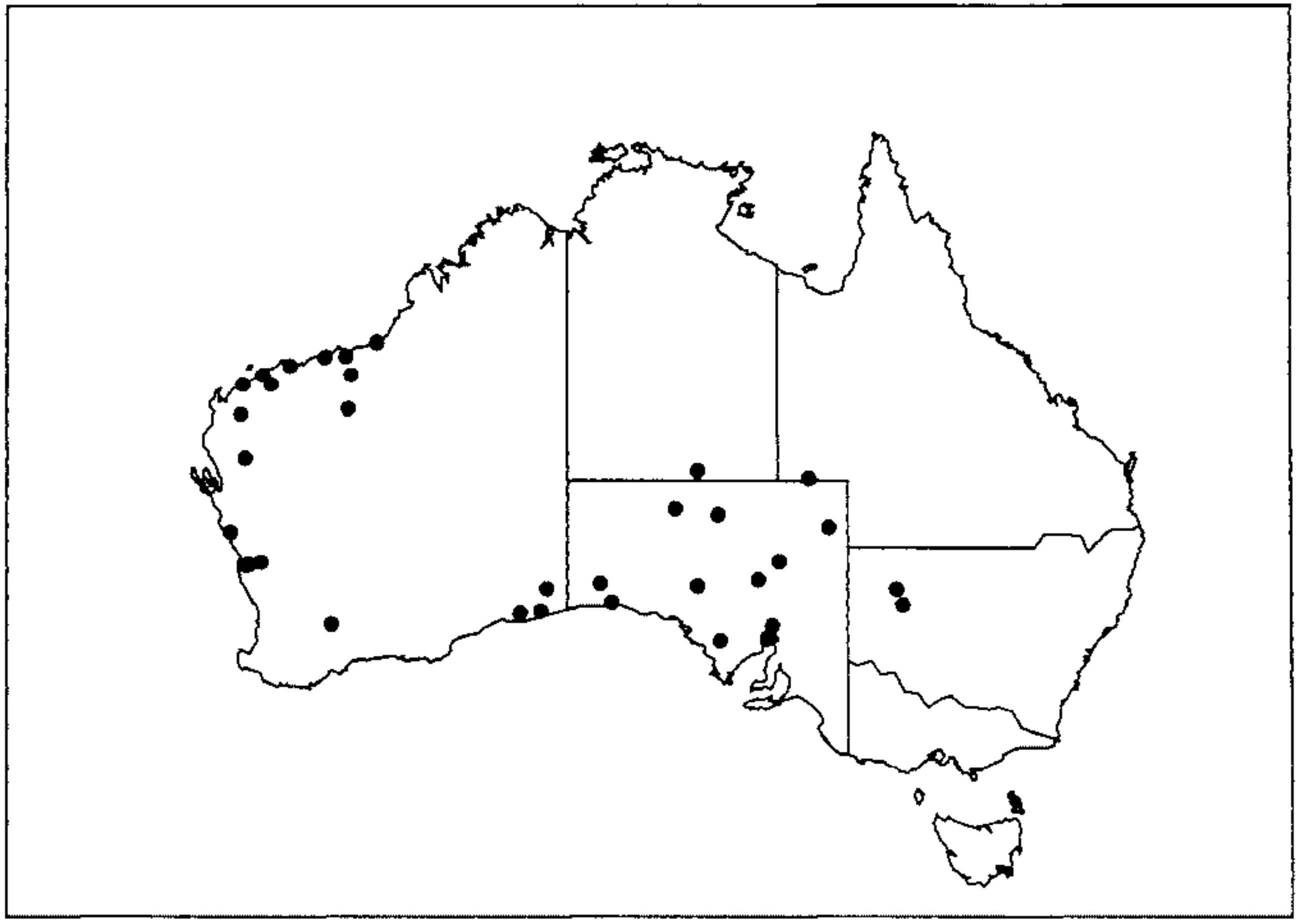
There have been some past investigations of the Cloncurry observation (e.g. Longton, 1975). These, however, were confined to checking that the reading was correctly transcribed from the original manuscript, and did not consider the possibility that the observation may not have been a true indication of the temperature on that day. Longton (1975) found no evidence that the observation was incorrect.

Doubts about the validity of extreme high and low temperatures are not confined to Australia. Fantoli (1958) and Whittle (2001) raise queries about the generally accepted highest temperature in the world, an observation of 58.0°C at Al Azizia, Libya, in September 1922, whilst Stepanova (1958) discusses doubts about the lowest temperature recorded in the (former) Soviet Union, noting that several observations widely quoted in non-Soviet sources had no known basis in the Soviet literature - something which illustrates that an extreme observation, irrespective of how suspect its original basis was, is very difficult to reject once it appears in the literature. Court (1963) notes that some extremes (specifically, the North American record low) were recorded at temperatures outside the design range of the instruments used, introducing additional sources of uncertainty.

5.2. Historical background of Cloncurry and comparison stations

A meteorological station was opened at Cloncurry in January 1888. Many Queensland stations were being opened at the time. The Queensland Meteorological Bureau was established in January 1887 as a branch of the Post and Telegraph Department, and by mid-1888 more than 100 stations were operating (Donaldson 1888). These stations were divided at the time into three categories, these being first, second and third order stations. Amongst the equipment noted as being supplied to first and second order stations was a 'Stevenson's double-louvred thermometer screen', while the notes for third-order stations simply specified 'a thermometer screen'. This distinction may or may not have been intentional. The report has been interpreted as meaning that all stations in Queensland were using Stevenson screens by 1888 (e.g. Parker 1994), but the distinction in wording suggests that any implication that Stevenson screens were in use at third-order stations is open to doubt. Cloncurry was a third-order station in 1888, as were the other two stations whose data are used in this paper, Boulia and Winton. By 1892, it had been upgraded to a

Fig. 5.1. Stations which have exceeded 48 degrees C since 1957



second-order station (Wragge, 1892). The locations of these stations are given in Fig. 5.2.

The catalogue *Climatological Stations: Queensland and Tasmania* (unpublished journal: lodged in the National Meteorological Library at the Bureau of Meteorology) notes that a Stevenson screen was installed at Cloncurry on 6 February 1889. It is possible that this could have been a replacement for an existing Stevenson screen but, as the station had only been in existence for 13 months at the time, this seems unlikely. The more probable scenario is that some other kind of stand was in place at Cloncurry from the opening of the station until 6 February 1889. The note for 6 February 1889 also indicates against the supply of a Stevenson screen: 'old screen presumably useless' and further that the maximum and minimum thermometers were 'defective'. It is not clear for how long prior to 6 February 1889 the instruments or screen (of whatever type it was) had been defective.

A Stevenson screen was installed at Boulia on 13 March 1896, although, as at Cloncurry, it is not definitely known what type of screen was in use prior to this date. No monthly mean temperature records for Winton appear in the Bureau of Meteorology's archives prior to 1938, but entries in *Climatological Stations: Queensland and Tasmania* suggest that the station has been open since 1888. A Stevenson screen was supplied there on 4 December 1891. It was a third-order station, which again opens the possibility that the screen in use there in 1888/89 may not have been a Stevenson screen.

Parallel records of monthly mean maximum temperature were obtained from the Bureau of Meteorology's digital archives for the Cloncurry and Boulia sites for the period from January 1888 to the closure of the Cloncurry site in 1975. The Cloncurry site moved from the Post Office to the airport in 1950, but Torok (pers.comm) did not find any evidence of a discontinuity in mean maximum temperature arising from this move; nevertheless, post-1950 records have not been used in the comparison of monthly mean temperatures between the two sites. Records of monthly mean maximum temperature for Winton are only available in the Bureau's digital archives from 1938, and are not used in this study. Digital records of daily maximum (and minimum) temperature are only available from

1939 at Cloncurry and 1957 at Winton and Boulia, but copies of original manuscripts were obtained for Cloncurry and Winton covering the period between November 1888 and January 1889.

5.3. Comparison of monthly mean temperatures between Cloncurry and Boulia

Fig. 5.3 shows the difference in anomalies of mean monthly maximum temperature (measured relative to the means from the period of digital daily records) between Cloncurry and Boulia over the 1888-89 period. This shows that Cloncurry's mean monthly maxima were anomalously high from November onwards, reaching a peak in December and January. The mean for December 1888 at Cloncurry is cited as 41.1°C in the Bureau of Meteorology records, but the mean of the daily maxima for the month was 44.7°C. This suggests that the mean was identified as suspect and adjusted at some stage, possibly at the time of initial processing. This was not an uncommon practice at the time (Torok, pers.comm.). Despite showing an even larger anomaly relative to Boulia, the January 1889 mean was not adjusted, perhaps because the absolute temperature was lower (42.9°C) and therefore did not arouse suspicion. Furthermore, numerous media reports of heatwaves in the 1920's and 1930's, as well as a letter written in 1938 by the then Commonwealth Meteorologist, W.S. Watt, refer to the Australian record high temperature as being 125°F (51.7°C) at Bourke, suggesting that, at the time, the Cloncurry observation may not have been recognised.

A multiple regression was carried out, using data from the period between 1890 and 1950, to estimate the mean January maximum temperature at Cloncurry using mean January maximum temperature at Boulia (correlation with mean January maximum temperature at Cloncurry, r, =0.80) and total January monthly rainfall at Boulia (r=-0.62) and Cloncurry (r=-0.70) as the independent variables. Fig. 5.4 shows this regression, which explained 84% of the variance in the Cloncurry mean maxima. This procedure predicted a January 1889 mean maximum temperature at Cloncurry of 38.4°C, which was 4.5°C, or 3.82 standard deviations, lower than that actually recorded. The residuals for the 1890-1950 period are approximately normally distributed; in a normal distribution, such a

Fig. 5.2. Location of stations used in Chapter 5

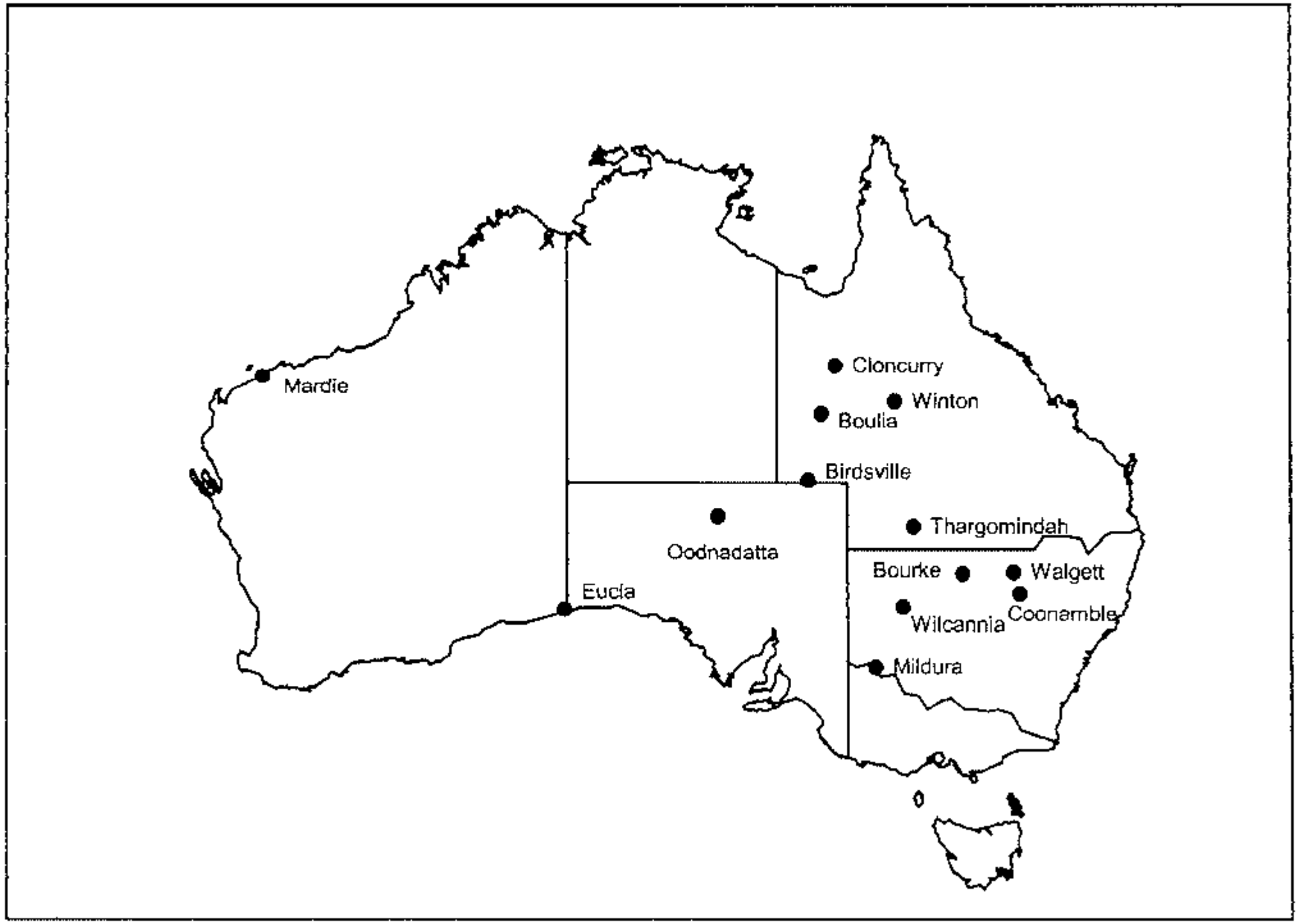


Fig. 5.3. Difference in monthly mean temperature anomalies (Cloncurry - Boulia), 1888-1889

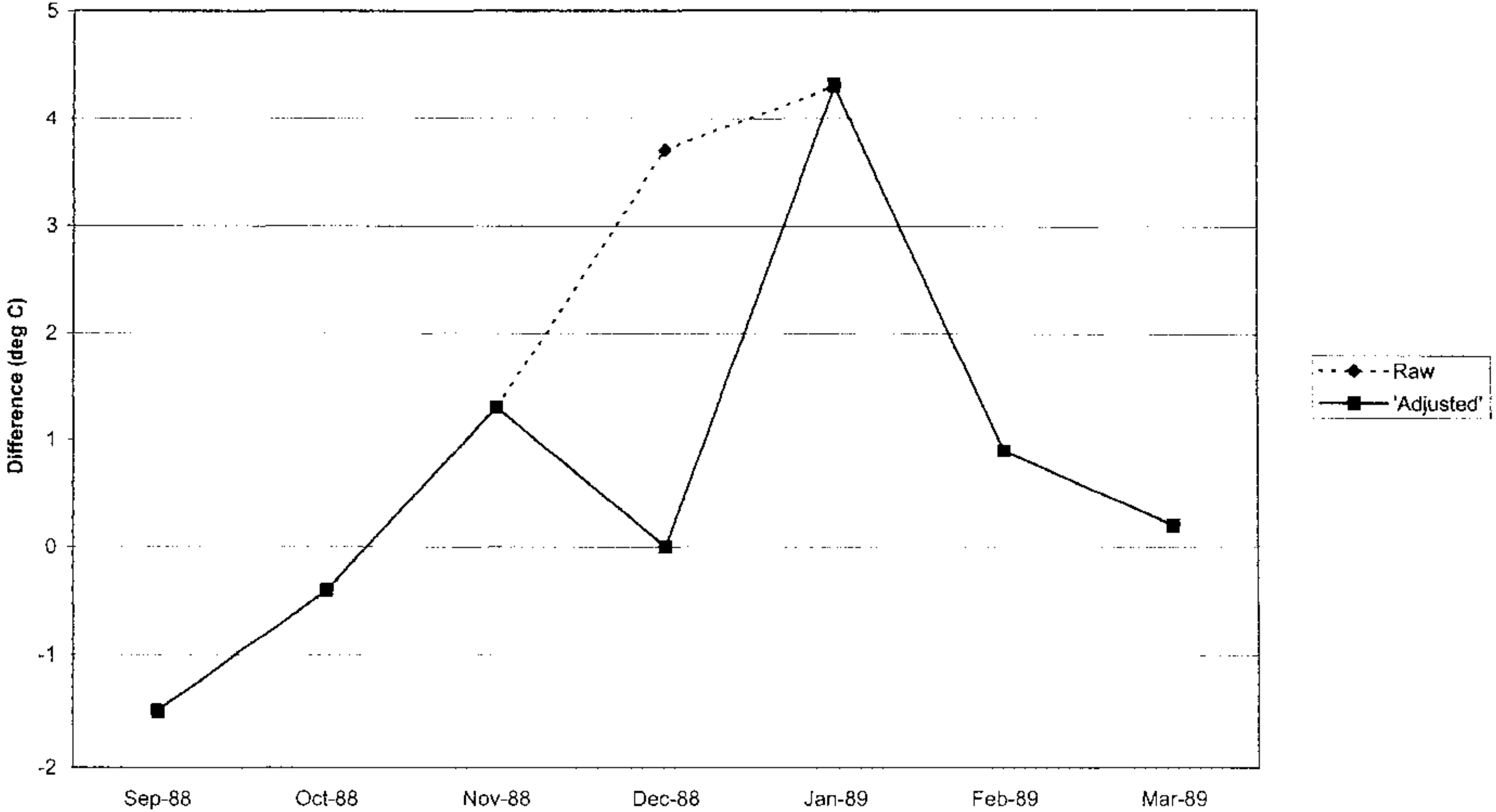
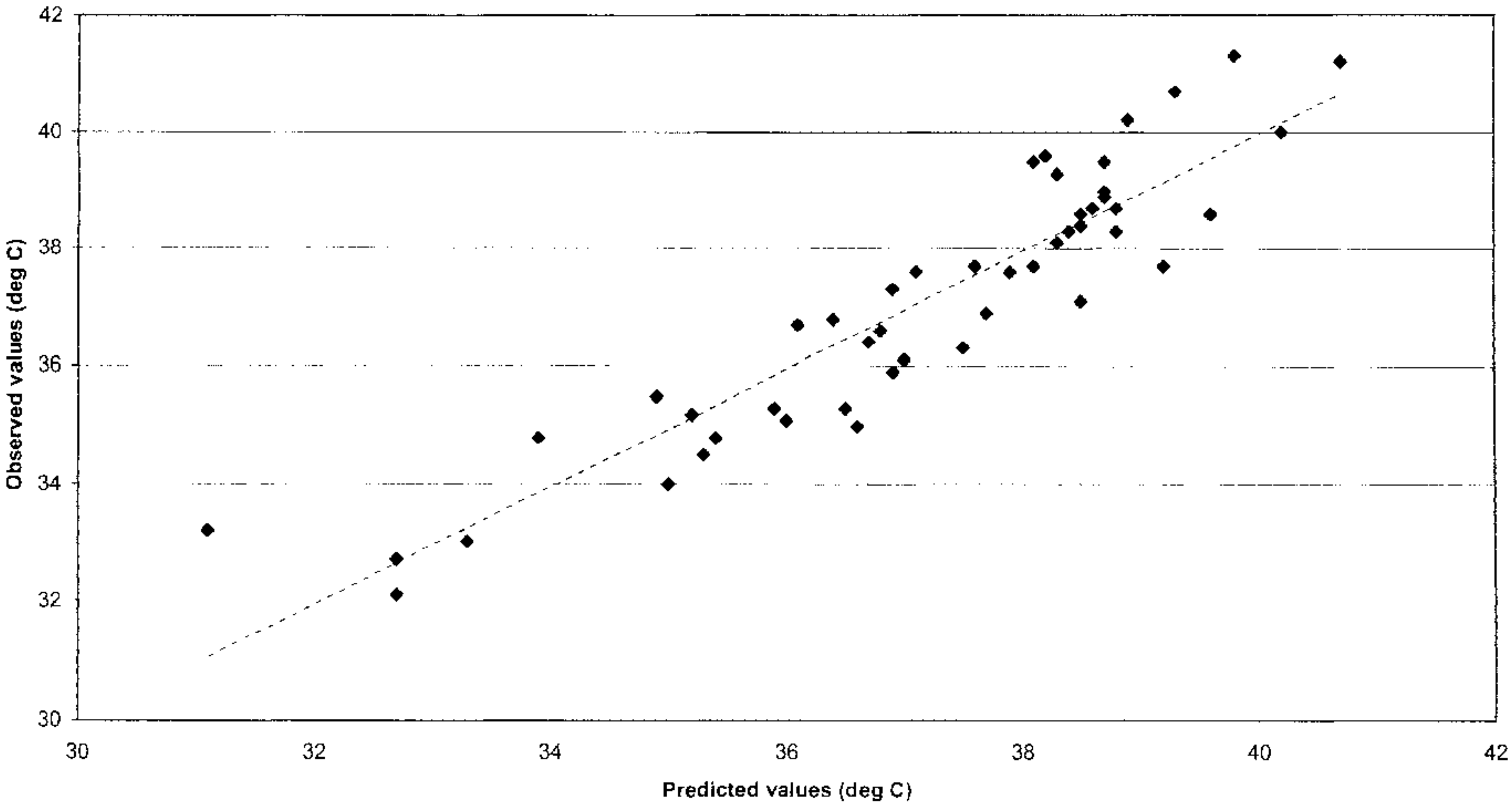


Fig. 5.4. Cloncurry mean January maximum temperature predicted by multiple regression, using 1890-1950 data



value could be expected once in approximately 13,000 observations.

5.4. Daily temperatures at Cloncurry and Winton

Daily maximum and minimum temperatures were not readily available from Boulia for the period of interest, but they were available from copies of original manuscript records for Cloncurry and Winton for the period from November 1888 to January 1889. Fig. 5.5 shows the difference between the maximum temperatures at these sites over this period. Over most of the three-month period, the 11-day running mean of the temperature difference is near zero, but it exceeds 2°C in early December and mid-January.

Fig. 5.6 shows the frequency distribution of the difference between the daily maximum temperatures of Winton and Cloncurry during the period for which daily records are available for both stations in the Bureau of Meteorology's digital database (1957-1975), on days when the temperature at Winton exceeded 40°C. The mean annual number of such days is 29. The greatest positive difference observed on such a day in this 19-year period was 2.8°C. The 1888-89 summer contained 17 days with temperature differences greater than this, reaching a peak of 8.6°C on December 6, 1888. On 16 January 1889, the maximum temperature at Winton was 49.0°C, 4.1°C lower than that at Cloncurry.

5.5. Possible explanations for the anomalously high temperatures at Cloncurry in the summer of 1888-89

The evidence presented above suggests that the maximum temperatures at Cloncurry were unreasonably high during the summer of 1888-89, and in particular in early December 1888 and mid-January, 1889.

The most likely cause of such a discrepancy is that the Cloncurry thermometer was exposed to excessive solar radiation during this period. As noted previously, it is likely that a non-Stevenson shelter was in use at Cloncurry at the time. If a Stevenson screen had been in use at Boulia, it would be expected that anomalously high maximum temperatures would have been recorded at Cloncurry (relative to Boulia) throughout 1888, but there is no evidence of any such anomalies prior to November. This, together with the documentary evidence of Stevenson screens being installed at all three stations at later dates, suggests that non-Stevenson screens were in use at both Cloncurry and Boulia, and probably at Winton as well. As noted earlier in Chapter 3, this was common at many Australian stations at this time.

In particular, the Glaisher stand was in common use in many parts of Australia until about 1910, particularly in South Australia and the Northern Territory (Nicholls et al., 1996b; Torok, 1996), although other stands and instrument exposures apart from the Glaisher stand were in widespread use in Queensland during the 1880s (Nicholls et al. 1996b). The Glaisher stand consisted of a vertical board, shaded from above, on which the thermometers were mounted. It could be rotated to keep the instruments shielded from the direct rays of the sun.

Stevenson screens progressively replaced other types of shelters through the period prior to 1910. This process took place earlier in Queensland than in most other states (or colonies as they were then), as the then Government Meteorologist, Clement Wragge, was a keen proponent of the Stevenson screen (Parker, 1994).

Thermometers in a Glaisher stand were shielded from the direct rays of the sun, but were still open to radiation from the ground, part of the sky and surrounding objects, and hence higher mean maximum and lower mean minimum temperatures were recorded on them than on those in a Stevenson screen, even when the stand was operated correctly (Laing 1977; Parker 1994). The difference in mean temperatures over 61 years of parallel observations at Adelaide was approximately 0.2°C throughout the year for minima, and ranged from 0.2°C in winter to 1.0°C in summer for maxima (Nicholls et al. 1996b).

Fig. 5.5. Difference in daily maximum temperature (Cloncurry - Winton), November 1888 - January 1889

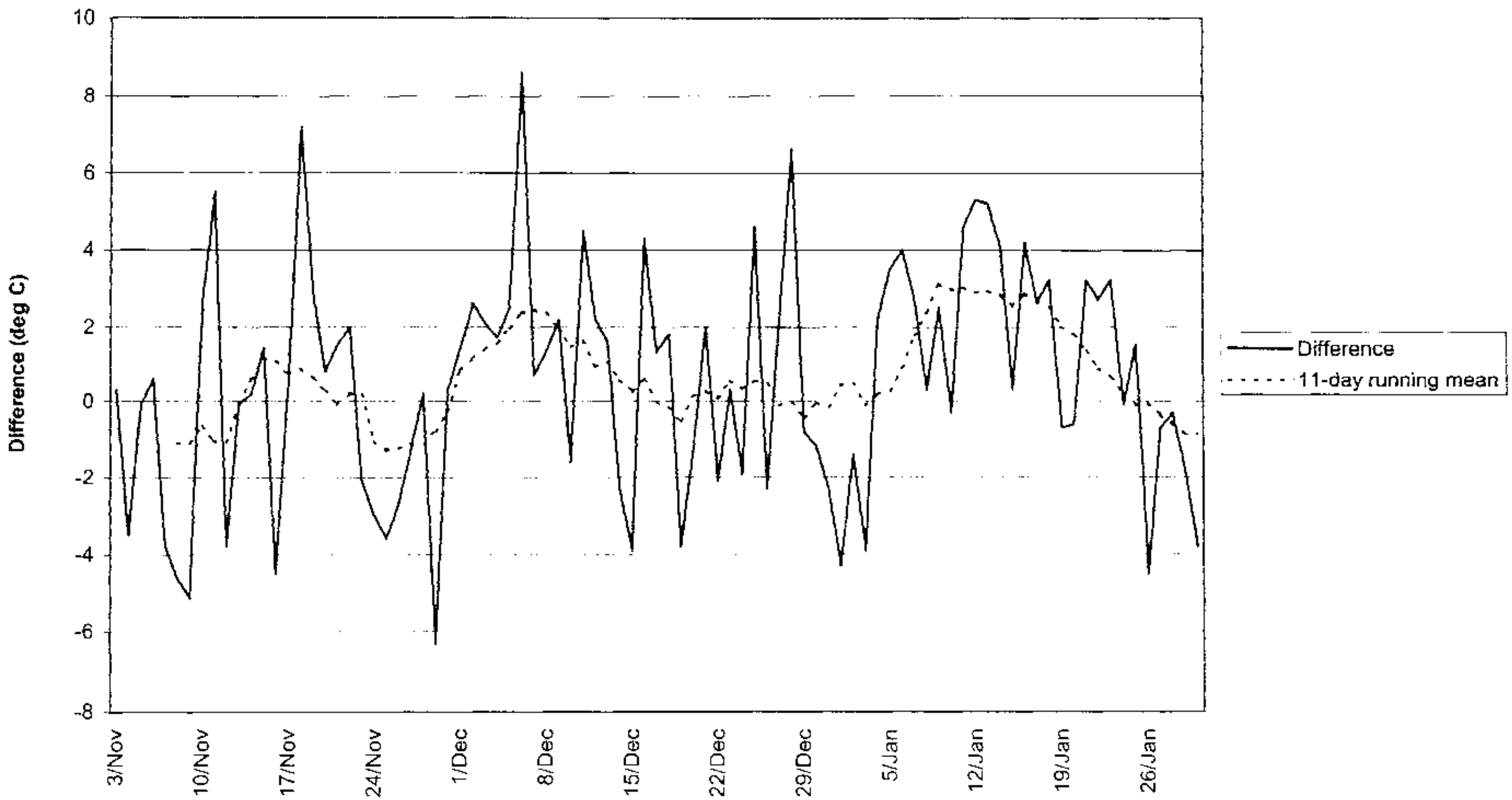
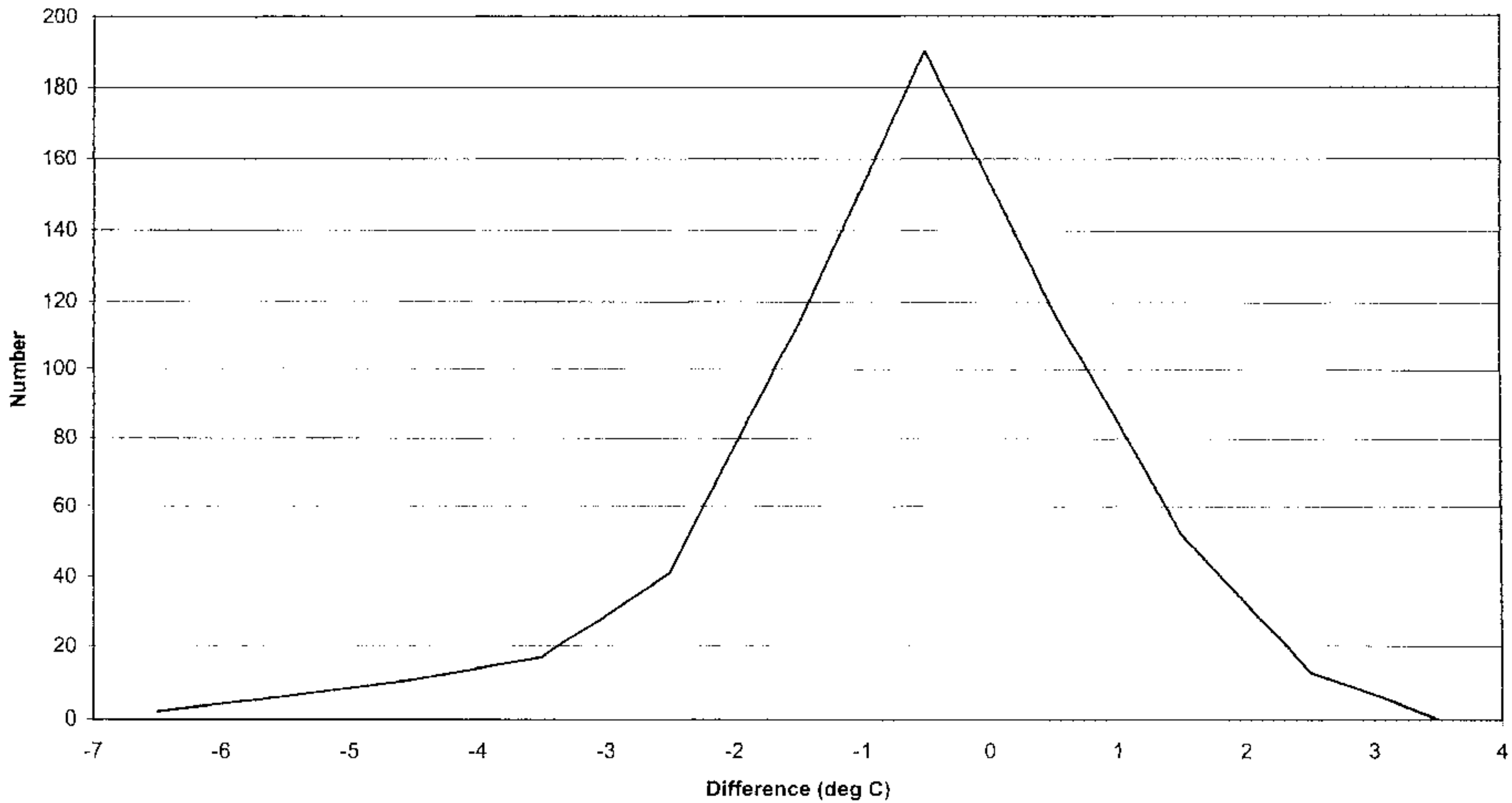


Fig. 5.6. Frequency distribution of difference in daily maximum temperature (Cloncurry - Winton) on days exceeding 40 degress C at Winton, 1957-1975



Furthermore, if the stand was not rotated as required, the instruments could be exposed to direct sunlight. In temperate latitudes this was most commonly a problem in the morning and evening, but in the tropics the seasonal reversal of the direction of direct sunlight also had to be taken into account. There have been no similar comparisons done over such periods between the Stevenson screen and other types of shelters used in Australia, but it is reasonable to believe that any change of instrument shelter may involve a bias in recorded temperatures.

The sun is south of overhead at Cloncurry (latitude 20°43' S) at local noon for the approximate period 28 November to 18 January, and at Winton (latitude 22°24'S) for the period 6 December to 8 January. This makes the period from 8 to 18 January, during which the record occurred, of particular interest, as the sun is south of overhead at Cloncurry during this period, but not at Winton. If both stations were incorrectly exposed to the south, it would be expected that they would observe anomalously high temperatures for the periods when the sun was south of overhead, with the possible exception of a few days at either end of the period when the sun was approximately directly overhead at local noon. Hence, Cloncurry would be expected to be too warm from late November or early December to mid-January, and Winton from mid-December to early January. It follows from this that the greatest temperature difference between the sites would be expected in the period when the sun is south of Cloncurry but north of Winton, in early December and mid-January, and that little difference between the two would be expected when both are too hot, around the time of the summer solstice. This is entirely consistent with the results observed in Fig. 5.5. If Winton was also incorrectly exposed to the south, as the minimal temperature differences in late December suggest, it also brings into question the Winton observation of 50.6°C on 14 December 1888.

There are a number of possible explanations for the thermometers being incorrectly exposed to the south. As previously noted, the effectiveness of the Glaisher stand was dependent on the conscientiousness of the observer in turning it to keep the thermometers out of the sun's direct rays. Observers needed to be particularly diligent at tropical sites, where the sun is south of overhead (in the Southern Hemisphere) for a period during summer and the stand would therefore have to be turned in the opposite direction to that in which it was turned for the rest of the year. If Glaisher stands were in use at the two sites, it is possible that the stand was not turned at either site to take the reversed direction of direct sunlight into account and that the thermometers were subject to direct solar radiation in mid-summer, or to excessive radiant energy from the shelter structure. This would also be the case if the thermometers were mounted on a south-facing wall, a practice which Nicholls et al. (1996b) suggest was not unknown in Queensland at the time. It is even possible that problems could arise in a Stevenson screen if the door is facing south (as is the usual practice in Australia) and the door is left open for long enough while observations are made for direct solar radiation to affect the instruments. This has been noted as a problem in recent times (Bate, pers.comm.), but there is no evidence of it causing discrepancies of the magnitude of those observed between Cloncurry and Winton in 1888/89.

5.6. Implications for the Australian record high temperature

All known daily maximum temperatures in excess of 50°C in Australia are listed in Table 5.1. Of these, the 1877 Bourke and the Mildura and Eucla observations are known to have been taken using non-standard instrumentation (Crowder, 1995), and the Cloncurry and Winton observations are discussed earlier in this chapter. The Oodnadatta, Wilcannia and Mardie observations are known to have been taken in Stevenson screens. The Oodnadatta observation is consistent with other observations throughout the region. Four other stations exceeded 48°C on this day; Finke (48.3°C, a Northern Territory record), Port Augusta (48.3°C), Whyalla (49.4°C) and Marree (49.4°C). Its authenticity is not in serious doubt. The Wilcannia observation is also consistent with other observations in the region (such as 49.7°C at Menindee and 47.8°C at Cobar), and took place during a period of exceptionally high temperatures in south-eastern Australia, which saw records set at many centres, including Adelaide, Melbourne and Sydney. The Mardie observation, which occurred very recently, also took place during a period of general extreme heat in the region, with record highs being set at Port Hedland (48.2°C), Roebourne (49.1°C), Pannawonica (48.2°C) and Onslow (48.0°C) either that day or the preceding day.

Table 5.1. Known daily maximum temperatures of 50°C or greater in Australia

Temperature (°C)	Station	Month
53.1	Cloncurry	January 1889
52.8*	Bourke	January 1877
51.9	Cloncurry	December 1888
51.7	Bourke	January 1909
50.8*	Mildura	January 1906
50.7*	Eucla	January 1906
50.7	Oodnadatta	January 1960
50.6**	Winton	December 1888
50.5	Mardie	February 1998
50.0	Wilcannia	January 1939

* Observations previously known to have been taken with non-standard instrumentation.
** The Winton observation has been cited as being higher in other sources, but these failed to take an index correction into account.

This leaves the Bourke observation of 3 January 1909 remaining for consideration. The catalogue *Climatological Stations: New South Wales* (unpublished journal: lodged in the National Meteorological Library at the Bureau of Meteorology) indicates that a Stevenson screen was installed at Bourke in August 1908. However, no other station in New South Wales or southern Queensland is known to have exceeded 47.2°C on this day.

The original manuscript record for Bourke shows temperatures of 125°F (51.7°C) observed on both 2 and 3 January. The observation on 2 January has been corrected on the manuscript to 112°F (44.4°C), which is consistent with the temperatures over the region, and with the 1500 temperature of 110°F (43.3°C). The 3 January observation was not corrected. However, 3 January was a Sunday, and no other observations were made on this day (as was the usual practice at Bourke, and many other stations, at the time). It is therefore likely that the observation is actually the maximum temperature for the 48 hours to 0900, 4 January, and therefore it would be affected by the same error which was corrected in the case of the 2 January observation. Reports from those stations in the region which did take observations on both days suggest that temperatures in the region on 3 January were similar to those of 2 January.

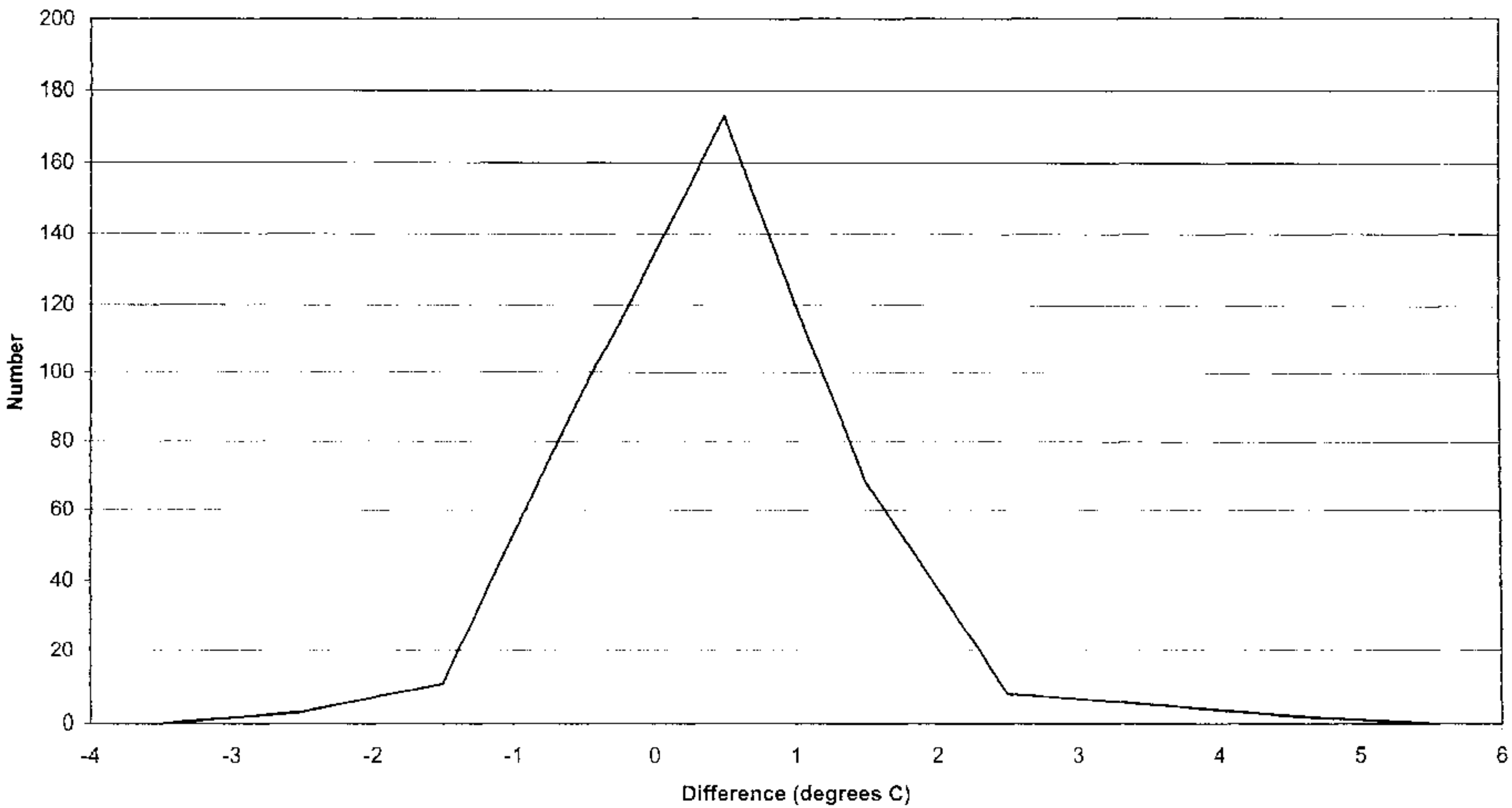
Fig. 5.7 compares the temperature at Bourke with the mean of temperatures observed at Thargomindah, Walgett and Coonamble on days when the daily maximum temperature at Bourke exceeds 40°C during the period 1959-95. The mean difference is 0.5°C, and the largest difference observed during this 37-year period is 4.1°C, while the difference on January 3, 1909 was 6.9°C. This difference is sufficiently large to render the observation suspect. As the screen and instrumentation are known to be standard, a possible cause of any error would be clerical or observational. Nicholls et al. (1996b) note that many Stevenson screens used at this time were in poor condition, and some had split wood on top which allowed direct sunlight to enter the screen through the cracks, although the fact that the screen was only a few months old makes this unlikely in the case of Bourke, and the remainder of the month was not exceptionally hot compared with other stations in the region. An observational error is more likely.

5.7. Conclusion

It is likely that the temperature presently recognised as the highest observed in Australia was not recorded under conditions comparable with current standards. The most plausible cause of the irregular observation appears to be a failure to adequately shelter the instruments from incoming solar radiation during the period of the year when the sun is south of overhead. If this was a widespread occurrence, it has potential implications for the accuracy of climatic records throughout the tropics prior to the introduction of the Stevenson screen.

The highest temperature in Australia known to have been taken under standard conditions, and consistent with supporting observations from other sites, is 50.7°C, recorded at Oodnadatta, South Australia, on 2 January 1960.

Fig. 5.7. Frequency distribution of difference in daily maximum temperature (Bourke - (Walgett + Thargomindah + Coonamble)/3) on days exceeding 40 degrees C at Bourke, 1959-1995



Chapter 6

Models for the frequency distribution of daily maximum and minimum temperatures

6.1. The data set for use in this study

The data set used in this chapter is a deseasonalised set of daily maximum and minimum stations, with quality control carried out as described in Chapters 3 and 4, chosen from the station network defined in Chapter 2.

The deseasonalisation for each station was carried out by computing a set of climate means for each day of the calendar year (including February 29) for each station, using the full period of record in each case. The means for each of these 366 days were then smoothed using an unweighted 11-day running mean. The deseasonalised series for each day was defined as:

$$S_{y,m,d} = T_{y,m,d} - N_{m,d}$$

where $S_{y,m,d}$ is the deseasonalised daily maximum or minimum (as appropriate) temperature (henceforth referred to as a temperature anomaly), $T_{y,m,d}$ is the observed temperature and $N_{m,d}$ is the smoothed mean temperature, for the d-th day of the m-th month of year y.

The major benefit of the use of deseasonalised data in the analysis of extremes is that, in months in which the mean temperature changes substantially within a month, as occurs in spring and autumn in southern Australia (and even more so in continental regions of higher latitudes, in the event of such an analysis being extended to them), data from the start of a month can be considered, to some degree of approximation, as being drawn from the same statistical population as that from the end of a month. This approach does not take into account changes in the variance of daily temperature between the start and end of a month, but the variance shows a smaller annual cycle than the mean at most stations (see Table 6.1).

An unpublished study carried out by the author compared the use of an 11-day running mean to define daily temperature normals with six other methods, by determining the root-mean-square error in using normals derived for the 1961-90 period at a selection of 40 Australian stations as a predictor for daily temperatures in 1991-98. This found that six of the seven techniques tested (an 11-day running mean; an 11-day binomial filter; the fitting of a cubic spline to the monthly means; the fitting of three and five harmonics respectively to the monthly means; linear interpolation from the monthly means) produced RMS errors differing by no more than 0.02°C, with only the unsmoothed mean of daily temperatures performing substantially worse than these. It follows that the selection of technique from within those tested to define daily temperature normals makes little difference to the outcome.

6.2. Is the Gaussian distribution a satisfactory model for Australian daily maximum and minimum temperatures?

6.2.1. The historical background

Historically, many studies of temperature have assumed, explicitly or implicitly, that daily maximum and minimum temperatures follow the Gaussian (normal) distribution. In particular, this assumption is implicit or explicit in many studies of extreme or threshold temperature events, notably those of Mearns et al. (1984) and Katz and Brown (1992), although the former paper does acknowledge the possibility of a non-Gaussian distribution without using it in any analysis. Kestin (2000), in her study of Australian temperatures, used the Gaussian distribution whilst acknowledging that it did not perform well at the extremes.

The source of this assumption is unclear; it appears periodically through publishing history, but without any systematic global study to determine whether it is a realistic assumption. Typical of the statements in the literature is that of Klein and Hammons (1975), who assert that 'temperature is a continuous and nearly normally distributed variable', whilst Thom (1973) goes further, asserting (without any supporting evidence) that studies finding a departure from the normal distribution were 'the result of a lack of understanding of the statistical problem, i.e. that the data series must be a

Station number	Station name	Annual range of mean		Annual range of standard deviation	
		Maximum	Minimum	Maximum	Minimum
1021	Kalumburu	5.3	11.2	1.3	2.9
2012	Halls Creek	12.0	12.5	1.4	2.0
3003	Broome	6.0	12.8	1.4	3.0
4032	Port Hedland	9.8	12.9	1.5	2.0
5007	Learmonth	13.8	12.6	1.7	1.2
5026	Wittenoom	15.7	14.9	1.2	0.9
6011	Carnarvon	10.5	12.7	2.1	1.9
7045	Meekatharra	19.4	17.3	1.5	0.8
8039	Dalwallinu	18.3	11.8	2.5	1.0
8051	Geraldton	13.0	10.2	3.5	0.4
9021	Perth Airport	14.1	9.1	2.9	0.7
9518	Cape Leeuwin	7.2	6.4	1.2	0.4
9741	Albany	9.4	7.1	3.1	0.7
9789	Esperance	9.6	7.5	3.3	0.9
10035	Cunderdin	17.7	11.6	2.6	0.9
10648	Wandering	16.9	10.4	2.6	0.8
11052	Forrest	14.9	11.3	2.7	0.9
12038	Kalgoorlie	17.0	13.6	2.3	0.7
13017	Giles	17.3	15.6	1.3	1.9
14015	Darwin Airport	2.8	6.0	0.3	0.9
14825	Victoria River Downs	9.4	13.9	0.8	3.2
15135	Tennant Creek	13.2	13.2	0.9	1.4
15548	Rabbit Flat	13.3	16.7	0.7	2.1
15590	Alice Springs	16.7	17.0	0.9	2.0
16001	Woomera	17.4	13.3	2.7	1.9
16044	Tarcoola	16.9	13.2	2.7	1.1
17031	Marree	18.2	16.1	2.3	0.9
17043	Oodnadatta	17.9	17.1	1.8	1.4
18012	Ceduna	11.1	9.7	4.1	1.5
18070	Port Lincoln	9.2	7.8	2.6	0.4
21046	Snowtown	15.7	9.5	3.6	1.3
22801	Cape Borda	9.5	5.5	2.2	1.2
23090	Adelaide RO	13.5	10.2	4.3	1.3
23373	Nuriootpa	15.5	9.6	3.4	1.3
26021	Mount Gambier	12.0	6.4	4.4	1.1
26026	Robe	8.6	6.0	2.6	0.8
27022	Thursday Island	3.5	2.9	0.5	0.4
27045	Weipa	4.7	5.1	1.1	1.2
28004	Palmerville	6.4	8.3	0.8	1.9
29004	Burketown	8.0	11.5	1.1	1.9
30045	Richmond	11.9	14.6	1.0	1.9
31011	Cairns	6.4	6.8	0.8	1.6
32040	Townsville	6.4	10.9	0.4	2.6
33119	Mackay MO	8.8	10.7	0.6	1.9
34084	Charters Towers	10.0	12.1	0.6	1.6
36007	Barcaldine	13.3	15.2	0.9	2.1
36031	Longreach	14.2	16.2	0.9	1.8
37010	Camooweal	12.3	15.4	0.7	2.1
38002	Birdsville	17.9	17.9	1.5	0.9
38003	Boulia	15.4	16.8	1.1	1.7
39039	Gayndah	10.7	13.8	0.7	2.0
39083	Rockhampton	9.0	13.0	0.8	2.5
39128	Bundaberg	8.1	11.8	0.6	1.8
40004	Amberley	10.1	14.3	1.4	2.4
40223	Brisbane Airport	8.6	12.1	0.7	1.9

Table 6.1. Annual range of mean and standard deviation of daily maximum and minimum temperature

Station number	Station name	Annual range of mean		Annual range of standard deviation	
		Maximum	Minimum	Maximum	Minimum
40908	Tewantin	7.8	11.3	1.0	1.6
42023	Miles	13.6	16.4	1.1	2.4
43109	St. George	15.4	16.1	1.0	1.3
44021	Charleville	15.6	17.3	0.7	1.8
45017	Thargomindah	18.0	17.6	1.7	1.1
46037	Tibooburra	18.1	16.2	1.8	0.9
46043	Wilcannia	17.6	15.6	2.5	1.2
48027	Cobar	18.2	15.3	2.2	1.5
48239	Bourke	17.2	16.0	1.6	0.8
52088	Walgett	16.9	16.6	1.6	1.2
53048	Moree	16.3	15.9	1.6	1.6
55024	Gunnedah SC	15.6	13.9	1.7	0.8
56017	Inverell PO	14.3	15.5	1.0	1.2
58012	Yamba	7.7	10.9	1.0	0.9
59040	Coffs Harbour	8.2	12.2	1.4	1.5
60026	Port Macquarie	7.7	12.2	1.0	1.6
61078	Williamtown	10.7	11.9	2.6	1.0
61089	Scone SC	14.2	12.3	2.3	0.7
63005	Bathurst ARS	16.9	12.7	2.2	0.9
65012	Dubbo	17.7	15.1	1.8	1.1
66062	Sydney RO	8.9	10.7	1.8	0.6
67105	Richmond	12.5	13.5	2.8	1.9
68034	Jervis Bay	8.8	8.9	1.9	0.4
68076	Nowra	10.1	10.0	2.8	0.5
69018	Moruya Heads	7.8	10.7	1.7	0.9
70014	Canberra Airport	16.4	13.4	2.8	1.4
72150	Wagga Wagga	18.7	13.4	2.6	1.1
72161	Cabramurra	16.7	11.5	1.7	1.9
73054	Wyalong	18.3	14.2	2.4	1.1
74128	Deniliquin	17.5	12.5	2.8	1.6
76031	Mildura	17.3	11.8	2.9	1.3
78031	Nhill	15.9	9.4	3.5	1.6
80023	Kerang	17.0	11.0	3.0	1.4
82039	Rutherglen	18.8	11.4	2.6	1.0
84016	Gabo Island	7.8	8.0	1.3	0.6
84030	Orbost	10.6	9.0	3.3	0.8
85072	Sale	11.3	9.4	3.0	0.6
85096	Wilsons Promontory	8.4	6.4	3.0	0.8
86071	Melbourne	12.5	8.6	4.1	0.5
87031	Laverton	12.7	8.9	4.2	1.0
90015	Cape Otway	8.5	6.7	3.3	1.0
91057	Low Head	9.9	7.7	1.0	1.0
91104	Launceston Airport	12.3	7.8	1.9	0.7
92045	Eddystone Point	7.8	7.4	1.1	1.2
94010	Cape Bruny	7.7	6.4	2.2	0.5
94029	Hobart RO	10.0	7.6	2.2	0.6
94069	Grove	10.6	7.5	2.5	0.6
96003	Butlers Gorge	11.6	6.7	3.3	0.7

Table 6.1 (cont.). Annual range of mean and standard deviation of daily maximum and minimum temperature

climatological series', where he defines a climatological series as 'a homogeneous series of values of the predictand variable, one value taken from each year'. The WMO Guide to Climatological Practices (1983) also suggests a 'nearly normal' distribution for daily maximum and minimum temperatures. The assumption may be founded on the climates of western Europe and the eastern United States. A number of local studies (e.g. Bruhn et al., 1980) have found that daily temperatures in specific regions and seasons are approximately normally distributed.

As the methodology of Katz and Brown forms a substantial part of the theoretical foundations of this thesis, the assumption needs to be evaluated for its validity under Australian conditions.

6.2.2. Results of a study of the Australian data set

The question of whether the data are normally distributed is of more than trivial consequence for the expected frequency of extreme temperature events. Table 6.2 shows the frequency of daily maximum and minimum temperature anomalies departing from the mean by more than 3 standard deviations (defined as extreme events in this section), using the standard deviation derived for each calendar month. In a normal distribution, the expected frequency of such events is 0.27%.

The results shown in Table 6.3 show that the assumption of a Gaussian distribution for Australian data would result in a highly misleading estimate of the frequency of extremes in many cases. The median frequency of maximum temperature anomalies of this magnitude across the 103-station network ranges from 0.47% in spring to 0.57% in autumn, approximately double the expected value in a normal distribution. In contrast, winter minimum temperature anomalies of this size occur with less than half the expected frequency, with a value of 0.12%, although departures in other seasons are less prominent. As a further indicator of the extent to which the normal distribution fails to represent the expected frequency of extremes, 39 of the 103 stations have extreme event frequencies below 0.07% (one-quarter of the expected value) for winter minima, whilst for maxima, 28 stations have frequencies exceeding 1.08% (four times the expected value) in summer, and 21 in spring. High frequencies of extreme maxima are particularly pronounced in coastal locations, whilst low frequencies of extreme minima in winter are most pronounced in Queensland (other than the far north and west) and inland New South Wales.

6.2.2.1. Assessment of the normality of Australian daily temperature data

Five tests were carried out to detect departures of a frequency distribution from a normal (Gaussian) distribution of unspecified mean and variance, applied to Australian daily maximum and minimum temperature anomaly data. The tests used are those of Kolmogorov-Smirnov (D), Kuiper (V), Cramér-von Mises (W^2), Watson (U^2), and Anderson-Darling (A).

Full details of the tests are given in Appendix A. According to Stephens (1970) and Pearson and Hartley (1976), in the tails of a distribution – an area of particular interest in this study – A, followed by W^2, is the most powerful of the tests for detecting deviations. The chi-square test, used in some literature (e.g. Grace et al., 1991), has the limitations that the values it generates are dependent upon the (arbitrary) choice of the width of the class interval used in the test, introducing an element of subjectivity, and that it is extremely sensitive to a small number of outliers, irrespective of the goodness-of-fit of the remainder of the distribution (although this is not necessarily a disadvantage if the modelling of extreme outliers is the highest priority).

A full listing of the outcome of the tests is given in Appendix C (Tables C.1 and C.2).

The frequency distribution of daily temperature anomalies, in an examination of the 103 stations for the 12 calendar months (1236 station-months in total), was found to differ from the normal distribution at the 99% level in all five tests:

- In 86% of station-months for maximum temperature
- In 81% of station-months for minimum temperature

Station number	Name	Summer		Autumn		Winter		Spring	
		Min	Max	Min	Max	Min	Max	Min	Max
39083	Rockhampton	**0.33**	**0.50**	0.79	**0.80**	0.00	**0.78**	**0.46**	**0.48**
39128	Bundaberg	0.17	**1.37**	**0.49**	**0.87**	0.00	**0.66**	0.08	**1.11**
40004	Amberley	0.22	**0.50**	0.12	**0.98**	0.00	**0.63**	0.04	**0.53**
40223	Brisbane AP	0.12	**1.10**	**0.65**	**1.16**	0.00	1.02	**0.34**	**1.37**
40908	Tewantin	**0.35**	1.56	**0.83**	**1.18**	0.00	**0.97**	0.22	0.75
42023	Miles	**0.64**	**0.47**	**0.31**	**0.62**	0.00	0.13	0.09	**0.44**
43109	St. George	0.16	**0.87**	0.03	**0.57**	0.03	0.06	0.03	0.16
44021	Charleville	0.19	**0.77**	**0.28**	**0.46**	0.00	0.06	0.02	0.18
45017	Thargomindah	0.21	**0.55**	0.06	0.17	**0.35**	0.11	0.03	0.08
46037	Tibooburra	0.14	0.26	0.14	0.15	**0.45**	0.18	0.14	0.08
46043	Wilcannia	0.24	0.23	0.15	0.09	0.21	**0.38**	**0.38**	0.06
48027	Cobar	0.16	**0.36**	0.00	0.14	0.22	**0.41**	0.16	0.05
48239	Bourke	0.08	**0.45**	0.08	0.22	**0.28**	**0.41**	0.11	0.03
52088	Walgett	**0.32**	**0.64**	0.09	**0.48**	0.23	0.09	0.18	0.06
53048	Moree	**0.47**	**0.56**	0.27	**0.64**	0.05	0.21	0.04	0.23
55024	Gunnedah SC	**0.31**	**0.31**	0.24	**0.61**	0.07	0.20	**0.32**	0.17
56017	Inverell PO	0.11	**0.31**	0.08	**0.83**	0.14	0.25	0.03	0.25
58012	Yamba	**0.56**	**1.39**	0.19	1.03	0.23	**0.83**	0.21	**1.81**
59040	Coffs Harbour	**0.29**	**1.18**	**0.43**	**0.93**	0.05	**0.90**	0.21	1.30
60026	Port Macquarie	0.19	**0.97**	0.13	**0.85**	0.09	**0.70**	0.10	1.35
61078	Williamtown	0.26	**0.62**	0.02	**0.71**	0.09	**0.75**	0.07	**0.60**
61089	Scone SC	**0.28**	0.07	0.14	0.10	0.07	0.24	**0.31**	0.10
63005	Bathurst ARS	0.16	0.10	0.04	0.26	0.04	0.16	0.22	0.12
65012	Dubbo	**0.33**	0.22	0.03	**0.38**	0.03	0.16	0.11	0.22
66062	Sydney RO	**0.39**	**1.56**	**0.33**	**0.79**	**0.50**	**0.61**	**0.39**	**0.99**
67105	Richmond	**0.38**	0.12	0.15	**0.54**	0.09	**0.77**	0.09	0.19
68034	Jervis Bay	**0.62**	1.21	**0.35**	**0.61**	**0.58**	**0.57**	**0.49**	**1.07**
68076	Nowra	0.08	**1.19**	0.21	**0.53**	0.22	**0.70**	**0.38**	**0.89**
69018	Moruya Heads	**0.41**	2.37	**0.35**	1.13	**0.45**	**0.89**	0.25	**2.13**
70014	Canberra Airport	0.21	0.06	0.07	**0.45**	0.00	**0.49**	0.11	0.27
72161	Cabramurra	0.00	**0.41**	0.06	**0.50**	**0.34**	0.25	0.22	0.06
72150	Wagga Wagga	0.24	0.20	0.00	0.12	0.06	**0.36**	0.14	**0.40**
73054	Wyalong	0.21	**0.32**	0.10	0.09	0.17	**0.34**	0.17	**0.22**
74128	Deniliquin	**0.28**	0.03	0.03	0.11	0.03	**0.60**	0.19	**0.47**
76031	Mildura	0.26	0.04	0.13	0.09	0.15	**0.48**	**0.37**	**0.43**
78031	Nhill	**0.31**	0.06	0.00	0.19	0.16	**1.12**	0.16	**0.63**
80023	Kerang	0.17	0.00	0.21	0.20	0.21	**0.91**	0.21	**0.38**
82039	Rutherglen	0.10	**0.28**	0.10	0.07	0.00	**0.48**	0.18	**0.42**
84016	Gabo Island	**0.29**	1.29	**0.31**	**0.82**	0.25	**0.98**	**0.45**	**1.90**
84030	Orbost	0.20	**0.45**	0.08	0.22	0.14	**0.42**	0.25	**0.43**
85072	Sale	0.04	**0.69**	0.09	**0.66**	0.22	**0.87**	0.15	**1.12**
85096	Wilsons Prom.	**1.13**	**2.19**	**0.66**	**1.29**	**1.06**	**1.28**	**1.27**	**1.82**
86071	Melbourne RO	**0.80**	0.08	0.21	0.27	0.05	**0.38**	**0.58**	**0.32**
87031	Laverton	**0.64**	0.10	0.02	0.23	0.06	**0.71**	**0.37**	**0.66**
90015	Cape Otway	**0.99**	**1.88**	**0.62**	1.29	**0.42**	1.02	**1.14**	**1.31**
91057	Low Head	**0.50**	**0.30**	0.08	0.14	0.00	0.11	0.06	**0.47**
91104	Launceston AP	0.04	**0.73**	0.00	**0.29**	0.00	**0.44**	0.02	**0.58**
92045	Eddystone Point	**0.33**	**1.41**	0.03	**0.54**	0.06	**0.63**	0.21	**1.28**
94010	Cape Bruny	**0.72**	**1.64**	**0.49**	**0.94**	**0.28**	**0.41**	**0.54**	**1.39**
94029	Hobart RO	**0.60**	**1.27**	0.18	**0.56**	0.21	0.18	**0.39**	**1.04**
94069	Grove	**0.30**	**0.95**	0.16	**0.36**	**0.30**	0.22	0.14	**0.95**
96003	Butlers Gorge	**0.29**	0.00	0.12	0.06	0.12	0.15	0.25	0.21

Table 6.2 (cont). Percentage frequency of maximum and minimum temperatures more than 3 standard deviations from mean

Station number	Name	Summer		Autumn		Winter		Spring	
		Min	Max	Min	Max	Min	Max	Min	Max
1021	Kalumburu	0.20	**0.40**	**0.68**	**0.98**	0.06	**0.49**	**0.69**	**0.72**
2012	Halls Creek	**0.70**	**0.73**	**0.79**	**1.13**	0.25	**0.51**	**0.51**	**0.80**
3003	Broome	**0.56**	**1.58**	0.23	**0.82**	0.00	**0.44**	**0.45**	**0.47**
4032	Port Hedland	**0.51**	0.19	0.18	**0.90**	0.02	**0.65**	**0.41**	0.02
5007	Learmonth	0.15	0.15	**0.45**	**0.35**	0.10	**0.39**	**0.70**	0.15
5026	Wittenoom	0.12	**1.32**	**0.29**	**1.01**	0.14	**0.54**	0.14	**0.65**
6011	Carnarvon	**0.69**	**1.24**	0.11	0.27	0.09	**0.64**	0.13	**1.30**
7045	Meekatharra	0.24	**0.78**	0.16	0.26	0.12	0.09	0.21	0.12
8039	Dalwallinu	0.17	0.17	0.20	0.08	0.03	**0.42**	**0.37**	0.17
8051	Geraldton	0.24	0.06	0.14	0.12	0.06	**0.74**	0.20	**0.87**
9021	Perth Airport	**0.27**	0.02	0.13	0.17	0.00	**0.70**	0.17	**0.91**
9518	Cape Leeuwin	**0.71**	**2.26**	**0.44**	**1.29**	**0.46**	**0.60**	**0.45**	**1.21**
9741	Albany	0.15	**1.34**	0.15	**0.82**	0.23	**0.44**	0.09	**1.31**
9789	Esperance	**0.28**	**0.91**	**0.27**	**0.54**	**0.38**	**0.57**	**0.39**	**1.21**
10035	Cunderdin	**0.28**	0.19	0.11	0.14	0.22	**0.61**	0.20	**0.34**
10648	Wandering	**0.31**	0.09	0.03	0.11	0.00	**0.39**	0.06	**0.36**
11052	Forrest	**1.05**	0.02	**0.72**	0.13	**0.47**	**0.52**	**0.90**	0.00
12038	Kalgoorlie	0.16	**0.30**	0.22	0.02	0.20	**0.33**	0.20	0.06
13017	Giles	**0.30**	**1.18**	**0.33**	**0.84**	**0.41**	0.08	0.11	**0.51**
14015	Darwin AP	0.08	**0.74**	**0.70**	**1.15**	**0.29**	**0.45**	**0.59**	**0.73**
14825	Vict. R. Downs	**0.68**	**0.47**	**0.43**	**0.70**	0.00	0.20	0.21	**1.50**
15135	Tennant Creek	**0.42**	**0.70**	**0.49**	**0.93**	0.05	0.19	0.25	**0.94**
15548	Rabbit Flat	**0.33**	**0.59**	0.12	**1.39**	0.00	**0.29**	0.08	**0.98**
15590	Alice Springs	0.06	**1.10**	0.10	**0.34**	0.26	0.04	0.10	**0.32**
16001	Woomera	**0.28**	**0.32**	0.12	0.11	0.20	**0.39**	0.19	0.18
16044	Tarcoola	0.17	0.13	0.16	0.16	0.16	**0.47**	**0.48**	0.06
17031	Marree	0.08	**0.31**	0.08	0.11	**0.33**	**0.59**	0.20	0.11
17043	Oodnadatta	0.05	**0.46**	0.11	0.21	**0.29**	**0.75**	0.09	0.11
18012	Ceduna	**0.36**	0.02	0.14	0.24	0.08	**0.82**	0.18	0.18
18070	Port Lincoln	**0.45**	**1.74**	**0.27**	**1.45**	**0.44**	**1.01**	0.25	**1.57**
21046	Snowtown	**0.33**	0.00	0.15	0.06	0.18	**0.59**	**0.42**	0.12
22801	Cape Borda	**1.88**	**0.32**	**0.72**	**0.50**	0.23	**0.53**	**0.91**	**0.87**
23090	Adelaide RO	**0.73**	0.00	**0.50**	0.15	0.13	**0.81**	**0.67**	0.25
23373	Nuriootpa	0.19	0.00	0.25	0.11	0.05	**0.87**	**0.36**	0.08
26021	Mount Gambier	**0.63**	0.24	**0.28**	**0.57**	0.10	**0.79**	**0.46**	**0.74**
26026	Robe	**0.68**	**1.14**	0.25	**0.74**	0.24	**0.42**	0.12	**0.77**
27022	Thursday Island	0.26	**0.44**	**0.31**	**0.52**	**0.56**	**0.85**	**0.31**	**0.91**
27045	Weipa	**1.18**	**0.48**	**0.81**	**1.16**	**0.65**	**0.91**	**0.76**	**0.37**
28004	Palmerville	**0.79**	**1.07**	**0.57**	**1.24**	**0.73**	**0.83**	**0.91**	**0.68**
29004	Burketown	**0.36**	**0.35**	**0.52**	**1.03**	0.17	**0.49**	**0.52**	**0.61**
30045	Richmond	**0.67**	**0.97**	0.26	**1.25**	0.03	**0.29**	0.24	**1.07**
31011	Cairns	**0.55**	**1.44**	**0.93**	**0.87**	**0.50**	**0.54**	**0.51**	**1.24**
32040	Townsville	**0.41**	**1.41**	**0.37**	**1.44**	0.10	**1.09**	**0.43**	**1.52**
33119	Mackay MO	0.27	**0.65**	**0.51**	**0.83**	0.00	**0.89**	0.20	**0.44**
34084	Charters Towers	**0.32**	**0.74**	**0.42**	**0.95**	0.03	**0.59**	0.16	**0.84**
36007	Barcaldine	**0.29**	**1.04**	**0.32**	**1.01**	0.00	0.25	**0.35**	**0.42**
36031	Longreach	**0.30**	**1.32**	**0.29**	**1.20**	0.00	0.16	0.00	**0.47**
37010	Camooweal	**0.47**	**0.61**	0.12	**1.16**	0.03	**0.28**	0.20	**1.08**
38002	Boulia	0.19	**1.11**	**0.45**	**1.01**	0.12	0.14	0.16	**0.42**
38003	Birdsville	0.14	**0.79**	0.06	**0.31**	**0.45**	0.23	0.14	0.06
39039	Gayndah	0.14	**0.64**	0.14	**0.79**	0.05	**0.52**	0.22	**0.47**

Table 6.2. Percentage frequency of maximum and minimum temperatures more than 3 standard deviations from mean

The expected frequency of such events in a normal distribution is 0.27%. Values exceeding this in the table have been shown in bold type.

	Summer		Autumn		Winter		Spring	
	Min	Max	Min	Max	Min	Max	Min	Max
Number of stations with frequency: > 0.27%	59	74	41	67	24	74	39	71
< 0.07%	5	13	15	3	39	3	10	10
> 1.08%	3	28	0	26	0	3	2	21
Median frequency (%)	0.29	0.55	0.19	0.57	0.12	0.48	0.21	0.47

Table 6.3. Summary statistics for frequencies of temperature anomalies exceeding 3 standard deviations

Notes:

- There are 103 stations in total.
- 0.07% and 1.08% are approximately ¼ and 4 times, respectively, the expected frequency (in a normal distribution) of 0.27%.

At least one of the five tests showed a departure from the normal distribution at the 95% level:

- In 95% of station-months for maximum temperature
- In 94% of station-months for minimum temperature

These figures are clearly far above those which would be expected by chance, and indicate that it cannot be validly assumed that Australian daily maximum and minimum temperature data are normally distributed.

6.2.2.2. The nature of the departures from normality

Figs. 6.1 and 6.2 show the skewness over Australia for maximum and minimum temperature anomalies respectively for sample months in each season. The full listing of skewness values is given in Table C.7.

Table 6.4 shows that the skewness of the distribution differs significantly from 0 at the 5% level for 84% of station-months for maximum temperature, and 70% for minimum temperature. Differences significant at the 1% level occur for 80% of station-months for maximum temperature and 60% for minimum temperature. This degree of skewness is common to all seasons.

As a very broad generalisation, maximum temperature tends to be positively skewed in southern mainland Australia, and negatively skewed in northern Australia. The boundary between the two regions displays considerable seasonal variation. In summer and autumn, positively skewed distributions are found in the immediate vicinity of the western coast (except for the Pilbara coast in autumn), and the eastern coast south of Fraser Island, as well as in a broader region within about 500 kilometres of the southern coast, and throughout Tasmania. The greatest positive skew occurs at sites highly exposed to coastal influences, such as Cape Leeuwin, Cape Otway, Wilsons Promontory and Moruya Heads, where the maximum temperature regime is dominated by maritime influences, but where temperatures occasionally rise to very high levels when strong offshore winds occur. The strongest negative skew in summer is found over a broad region of western and central inland Australia centred on latitude 25°S, whilst in autumn it occurs north of 20°S. These are regions where occasional rainy and/or cloudy days result in maximum temperatures well below those which occur during the (more usual) clear conditions.

In winter, the skewness (both negative and positive) of the distribution tends to be lower (only one station has skewness outside the range −1.0 to 1.0 in July, compared with 20 in January), and positive skew is found much further north, occurring in most of the region south of the Tropic of Capricorn, except in the vicinity of the Great Dividing Range in New South Wales and southern Queensland. (This is illustrated by the occurrence of positive skew for 76% for station-months in spring and 64% in winter (Table 6.4), compared with 41% in summer). The marked increase in skewness towards the western and southern coast which occurs in summer is also largely absent in winter. In spring, positive skew is found in similar areas to those in winter, but the magnitude of skewness is greater, particularly near the southern coast and in the northern inland.

The pattern of skewness of minimum temperature is more complex, with degrees of skewness generally lower than for maximum temperature, as suggested by the frequency of significant departures from 0 described above, and marked seasonal variations in the spatial distribution of skewness. In spring and summer, positively skewed distributions occur in similar regions of southern Australia to those where they occur for maxima (but not on the eastern and western coasts, except for the west in spring). Weak negative skew occurs over much of the rest of the country, but it is only locally significant. Autumn and winter show a markedly different pattern Significantly positively skewed distributions occur in winter over a broad belt between 20° and 30°S, with the strongest skewness in inland southern Queensland and northern New South Wales, whilst the largest regions with negative skew are on and near the coasts of south-western Western Australia, South Australia and Victoria, as well as those of north Queensland and the Northern Territory. Conversely, in autumn significant positively skewed distributions are largely confined to Victoria and South Australia, with negative skew being most prominent in northern Australia and near the Queensland coast.

A model of a skewed, unimodal distribution, as used by authors such as Horton et al.

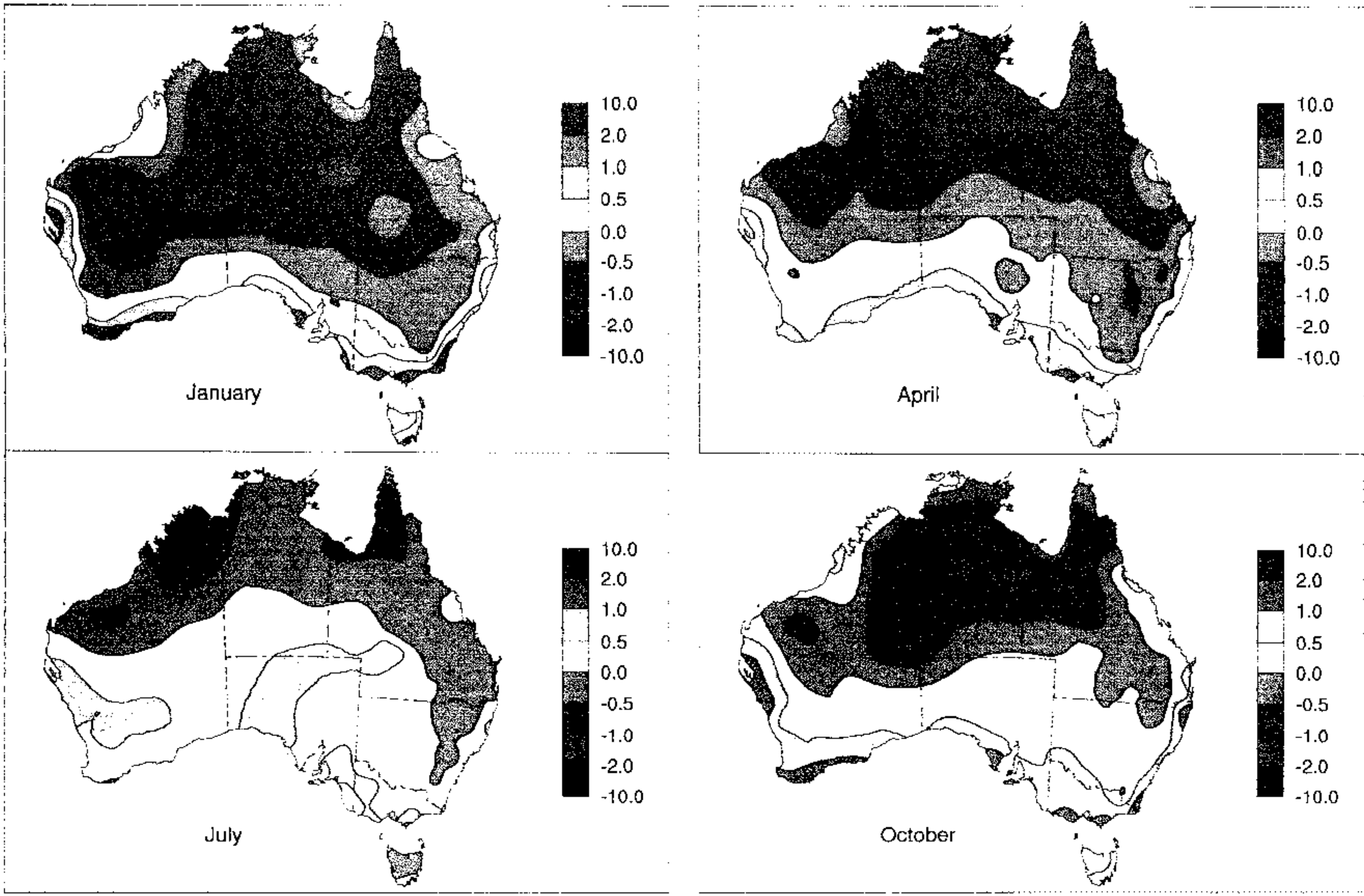


Fig. 6.1. Skewness of daily maximum temperature

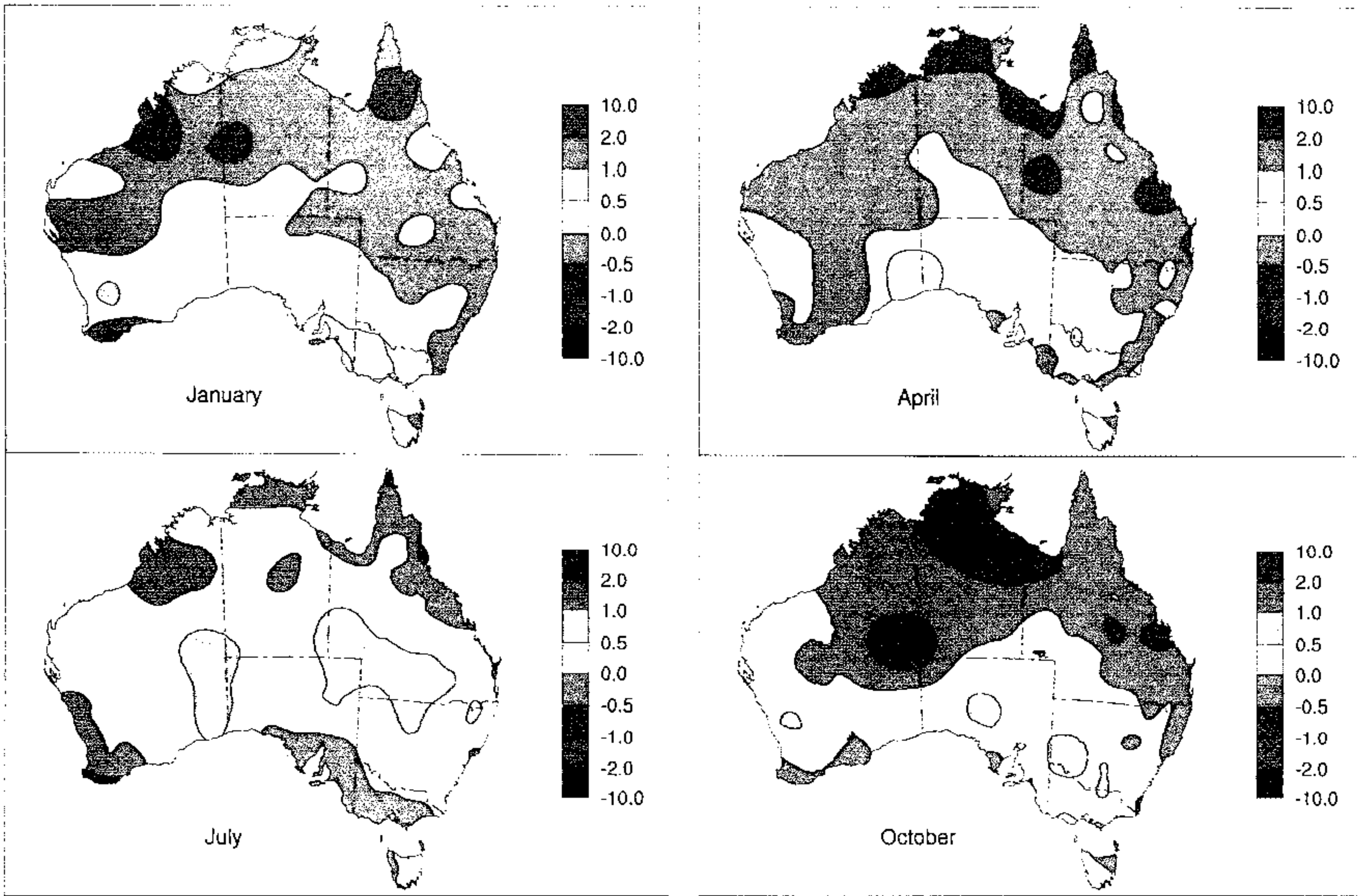


Fig. 6.2. Skewness of daily minimum temperatures

Skewness	Maximum (% of station-months)					Minimum (% of station-months)				
	Sum	Aut	Win	Spr	Tot	Sum	Aut	Win	Spr	Tot
Negative – significant at 99% level	48	40	24	18	32	30	29	20	27	27
Negative – significant at 95% level	4	3	2	1	3	5	5	4	4	4
Negative – not significant	7	8	10	5	7	17	17	14	10	15
Total negatively skewed	59	50	36	24	42	52	51	38	41	46
Positive – significant at 99% level	32	40	53	63	47	29	30	37	40	34
Positive – significant at 95% level	3	2	1	3	2	4	4	7	6	5
Positive – not significant	6	8	10	10	9	15	15	17	13	15
Total positively skewed	41	50	64	76	58	48	49	62	59	54
Total skewed at 99% level of significance	80	80	77	81	80	59	59	57	67	60
Total skewed at 95% level of significance	87	84	80	85	84	68	68	69	77	70

Table 6.4. Station-months with positive and negative skewness of daily temperature

1. The seasons are defined as summer (1 December - 29 February), autumn (1 March – 31 May), winter (1 June – 31 August), and spring (1 September – 30 November).
2. Totals may not add due to rounding.

(2001), is also an incomplete description of the frequency distribution of daily temperature within Australia. Two interesting local examples of frequency distributions which are broadly symmetric, but nevertheless depart significantly from the normal distribution, illustrate this, with sample distributions shown in Figs. 6.3a and 6.3b. In mid-winter, the frequency distribution of minimum temperature in much of inland southern New South Wales generally shows small (and non-significant) positively skewness, but displays no clear mode, with peak frequencies distributed fairly uniformly over a range of several degrees Celsius. This manifests itself in values of kurtosis widely in the 2-2.5 range, well below the value of 3 expected in a normal distribution. Conversely, on parts of the coast of northern Queensland in summer, the tendencies to marked negative outliers in the tropical inland, and to positive outliers on the coasts, coincide to produce a distribution with relatively high frequencies of extreme anomalies, both positive and negative.

6.3. Alternative models for the frequency distribution of Australian daily maximum and minimum temperatures

6.3.1. The gamma distribution

The 3-parameter gamma distribution has been used in recent work, notably Horton et al. (2001), as a model for the frequency distribution of mean temperatures on the daily, monthly and annual timescale. This follows initial work by Lehman (1987), who used a 2-parameter gamma distribution to describe the frequency distribution of daily mean temperatures. In effect, this is based on a 2-parameter gamma distribution (which, by definition, must be positively skewed and is bounded below by 0), with a third parameter allowing location, scale and sign transformations possible to allow for positive and negative values of the variable, and possible negatively skewed distributions. It is a unimodal distribution.

The 2-parameter gamma distribution is defined as:

$$f(x) = \frac{1}{b^a \Gamma(a)} \int_0^\infty e^{-x/b} x^{a-1} dx$$

where x is the variable being studied, a and b are parameters which describe the distribution, and $\Gamma(a) = (a-1)!$ is the gamma function.

This distribution is defined only for $x \geq 0$. In order to use this distribution to model a temperature frequency distribution which is, for all practical purposes, unbounded above and below, it is necessary to transform the data using a third parameter, c, and the transformation:

$$z_i = c + g\frac{x_i - \bar{x}}{s}$$

where $\bar{x}$ and s are the sample mean and standard deviation respectively of the data points x_i, and g takes the value 1 if the data are positively skewed, or -1 is it is negatively skewed.

6.3.2. The compound Gaussian distribution

The first known use of this distribution to model the frequency distributions of Australian daily maximum and minimum temperature was by Grace et al. (1991), with further development by Grace and Curran (1993). It has also been used elsewhere by Bryson (1966) and Colman (1986) for daily maximum and minimum temperature, by Marchenko and Minakova (1980) for hourly air temperature, and by Essenwanger (1954, 1955) for monthly precipitation. Grace and Curran refer to the distribution as the 'binormal' distribution, but this term has also been used to refer to other distributions (e.g. Toth and Szentimrey, 1990) and implies a mixture of only two distributions. For these reasons the term 'compound Gaussian' is used in this thesis.

The model used in this thesis is defined by the equation:

$$f(x) = \sum_{1}^{k} w_k N(\mu_k, \sigma_k),$$

Fig. 6.3a. Frequency distribution of June minimum temperature, Canberra

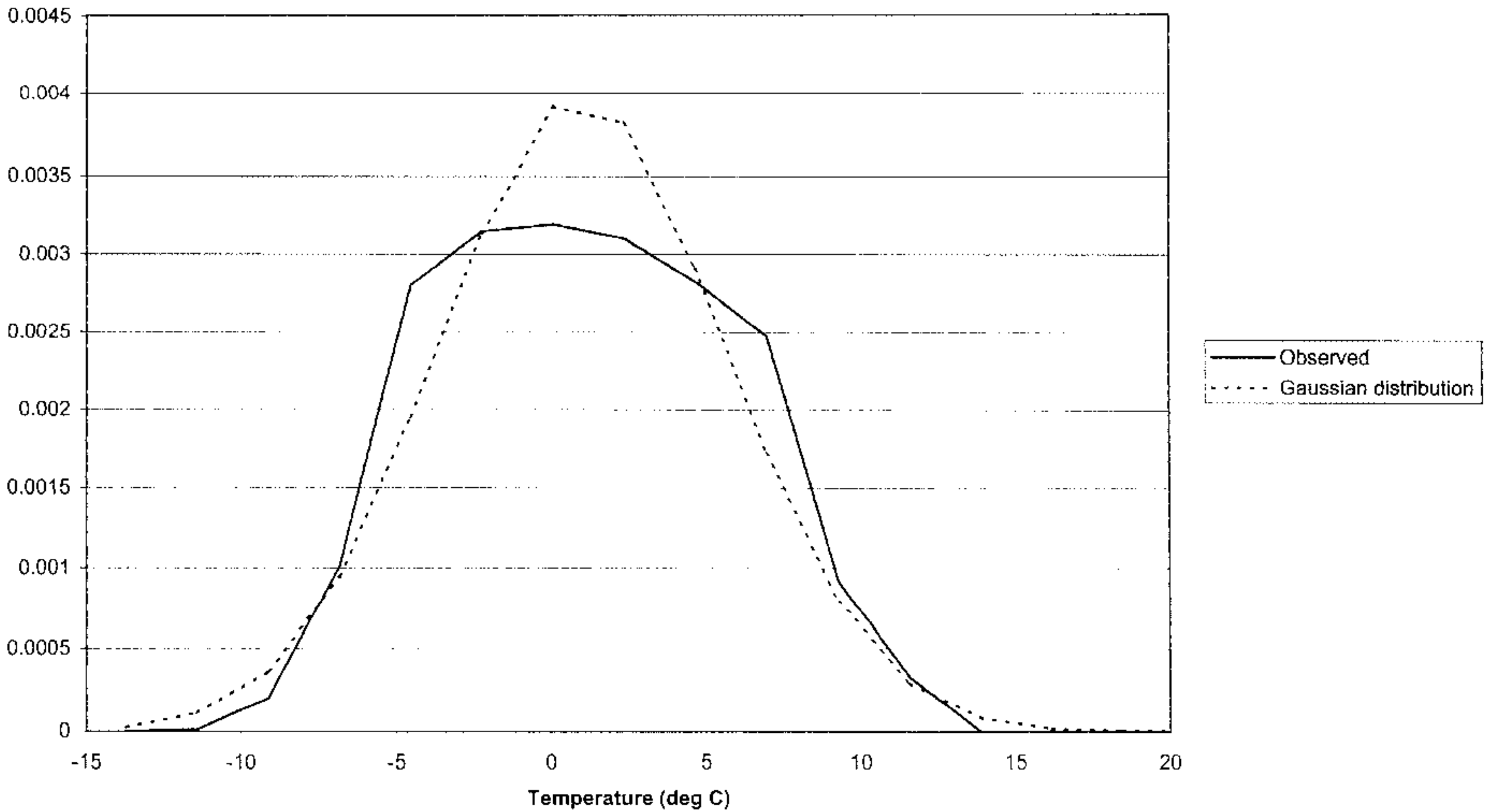
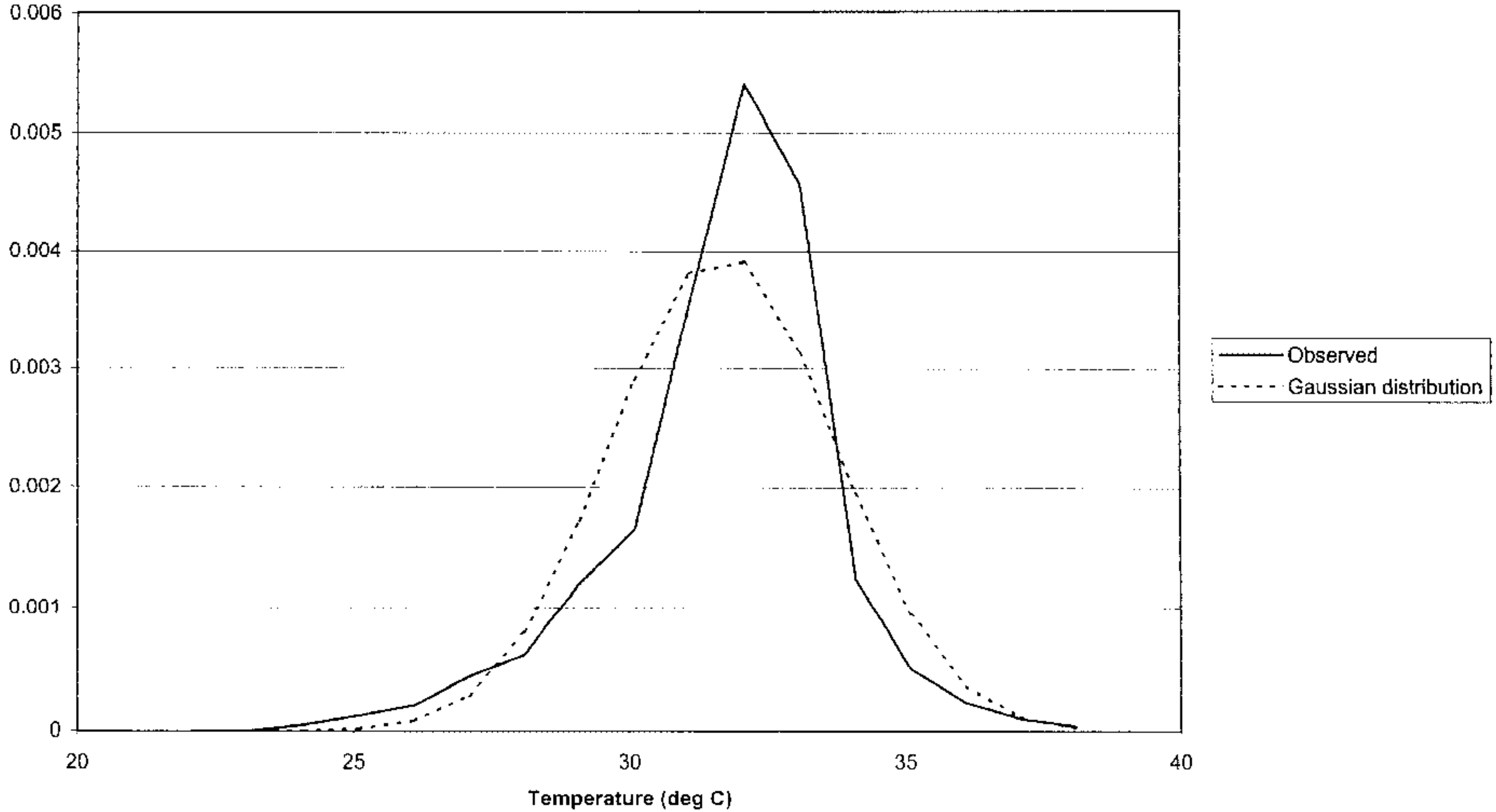


Fig. 6.3b. Frequency distribution of January maximum temperature, Cairns



where $\sum_{1}^{k} w_k = 1$ and $N(\mu_k, \sigma_k)$ is the Gaussian distribution function with mean μ_k and standard deviation σ_k.

An example of such a distribution is given in Fig. 6.4.

6.3.3. Other distributions used to model daily maximum and minimum temperature

Toth and Szentimrey (1990) describe what they refer to as the 'binormal' distribution. The probability density function is defined as follows:

$$f(x) = (1/\sqrt{2\pi})\frac{2}{\sigma_1 + \sigma_2}\exp(-\frac{(x-m)^2}{2\sigma_1^{\,2}}), x \le m$$

$$f(x) = (1/\sqrt{2\pi})\frac{2}{\sigma_1 + \sigma_2}\exp(-\frac{(x-m)^2}{2\sigma_2^{\,2}}), x > m$$

where m is the mode of the distribution.

In effect, this is a combination of two Gaussian distributions with different standard deviations σ_1 and σ_2, with one distribution being used for values of x below the mode and the other being used for values of x above it.

They use this distribution to model the frequency distribution of daily maximum and minimum temperature anomalies at Budapest, estimating the parameters of the distributions by a maximum-likelihood method. Using a chi-square test for goodness-of-fit, they find that the 'binormal' distribution provides a substantially better fit than the single Gaussian distribution for 6 out of 12 months for minimum temperature, and 3 out of 12 months for maximum temperature. (As the single Gaussian distribution is a special case of the 'binormal' distribution, the other months show similar results for the two methods). The 'binormal' distribution performs particularly well in the case of winter minimum temperatures, which are strongly negatively skewed. Nevertheless, their results show that the 'binormal' distribution still differs from the actual distribution at the 5% level in 6 months for minimum temperature, and 3 months for maximum temperature.

6.4. An evaluation of the three-parameter gamma and compound Gaussian distributions

6.4.1. Methods of fitting distributions to empirical data

6.4.1.1. The gamma distribution

The procedure used by Horton et al. (2001) was used. This involved, in the first instance, defining q as follows:

- where the data are positively skewed: $c = q + |\min(x)|$
- where the data are negatively skewed: $c = q + |\max(x)|$

where min(x) and max(x) are the lowest and highest values of the series x and c is a parameter of the gamma distribution as defined in section 6.3.1;. This definition ensures that, for positive q, the z_i are also positive, as required in order to fit the definition of the gamma distribution.

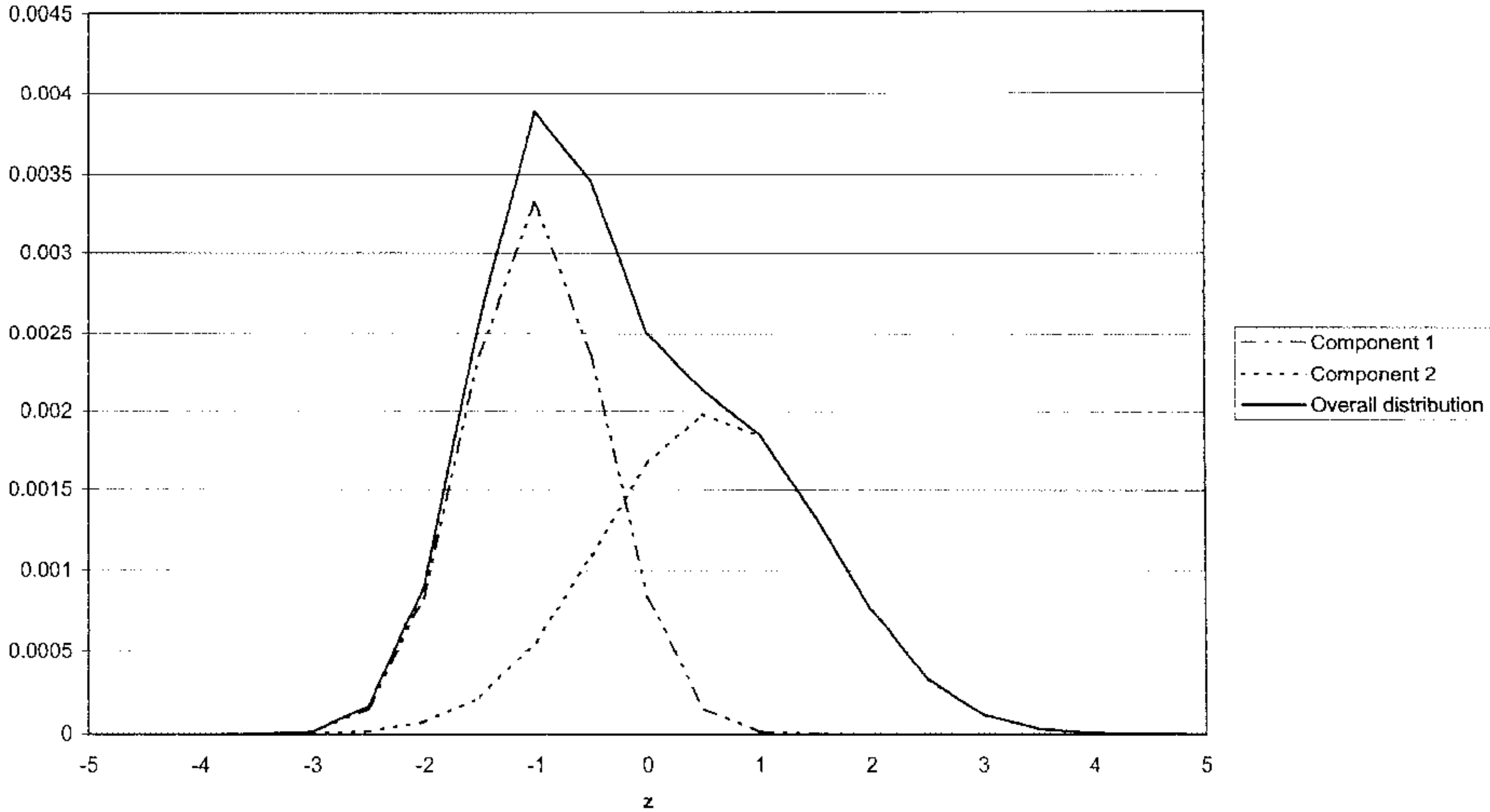
The best-fit value of q was determined by a process of iteration. The first-guess value of q was taken as 0.5. The maximum-likelihood method was used to calculate a:

$$a = (1 + \sqrt{1 + 4A/3})/4A$$

with $A = \ln \bar{x} - \frac{1}{N}\Sigma \ln x_i$, where N is the sample size.

Using the relationship $ab = \bar{x}$, b was then estimated and the skewness of the distribution (which is equal to $2a^{-1/2}$) was calculated.

Fig. 6.4. Example of the compound Gaussian distribution



The value of q was then raised by 0.5 and the process repeated. This was continued until the difference between the observed and fitted skewness reached a minimum – in which case the value of q giving the closest fit to the skewness was used – or a exceeded 50.

6.4.1.2. The compound Gaussian distribution

A number of procedures have been used in previous work. Grace et al. (1991) used an iterative process on the unknowns (of which there were five, as they were constrained to two subdistributions), with the aim of optimising the goodness-of-fit as determined by the chi-squared statistic. Colman (1986) used the assumption that the two tails of the overall frequency distribution were each generated entirely from one of the sub-distributions, and used this to estimate the parameters of those sub-distributions (and, by means of examining the residuals, any additional sub-distributions). Marchenko and Minakova (1980) used a moments-based method.

The method used in this study was based on the method of Hasselblad (1966). This involves finding, iteratively, maximum likelihood estimates for the parameters of the sub-distributions. The procedure can be explained as follows:

Let there be K sub-distributions, and define $w_{k,t}$, $u_{k,t}$ and $s_{k,t}$ as the t-th iteration of the estimates of the weighting, mean and standard deviation of the k-th sub-distribution. Let there be a total of N observations, $x_1, x_2, ..., x_N$ in the distribution being modelled (which, in this case, is the set of all observations of maximum or minimum temperature at a station for a given month of the year). Furthermore, let $f_{k,i}$ be the probability that an observation x_i will lie in the k-th sub-distribution, assuming that the distribution is the mixture of Gaussian sub-distributions with the estimated parameters $w_{k,t}$, $u_{k,t}$ and $s_{k,t}$. For iteration $(t+1)$ we then have:

$$w_{k,t+1} = \frac{\sum_{i=1}^{N} f_{k,i}}{N}$$

$$u_{k,t+1} = \frac{\sum_{i=1}^{N} f_{k,i} x_{k,i}}{N w_{k,t+1}}$$

$$(s_{k,t+1})^2 = \frac{\sum_{i=1}^{N} f_{k,i} (x_i - \bar{x})^2}{N w_{k,t+1}}$$

Initially, this system of equations was evaluated for K=2, and with the initial estimates:

$w_{1,1} = w_{2,1} = 0.5$

$u_{1,1} = -0.5$

$u_{2,1} = 0.5$

$s_{1,1} = s_{2,1} = 0.6$

The iteration was carried out until the following convergence criteria were satisfied for all k:

$|(w_{k,(t+1)} - w_{k,t})| < 0.005$

$|(u_{k,(t+1)} - u_{k,t})| < 0.001$

$|(s_{k,(t+1)} - s_{k,t})| < 0.001$

The closeness of the fit between the compound Gaussian distribution with these parameters and the actual distribution was then tested, using the same five tests as those used in section 6.2.2.1. If all five tests showed a difference between the modelled and actual distribution significant at the 95% level, or at least two of the five showed a difference significant at the 99% level, the procedure was repeated with K=3, and the initial estimates:

$w_{1,1} = w_{3,1} = 0.33$

$w_{2,1} = 0.34$

$u_{1,1} = -0.5$

$u_{2,1} = 0.0$

$u_{3,1} = 0.5$

$s_{1,1} = s_{2,1} = s_{3,1} = 0.6$

otherwise the distribution from the first iterative procedure was taken as the final modelled distribution.

The final modelled distribution was taken as the combination of the two or three Gaussian distributions with the parameters derived by the procedure above. A full listing of the parameters for these distributions is given in Table C.3.

6.4.2. An evaluation of the methods

6.4.2.1. Goodness-of-fit

The five goodness-of-fit tests first described in section 6.2.2.1 were carried out on the modelled distributions derived using the three-parameter gamma distribution and the compound Gaussian distribution, and the actual data for each station for each month. The (single) Gaussian distribution is included for comparison.

The aggregate results from these tests are shown in Table 6.5. Full results of the goodness-of-fit tests are shown in Appendix C, in tables C.1 and C.2 (single Gaussian), C.4 and C.5 (compound Gaussian) and C.6 (gamma).

It is apparent from these results that the compound Gaussian distribution is by far the most effective model for the simulation of the full frequency distribution of Australian daily maximum and minimum temperatures. The three-parameter gamma distribution is a substantial improvement on the single Gaussian distribution, but it still fits the actual distribution less well than the compound Gaussian distribution.

6.4.2.2. Frequency of extremes

The tests used in 6.4.2.1 show the goodness-of-fit between the modelled distribution and the actual distribution over the entire data range. The particular purpose of the present study is to examine the frequency of extreme temperature events, so the effectiveness of the distributions at simulating the observed frequency of extreme events is of great importance in this study.

Following the approach used in Tables 6.2 and 6.3, Table 6.6 shows the actual frequency of temperatures more than 3 standard deviations from the mean, along with the estimated frequency using the single Gaussian, three-parameter gamma and compound Gaussian distributions. Table 6.7 shows the effectiveness of the three distributions at estimating the frequency of such temperatures.

Of the 412 station-seasons examined, the actual frequency of such events was most accurately estimated by the distributions as follows:

- single Gaussian: 11% maxima, 19% minima
- three-parameter gamma: 16% maxima, 11% minima
- compound Gaussian: 73% maxima, 70% minima

Furthermore, the estimated frequency is between 0.5 and 2 times the actual frequency:

- single Gaussian: 37% maxima, 56% minima
- three-parameter gamma: 60% maxima, 55% minima
- compound Gaussian: 90% maxima, 83% minima

Distribution	% of station-months with difference between actual and modelled frequency distribution significant at 99% level on all five tests		% of station-months with difference between actual and modelled frequency distribution significant at 95% level on at least one test	
	Maxima	Minima	Maxima	Minima
Single Gaussian	86	81	95	94
Gamma	29	21	75	75
Compound Gaussian	1	2	24	35

Table 6.5. Comparison of results of goodness-of-fit tests – single Gaussian, compound Gaussian and three-parameter gamma distributions

Station number	Station name	Summer (Dec-Feb)				Autumn (Mar-May)				Winter (Jun-Aug)				Spring (Sep-Nov)			
		A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
1021	Kalumburu	0.40	0.27	0.51	**0.36**	0.98	0.27	0.51	**1.19**	0.49	0.27	0.54	**0.49**	0.72	0.27	0.45	**0.65**
2012	Halls Creek	0.73	0.27	**0.70**	0.41	1.13	0.27	0.71	**0.80**	0.51	0.27	**0.53**	**0.49**	0.80	0.27	**0.67**	1.00
3003	Broome	1.58	0.27	0.62	**1.12**	0.82	0.27	0.50	**0.66**	0.44	0.27	**0.40**	0.31	0.47	0.27	**0.49**	**0.45**
4032	Port Hedland	0.19	0.27	0.45	**0.24**	0.90	0.27	0.51	**0.79**	0.65	0.27	0.45	**0.70**	0.02	0.27	0.40	**0.07**
5007	Learmonth	0.15	0.27	0.35	**0.16**	0.35	0.27	**0.34**	0.33	0.39	0.27	**0.36**	0.29	0.15	0.27	0.37	**0.16**
5026	Wittenoom	1.32	0.27	0.63	**1.23**	1.01	0.27	0.71	**0.86**	0.54	0.27	**0.51**	0.48	0.65	0.27	**0.58**	0.56
6011	Carnarvon	1.24	0.27	0.49	**1.32**	0.27	**0.27**	0.61	0.46	0.64	0.27	0.51	**0.69**	1.30	0.27	0.49	**0.97**
7045	Meekatharra	0.78	0.27	0.67	**0.78**	0.26	**0.27**	0.47	0.13	0.09	0.27	0.38	**0.09**	0.12	0.27	0.36	**0.11**
8039	Dalwallinu	0.17	0.27	0.33	**0.13**	0.08	0.27	0.37	**0.13**	0.42	0.27	**0.46**	0.48	0.17	0.27	0.43	**0.26**
8051	Geraldton	0.06	0.27	0.56	**0.23**	0.12	0.27	0.52	**0.26**	0.74	0.27	0.61	**0.86**	0.87	0.27	0.52	**0.98**
9021	Perth Airport	0.02	0.27	0.44	**0.14**	0.17	**0.27**	0.44	0.38	0.70	0.27	0.45	**0.68**	0.91	0.27	0.56	**0.82**
9518	Cape Leeuwin	2.26	0.27	0.41	**2.32**	1.29	0.27	0.49	**1.37**	0.60	0.27	0.46	**0.60**	1.21	0.27	0.62	**1.44**
9741	Albany	1.34	0.27	0.57	**1.28**	0.82	0.27	**0.62**	0.53	0.44	0.27	**0.38**	**0.38**	1.31	0.27	0.54	**1.14**
9789	Esperance	0.91	0.27	0.55	**0.91**	0.54	0.27	0.61	**0.51**	0.57	0.27	**0.49**	0.41	1.21	0.27	0.59	**0.94**
10035	Cunderdin	0.19	**0.27**	0.39	0.07	0.14	0.27	0.39	**0.17**	0.61	0.27	**0.55**	**0.55**	0.34	0.27	0.57	**0.39**
10648	Wandering	0.09	0.27	0.38	**0.07**	0.11	0.27	0.40	**0.23**	0.39	**0.27**	0.41	0.31	0.36	**0.27**	0.56	0.50
11052	Forrest	0.02	0.27	0.37	**0.09**	0.13	0.27	0.54	**0.22**	0.52	0.27	0.55	**0.52**	0.00	0.27	0.47	**0.20**
12038	Kalgoorlie	0.30	0.27	0.34	**0.16**	0.02	0.27	0.38	**0.11**	0.33	**0.27**	0.53	0.43	0.06	0.27	0.36	**0.13**
13017	Giles	1.18	0.27	0.73	**0.80**	0.84	0.27	**0.51**	**0.51**	0.08	0.27	0.37	**0.13**	0.51	**0.27**	0.60	0.22
14015	Darwin AP	0.74	0.27	0.61	**0.77**	1.15	0.27	0.67	**1.21**	0.45	0.27	**0.47**	0.37	0.73	0.27	0.49	**0.71**
14825	Vict. R. Downs	0.47	0.27	**0.53**	0.25	0.70	0.27	0.67	**0.72**	0.20	0.27	0.42	**0.16**	1.50	0.27	0.54	**1.76**
15135	Tennant Creek	0.70	0.27	**0.68**	0.49	0.93	0.27	0.70	**0.78**	0.19	**0.27**	0.34	0.07	0.94	0.27	**0.71**	0.60
15548	Rabbit Flat	0.59	0.27	**0.69**	0.47	1.39	0.27	0.60	**0.97**	0.29	**0.27**	0.39	0.13	0.98	0.27	0.73	**0.77**
15590	Alice Springs	1.10	0.27	**0.72**	0.66	0.34	0.27	0.49	**0.28**	0.04	0.27	0.38	**0.06**	0.32	**0.27**	0.45	0.11
16001	Woomera	0.32	0.27	**0.35**	0.06	0.11	0.27	0.35	**0.14**	0.39	0.27	**0.47**	0.68	0.18	0.27	0.44	**0.16**
16044	Tarcoola	0.13	0.27	0.39	**0.04**	0.16	0.27	0.40	**0.12**	0.47	0.27	0.62	**0.59**	0.06	0.27	0.40	**0.16**
17031	Marree	0.31	**0.27**	0.42	0.21	0.11	0.27	0.39	**0.12**	0.59	0.27	0.46	**0.57**	0.11	0.27	0.38	**0.15**
17043	Oodnadatta	0.46	0.27	0.54	**0.45**	0.21	**0.27**	0.40	**0.15**	0.75	0.27	**0.60**	0.59	0.11	0.27	0.35	**0.12**
18012	Ceduna	0.02	0.27	0.65	**0.26**	0.24	**0.27**	0.67	0.41	0.82	0.27	**0.60**	**0.60**	0.18	0.27	0.62	**0.26**
18070	Port Lincoln	1.74	0.27	0.57	**0.89**	1.45	0.27	0.59	**1.21**	1.01	0.27	0.50	**0.89**	1.57	0.27	0.52	**1.35**
21046	Snowtown	0.00	0.27	0.36	**0.02**	0.06	0.27	0.38	**0.05**	0.59	0.27	0.49	**0.56**	0.12	0.27	0.54	**0.18**
22801	Cape Borda	0.32	**0.27**	0.73	0.40	0.50	0.27	**0.61**	0.65	0.53	0.27	0.47	**0.54**	0.87	0.27	0.60	**0.84**

Table 6.6a. Actual and modelled percentage frequencies of maximum temperatures more than 3 standard deviations from the mean

A – actual value; B – single Gaussian distribution; C – three-parameter gamma distribution; D – compound Gaussian distribution

Table 6.6a (cont.). Actual and modelled percentage frequencies of maximum temperatures more than 3 standard deviations from the mean

A – actual value; B – single Gaussian distribution; C – three-parameter gamma distribution; D – compound Gaussian distribution

Station number	Station name	Summer (Dec-Feb)				Autumn (Mar-May)				Winter (Jun-Aug)				Spring (Sep-Nov)			
		A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
23090	Adelaide RO	0.00	0.27	0.48	**0.05**	0.15	**0.27**	0.64	0.30	0.81	0.27	0.57	**0.70**	0.25	0.27	0.62	**0.25**
23373	Nuriootpa	0.00	0.27	0.36	**0.04**	0.11	0.27	0.46	**0.17**	0.87	0.27	0.58	**0.71**	0.08	0.27	0.57	**0.22**
26021	Mount Gambier	0.24	**0.27**	0.72	0.43	0.57	0.27	0.66	**0.63**	0.79	0.27	0.47	**0.74**	0.74	0.27	0.61	**0.62**
26026	Robe	1.14	0.27	0.57	**0.88**	0.74	0.27	**0.57**	0.93	0.42	0.27	0.42	**0.44**	0.77	0.27	0.62	**0.81**
27022	Thursday Island	0.44	0.27	**0.42**	0.48	0.52	0.27	**0.55**	0.75	0.85	0.27	0.48	**0.79**	0.91	0.27	0.45	**0.68**
27045	Weipa	0.48	0.27	0.65	**0.44**	1.16	0.27	0.57	**1.10**	0.91	0.27	0.57	**1.12**	0.37	**0.27**	0.52	0.51
28004	Palmerville	1.07	0.27	0.62	**1.01**	1.24	0.27	0.60	**1.30**	0.83	0.27	0.70	**0.74**	0.68	0.27	0.52	**0.71**
29004	Burketown	0.35	0.27	**0.37**	0.49	1.03	0.27	0.66	**1.16**	0.49	0.27	0.58	**0.50**	0.61	0.27	0.44	**0.65**
30045	Richmond	0.97	0.27	0.70	**0.85**	1.25	0.27	0.65	**1.19**	0.29	**0.27**	0.40	0.16	1.07	0.27	0.67	**1.03**
31011	Cairns	1.44	0.27	0.51	**1.35**	0.87	0.27	0.46	**0.75**	0.54	0.27	**0.55**	0.67	1.24	0.27	0.49	**1.28**
32040	Townsville	1.41	0.27	0.46	**1.61**	1.44	0.27	0.50	**1.38**	1.09	0.27	0.46	**1.05**	1.52	0.27	0.46	**1.54**
33119	Mackay MO	0.65	0.27	0.38	**0.72**	0.83	0.27	0.37	**0.76**	0.89	0.27	0.42	**0.85**	0.44	0.27	**0.39**	0.31
34084	Charters Towers	0.74	0.27	0.52	**0.88**	0.95	0.27	0.57	**0.77**	0.59	0.27	0.45	**0.59**	0.84	0.27	0.50	**0.82**
36007	Barcaldine	1.04	0.27	0.70	**0.91**	1.01	0.27	0.71	**1.15**	0.25	**0.27**	0.34	0.19	0.42	0.27	**0.35**	0.54
36031	Longreach	1.32	0.27	0.58	**0.89**	1.20	0.27	0.63	**0.94**	0.16	0.27	0.35	**0.16**	0.47	0.27	**0.51**	0.57
37010	Camooweal	0.61	0.27	0.66	**0.54**	1.16	0.27	0.70	**0.85**	0.28	**0.27**	0.44	0.18	1.08	0.27	0.68	**0.95**
38002	Birdsville	0.79	0.27	**0.58**	0.54	0.31	**0.27**	0.41	0.17	0.23	**0.27**	0.47	0.18	0.06	0.27	0.49	**0.07**
38003	Boulia	1.11	0.27	0.70	**0.81**	1.01	0.27	0.53	**0.82**	0.14	0.27	0.37	**0.05**	0.42	0.27	**0.37**	0.29
39039	Gayndah	0.64	0.27	0.37	**0.73**	0.79	0.27	0.48	**0.87**	0.52	0.27	**0.47**	0.46	0.47	0.27	**0.41**	0.60
39083	Rockhampton	0.50	0.27	**0.42**	0.70	0.80	0.27	0.50	**0.98**	0.78	0.27	0.47	**0.74**	0.48	0.27	**0.39**	**0.39**
39128	Bundaberg	1.37	0.27	0.44	**1.15**	0.87	0.27	0.67	**1.06**	0.66	0.27	0.39	**0.77**	1.11	0.27	0.43	1.13
40004	Amberley	0.50	0.27	**0.42**	0.65	0.98	0.27	0.38	**0.95**	0.63	0.27	**0.42**	0.86	0.53	0.27	0.36	**0.64**
40223	Brisbane AP	1.10	0.27	0.50	**1.16**	1.16	0.27	0.46	**1.16**	1.02	0.27	0.42	**0.89**	1.37	0.27	0.59	**1.21**
40908	Tewantin	1.56	0.27	0.62	**1.43**	1.18	0.27	0.47	**1.17**	0.97	0.27	0.51	**0.87**	0.75	0.27	0.64	**0.78**
42023	Miles	0.47	0.27	0.45	**0.48**	0.62	0.27	**0.65**	0.81	0.13	0.27	0.37	**0.06**	0.44	0.27	**0.42**	0.36
43109	St. George	0.87	0.27	0.62	**0.82**	0.57	0.27	**0.58**	0.61	0.06	0.27	0.37	**0.10**	0.16	0.27	0.37	**0.24**
44021	Charleville	0.77	0.27	0.65	**0.68**	0.46	0.27	0.55	**0.43**	0.06	0.27	0.39	**0.07**	0.18	0.27	0.37	**0.18**

Station number	Station name	Summer (Dec-Feb)				Autumn (Mar-May)				Winter (Jun-Aug)				Spring (Sep-Nov)			
		A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
45017	Thargomindah	0.55	0.27	**0.48**	0.47	0.17	0.27	0.40	**0.16**	0.11	0.27	0.53	**0.17**	0.08	0.27	0.37	**0.16**
46037	Tibooburra	0.26	**0.27**	0.47	0.22	0.15	0.27	0.45	**0.11**	0.18	0.27	0.48	**0.11**	0.08	0.27	0.36	**0.09**
46043	Wilcannia	0.23	**0.27**	0.36	0.13	0.09	0.27	0.38	**0.04**	0.38	0.27	0.45	**0.40**	0.06	0.27	0.39	**0.16**
48027	Cobar	0.36	0.27	**0.36**	0.34	0.14	0.27	0.35	**0.14**	0.41	0.27	0.44	**0.39**	0.05	0.27	0.42	**0.16**
48239	Bourke	0.45	0.27	0.54	**0.46**	0.22	0.27	0.38	**0.22**	0.41	0.27	**0.47**	0.28	0.03	0.27	0.36	**0.10**
52088	Walgett	0.64	0.27	0.50	**0.51**	0.48	0.27	**0.54**	0.41	0.09	0.27	0.38	**0.20**	0.06	0.27	0.36	**0.17**
53048	Moree	0.56	0.27	0.39	**0.59**	0.64	0.27	0.50	**0.69**	0.21	0.27	0.38	**0.21**	0.23	**0.27**	0.37	0.30
55024	Gunnedah SC	0.31	**0.27**	0.43	0.41	0.61	0.27	0.45	**0.54**	0.20	0.27	0.38	**0.21**	0.17	0.27	0.37	**0.26**
56017	Inverell PO	0.31	**0.27**	0.36	0.48	0.83	0.27	0.64	**0.77**	0.25	0.27	0.44	**0.19**	0.25	**0.27**	0.36	0.28
58012	Yamba	1.39	0.27	0.58	**1.66**	1.03	0.27	0.41	**1.03**	0.83	0.27	0.48	**0.83**	1.81	0.27	0.45	**1.87**
59040	Coffs Harbour	1.18	0.27	0.57	**1.39**	0.93	0.27	0.56	**0.97**	0.90	0.27	0.54	**0.85**	1.30	0.27	0.55	**1.16**
60026	Port Macquarie	0.97	0.27	**0.58**	1.48	0.85	0.27	0.38	**0.76**	0.70	0.27	0.47	**0.74**	1.35	0.27	0.54	**1.42**
61078	Williamtown	0.62	0.27	**0.70**	0.51	0.71	0.27	0.56	**0.70**	0.75	0.27	0.51	**0.87**	0.60	0.27	0.67	**0.54**
61089	Scone SC	0.07	0.27	0.35	**0.10**	0.10	0.27	0.35	**0.21**	0.24	**0.27**	0.39	0.18	0.10	0.27	0.38	**0.18**
63005	Bathurst ARS	0.10	0.27	0.36	**0.14**	0.26	**0.27**	0.40	0.32	0.16	0.27	0.35	**0.18**	0.12	0.27	0.41	**0.17**
65012	Dubbo	0.22	0.27	0.35	**0.20**	0.38	0.27	0.48	**0.38**	0.16	0.27	0.38	**0.20**	0.22	0.27	0.37	**0.22**
66062	Sydney RO	1.56	0.27	0.56	**1.40**	0.79	0.27	0.51	**0.85**	0.61	0.27	0.45	**0.60**	0.99	0.27	0.60	**0.87**
67105	Richmond	0.12	0.27	0.42	**0.22**	0.54	0.27	0.44	**0.45**	0.77	0.27	0.47	**0.67**	0.19	**0.27**	0.40	0.36
68034	Jervis Bay	1.21	0.27	0.75	**1.26**	0.61	0.27	0.55	**0.56**	0.57	0.27	**0.54**	0.40	1.07	0.27	0.70	**0.84**
68076	Nowra	1.19	0.27	0.67	**0.72**	0.53	0.27	**0.47**	0.36	0.70	0.27	0.55	**0.75**	0.89	0.27	0.63	**0.80**
69018	Moruya Heads	2.37	0.27	0.39	**2.46**	1.13	0.27	0.54	**1.15**	0.89	0.27	0.45	**0.79**	2.13	0.27	0.41	**1.88**
70014	Canberra Airport	0.06	0.27	0.38	**0.13**	0.45	0.27	**0.35**	0.34	0.49	0.27	0.37	**0.47**	0.27	**0.27**	0.41	0.30
72161	Cabramurra	0.41	0.27	0.39	**0.40**	0.50	0.27	**0.46**	0.39	0.25	**0.27**	0.37	0.10	0.06	0.27	0.36	**0.25**
72150	Wagga Wagga	0.20	**0.27**	0.37	**0.27**	0.12	0.27	0.35	**0.17**	0.36	0.27	0.44	**0.29**	0.40	0.27	0.46	**0.37**
73054	Wyalong	0.32	0.27	**0.36**	**0.28**	0.09	0.27	0.36	**0.13**	0.34	0.27	0.44	**0.34**	0.22	**0.27**	0.44	0.28
74128	Deniliquin	0.03	0.27	0.37	**0.11**	0.11	0.27	0.37	**0.13**	0.60	0.27	**0.54**	0.68	0.47	0.27	0.57	**0.48**
76031	Mildura	0.04	0.27	0.40	**0.05**	0.09	0.27	0.42	**0.12**	0.48	0.27	**0.47**	0.51	0.43	0.27	0.60	**0.45**
78031	Nhill	0.06	0.27	0.40	**0.11**	0.19	**0.27**	0.52	0.30	1.12	0.27	0.63	**1.03**	0.63	0.27	**0.66**	0.51
80023	Kerang	0.00	0.27	0.39	**0.11**	0.20	0.27	0.43	**0.18**	0.91	0.27	0.54	**0.74**	0.38	0.27	0.58	**0.45**
82039	Rutherglen	0.28	**0.27**	0.39	0.22	0.07	0.27	0.36	**0.09**	0.48	0.27	**0.46**	0.38	0.42	0.27	**0.47**	0.50
84016	Gabo Island	1.29	0.27	0.58	**1.71**	0.82	0.27	**0.66**	0.99	0.98	0.27	0.58	**0.84**	1.90	0.27	0.54	**2.01**
84030	Orbost	0.45	0.27	0.72	**0.42**	0.22	**0.27**	0.54	0.34	0.42	0.27	**0.46**	0.35	0.43	0.27	0.63	**0.50**

Table 6.6a (cont.). Actual and modelled percentage frequencies of maximum temperatures more than 3 standard deviations from the mean

A – actual value; B – single Gaussian distribution; C – three-parameter gamma distribution; D – compound Gaussian distribution

Table 6.6a (cont.). Actual and modelled percentage frequencies of maximum temperatures more than 3 standard deviations from the mean

A – actual value; B – single Gaussian distribution; C – three parameter gamma distribution; D – compound Gaussian distribution

Station number	Station name	Summer (Dec-Feb)				Autumn (Mar-May)				Winter (Jun-Aug)				Spring (Sep-Nov)			
		A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
85072	Sale	0.69	0.27	0.58	**0.67**	0.66	0.27	0.55	**0.75**	0.87	0.27	0.56	**0.83**	1.12	0.27	0.58	**0.83**
85096	Wilsons Prom.	2.19	0.27	0.46	**1.72**	1.29	0.27	0.55	**1.22**	1.28	0.27	0.58	**1.33**	1.82	0.27	0.47	**1.60**
86071	Melbourne RO	0.08	0.27	0.64	**0.22**	0.27	**0.27**	0.54	0.26	0.38	0.27	0.42	**0.38**	0.32	0.27	0.60	**0.32**
87031	Laverton	0.10	**0.27**	0.73	0.32	0.23	**0.27**	0.57	0.18	0.71	0.27	0.41	**0.59**	0.66	0.27	**0.68**	0.42
90015	Cape Otway	1.88	0.27	0.47	**1.47**	1.29	0.27	0.58	**0.99**	1.02	0.27	0.60	**0.98**	1.31	0.27	0.54	**1.16**
91057	Low Head	0.30	**0.27**	0.38	0.24	0.14	0.27	0.40	**0.17**	0.11	0.27	0.34	**0.25**	0.47	0.27	0.40	**0.43**
91104	Launceston AP	0.73	0.27	0.56	**0.62**	0.29	**0.27**	0.39	**0.31**	0.44	0.27	**0.35**	0.29	0.58	0.27	0.52	**0.62**
92045	Eddystone Point	1.41	0.27	0.67	**1.51**	0.54	0.27	**0.55**	0.61	0.63	0.27	0.38	**0.52**	1.28	0.27	0.62	**1.39**
94010	Cape Bruny	1.64	0.27	0.57	**1.58**	0.94	0.27	0.54	**0.69**	0.41	0.27	**0.37**	0.25	1.39	0.27	0.57	**1.30**
94029	Hobart RO	1.27	0.27	0.60	**1.12**	0.56	0.27	**0.59**	0.50	0.18	0.27	0.39	**0.18**	1.04	0.27	0.59	**0.87**
94069	Grove	0.95	0.27	0.68	**0.76**	0.36	0.27	0.43	**0.31**	0.22	0.27	0.38	**0.19**	0.95	0.27	0.61	**0.84**
96003	Butlers Gorge	0.00	0.27	0.38	**0.05**	0.06	0.27	0.40	**0.11**	0.15	**0.27**	0.36	0.30	0.21	**0.27**	0.38	**0.15**

Station number	Station name	Summer (Dec-Feb)				Autumn (Mar-May)				Winter (Jun-Aug)				Spring (Sep-Nov)			
		A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
1021	Kalumburu	0.20	**0.27**	0.37	**0.27**	0.68	0.27	0.54	**0.69**	0.06	0.27	0.34	**0.17**	0.69	0.27	**0.48**	0.47
2012	Halls Creek	0.70	0.27	0.44	**0.57**	0.79	0.27	0.44	**0.79**	0.25	0.27	0.36	**0.15**	0.51	0.27	0.45	**0.56**
3003	Broome	0.56	0.27	**0.56**	0.61	0.23	**0.27**	0.41	0.17	0.00	0.27	0.35	**0.05**	0.45	0.27	0.40	**0.44**
4032	Port Hedland	0.51	0.27	0.43	**0.58**	0.18	**0.27**	0.40	0.29	0.02	0.27	0.36	**0.06**	0.41	0.27	0.47	**0.37**
5007	Learmonth	0.15	0.27	0.40	**0.13**	0.45	0.27	**0.38**	0.27	0.10	0.27	0.41	**0.18**	0.70	0.27	0.39	**0.52**
5026	Wittenoom	0.12	0.27	0.40	**0.08**	0.29	**0.27**	0.37	0.18	0.14	0.27	0.34	**0.13**	0.14	0.27	0.40	**0.09**
6011	Carnarvon	0.69	0.27	0.46	**0.83**	0.11	0.27	0.39	**0.05**	0.09	0.27	0.44	**0.21**	0.13	**0.27**	0.47	0.34
7045	Meekatharra	0.24	**0.27**	0.42	0.18	0.16	0.27	0.37	**0.21**	0.12	0.27	0.43	**0.27**	0.21	**0.27**	0.39	0.13
8039	Dalwallinu	0.17	0.27	0.43	**0.18**	0.20	**0.27**	0.39	**0.13**	0.03	0.27	0.37	**0.13**	0.37	0.27	0.46	**0.33**
8051	Geraldton	0.24	**0.27**	0.40	0.15	0.14	0.27	0.39	**0.13**	0.06	0.27	0.36	**0.10**	0.20	**0.27**	0.40	0.12
9021	Perth Airport	0.27	**0.27**	0.38	**0.27**	0.13	0.27	0.36	**0.16**	0.00	0.27	0.35	**0.11**	0.17	0.27	0.40	**0.20**
9518	Cape Leeuwin	0.71	0.27	0.45	**0.77**	0.44	0.27	**0.34**	0.32	0.46	0.27	**0.52**	0.54	0.45	0.27	0.40	**0.47**
9741	Albany	0.15	**0.27**	0.47	0.33	0.15	0.27	0.33	**0.15**	0.23	**0.27**	0.49	0.34	0.09	0.27	0.34	**0.16**
9789	Esperance	0.28	**0.27**	0.36	0.16	0.27	**0.27**	0.38	0.15	0.38	0.27	**0.39**	0.33	0.39	0.27	**0.37**	0.30
10035	Cunderdin	0.28	**0.27**	0.44	0.32	0.11	0.27	0.38	**0.17**	0.22	**0.27**	0.38	0.13	0.20	0.27	0.40	**0.18**
10648	Wandering	0.31	**0.27**	0.36	0.36	0.03	0.27	0.37	**0.06**	0.00	0.27	0.38	**0.04**	0.06	0.27	0.36	**0.07**
11052	Forrest	1.05	0.27	0.54	**0.89**	0.72	0.27	0.57	**0.71**	0.47	0.27	**0.59**	0.62	0.90	0.27	0.56	**0.82**
12038	Kalgoorlie	0.16	0.27	0.38	**0.19**	0.22	**0.27**	0.37	0.29	0.20	0.27	0.40	**0.12**	0.20	**0.27**	0.41	0.33
13017	Giles	0.30	**0.27**	0.49	0.41	0.33	0.27	**0.38**	0.42	0.41	0.27	0.49	**0.36**	0.11	0.27	0.50	**0.14**
14015	Darwin AP	0.08	0.27	0.38	**0.05**	0.70	0.27	0.54	**0.62**	0.29	**0.27**	0.43	0.23	0.59	0.27	0.59	**0.56**
14825	Vict. R. Downs	0.68	0.27	0.47	**0.68**	0.43	0.27	**0.48**	0.35	0.00	0.27	0.42	**0.04**	0.21	0.27	0.57	**0.21**
15135	Tennant Creek	0.42	0.27	**0.36**	0.34	0.49	0.27	**0.46**	0.70	0.05	0.27	0.38	**0.09**	0.25	**0.27**	0.44	0.29
15548	Rabbit Flat	0.33	**0.27**	0.49	0.41	0.12	0.27	0.39	**0.13**	0.00	0.27	0.38	**0.08**	0.08	0.27	0.36	**0.22**
15590	Alice Springs	0.06	0.27	0.40	**0.06**	0.10	0.27	0.38	**0.07**	0.26	**0.27**	0.54	0.19	0.10	0.27	0.38	**0.17**
16001	Woomera	0.28	**0.27**	0.48	0.07	0.12	0.27	0.38	**0.20**	0.20	**0.27**	0.38	0.38	0.19	**0.27**	0.55	0.61
16044	Tarcoola	0.17	0.27	0.41	**0.14**	0.16	0.27	0.42	**0.17**	0.16	0.27	0.37	**0.08**	0.48	0.27	0.57	**0.51**
17031	Marree	0.08	0.27	0.41	**0.08**	0.08	0.27	0.39	**0.14**	0.33	**0.27**	0.53	0.26	0.20	0.27	0.56	**0.25**
17043	Oodnadatta	0.05	0.27	0.38	**0.04**	0.11	0.27	0.40	**0.14**	0.29	**0.27**	0.49	0.22	0.09	0.27	0.38	**0.07**
18012	Ceduna	0.36	0.27	**0.37**	0.32	0.14	0.27	0.39	**0.12**	0.08	0.27	0.36	**0.09**	0.18	0.27	0.39	**0.21**
18070	Port Lincoln	0.45	0.27	0.49	**0.44**	0.27	**0.27**	0.36	0.31	0.44	0.27	**0.38**	0.34	0.25	0.27	0.36	**0.23**
21046	Snowtown	0.33	0.27	0.52	**0.29**	0.15	0.27	0.38	**0.13**	0.18	**0.27**	0.34	0.07	0.42	0.27	**0.53**	0.25
22801	Cape Borda	1.88	0.27	0.48	**1.69**	0.72	0.27	0.54	**0.58**	0.23	**0.27**	0.38	0.15	0.91	0.27	0.60	**0.79**

Table 6.6b. Actual and modelled percentage frequencies of minimum temperatures more than 3 standard deviations from the mean

A – actual value; B – single Gaussian distribution; C – three-parameter gamma distribution; D – compound Gaussian distribution

Table 6.6b (cont.). Actual and modelled percentage frequencies of minimum temperatures more than 3 standard deviations from the mean

A – actual value; B – single Gaussian distribution; C – three-parameter gamma distribution; D – compound Gaussian distribution

Station number	Station name	Summer (Dec-Feb)				Autumn (Mar-May)				Winter (Jun-Aug)				Spring (Sep-Nov)			
		A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
23090	Adelaide RO	0.73	0.27	**0.68**	0.64	0.50	0.27	0.52	**0.50**	0.13	0.27	0.36	**0.09**	0.67	0.27	**0.62**	0.52
23373	Nuriootpa	0.19	0.27	0.46	**0.25**	0.25	0.27	0.38	**0.26**	0.05	0.27	0.36	**0.04**	0.36	0.27	**0.40**	0.24
26021	Mount Gambier	0.63	0.27	**0.55**	0.48	0.28	**0.27**	0.38	0.37	0.10	0.27	0.45	**0.16**	0.46	0.27	**0.43**	0.39
26026	Robe	0.68	0.27	0.49	**0.65**	0.25	0.27	0.45	**0.25**	0.24	**0.27**	0.59	0.29	0.12	**0.27**	0.37	0.33
27022	Thursday Island	0.26	**0.27**	0.43	0.12	0.31	0.27	0.40	**0.32**	0.56	0.27	0.44	**0.52**	0.31	**0.27**	0.39	**0.27**
27045	Weipa	1.18	0.27	0.41	**1.04**	0.81	0.27	0.50	**0.77**	0.65	0.27	0.40	**0.54**	0.76	0.27	0.48	**0.53**
28004	Palmerville	0.79	0.27	0.52	**0.80**	0.57	0.27	**0.50**	0.49	0.73	0.27	0.47	**0.50**	0.91	0.27	0.49	**0.68**
29004	Burketown	0.36	0.27	0.46	**0.33**	0.52	0.27	**0.59**	0.12	0.17	0.27	0.36	**0.12**	0.52	0.27	**0.54**	0.59
30045	Richmond	0.67	0.27	0.41	**0.67**	0.26	**0.27**	0.39	0.24	0.03	0.27	0.38	**0.05**	0.24	0.27	0.41	**0.22**
31011	Cairns	0.55	0.27	0.36	**0.61**	0.93	0.27	0.64	**0.92**	0.50	0.27	0.72	**0.41**	0.51	0.27	**0.44**	0.59
32040	Townsville	0.41	0.27	0.47	**0.46**	0.37	0.27	0.49	**0.41**	0.10	0.27	0.36	**0.15**	0.43	0.27	0.53	**0.38**
33119	Mackay MO	0.27	**0.27**	0.34	0.15	0.51	0.27	0.47	**0.48**	0.00	0.27	0.32	**0.06**	0.20	**0.27**	0.43	0.11
34084	Charters Towers	0.32	0.27	**0.35**	**0.35**	0.42	0.27	0.39	**0.40**	0.03	0.27	0.36	**0.11**	0.16	0.27	0.33	**0.12**
36007	Barcaldine	0.29	**0.27**	0.35	0.41	0.32	0.27	0.47	**0.36**	0.00	0.27	0.38	**0.02**	0.35	**0.27**	0.45	0.26
36031	Longreach	0.30	**0.27**	**0.33**	0.43	0.29	0.27	0.39	**0.30**	0.00	0.27	0.38	**0.08**	0.00	0.27	0.35	**0.20**
37010	Camooweal	0.47	0.27	**0.51**	0.67	0.12	**0.27**	0.42	0.30	0.03	0.27	0.39	**0.08**	0.20	0.27	0.47	**0.17**
38002	Birdsville	0.14	0.27	0.39	**0.16**	0.06	0.27	0.35	**0.12**	0.45	0.27	0.64	**0.41**	0.14	0.27	0.40	**0.10**
38003	Boulia	0.19	0.27	0.38	**0.26**	0.45	0.27	**0.47**	0.39	0.12	0.27	0.43	**0.17**	0.16	0.27	0.39	**0.11**
39039	Gayndah	0.14	0.27	0.34	**0.17**	0.14	0.27	0.34	**0.13**	0.05	0.27	0.38	**0.09**	0.22	**0.27**	0.44	0.13
39083	Rockhampton	0.33	0.27	**0.35**	0.27	0.79	0.27	0.59	**0.76**	0.00	0.27	0.37	**0.02**	0.46	0.27	**0.46**	0.52
39128	Bundaberg	0.17	0.27	0.39	**0.18**	0.49	0.27	**0.43**	**0.55**	0.00	0.27	0.33	**0.02**	0.08	0.27	0.35	**0.15**
40004	Amberley	0.22	**0.27**	0.36	0.14	0.12	0.27	0.35	**0.13**	0.00	0.27	0.41	**0.08**	0.04	0.27	0.39	**0.09**
40223	Brisbane AP	0.12	0.27	0.35	**0.15**	0.65	0.27	0.50	**0.60**	0.00	0.27	0.41	**0.03**	0.34	0.27	0.46	**0.34**
40908	Tewantin	0.35	0.27	0.41	**0.37**	0.83	0.27	0.59	**0.62**	0.00	0.27	0.35	**0.03**	0.22	**0.27**	0.42	0.31
42023	Miles	0.64	0.27	**0.52**	0.45	0.31	0.27	0.37	**0.29**	0.00	0.27	0.39	**0.06**	0.09	0.27	0.43	**0.17**
43109	St. George	0.16	**0.27**	0.37	0.30	0.03	0.27	0.42	**0.16**	0.03	0.27	0.47	**0.18**	0.03	0.27	0.35	**0.04**
44021	Charleville	0.19	0.27	0.37	**0.21**	0.28	**0.27**	0.44	0.26	0.00	0.27	0.50	**0.18**	0.02	0.27	0.35	**0.08**

Station number	Station name	Summer (Dec-Feb)				Autumn (Mar-May)				Winter (Jun-Aug)				Spring (Sep-Nov)			
		A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
45017	Thargomindah	0.21	0.27	0.36	**0.23**	0.06	0.27	0.37	**0.07**	0.35	0.27	0.63	**0.39**	0.03	0.27	0.35	**0.07**
46037	Tibooburra	0.14	0.27	0.36	**0.15**	0.14	0.27	0.36	**0.15**	0.45	0.27	**0.46**	0.31	0.14	0.27	0.38	**0.15**
46043	Wilcannia	0.24	0.27	0.42	**0.20**	0.15	0.27	0.41	**0.15**	0.21	**0.27**	0.39	0.33	0.38	**0.27**	**0.49**	0.25
48027	Cobar	0.16	**0.27**	0.40	0.28	0.00	0.27	0.37	**0.09**	0.22	0.27	0.42	**0.23**	0.16	0.27	0.40	**0.24**
48239	Bourke	0.08	0.27	0.36	**0.25**	0.08	0.27	0.38	**0.13**	0.28	**0.27**	0.57	0.34	0.11	0.27	0.40	**0.22**
52088	Walgett	0.32	0.27	0.47	**0.35**	0.09	0.27	0.39	**0.12**	0.23	**0.27**	0.50	0.18	0.18	0.27	0.40	**0.14**
53048	Moree	0.47	0.27	0.44	**0.60**	0.27	**0.27**	0.40	0.16	0.05	0.27	0.39	**0.05**	0.04	0.27	0.35	**0.04**
55024	Gunnedah SC	0.31	**0.27**	0.42	0.42	0.24	**0.27**	0.39	0.39	0.07	0.27	0.37	**0.11**	0.32	**0.27**	0.39	0.24
56017	Inverell PO	0.11	0.27	0.38	**0.09**	0.08	0.27	0.39	**0.10**	0.14	0.27	0.55	**0.25**	0.03	0.27	0.44	**0.10**
58012	Yamba	0.56	0.27	**0.44**	0.43	0.19	0.27	0.34	**0.26**	0.23	**0.27**	0.42	0.18	0.21	0.27	0.39	**0.24**
59040	Coffs Harbour	0.29	**0.27**	0.37	0.13	0.43	0.27	0.61	**0.50**	0.05	0.27	0.37	**0.08**	0.21	**0.27**	0.44	0.34
60026	Port Macquarie	0.19	0.27	0.55	**0.23**	0.13	0.27	0.39	**0.21**	0.09	0.27	0.40	**0.17**	0.10	0.27	0.39	**0.08**
61078	Williamtown	0.26	**0.27**	0.38	0.29	0.02	0.27	0.38	**0.04**	0.09	**0.27**	0.37	0.33	0.07	0.27	0.36	**0.09**
61089	Scone SC	0.28	**0.27**	0.40	0.24	0.14	0.27	0.37	**0.10**	0.07	0.27	0.39	**0.07**	0.31	0.27	0.42	**0.30**
63005	Bathurst ARS	0.16	0.27	0.40	**0.20**	0.04	0.27	0.35	**0.15**	0.04	0.27	0.39	**0.05**	0.22	**0.27**	0.43	0.16
65012	Dubbo	0.33	0.27	0.40	**0.30**	0.03	0.27	0.38	**0.08**	0.03	0.27	0.38	**0.12**	0.11	0.27	0.36	**0.09**
66062	Sydney RO	0.39	0.27	**0.35**	0.30	0.33	**0.27**	0.36	0.26	0.50	0.27	**0.57**	0.42	0.39	0.27	**0.41**	0.27
67105	Richmond	0.38	0.27	**0.44**	0.52	0.15	0.27	0.54	**0.21**	0.09	0.27	0.38	**0.04**	0.09	0.27	0.43	**0.07**
68034	Jervis Bay	0.62	0.27	0.47	**0.54**	0.35	0.27	**0.33**	0.31	0.58	0.27	0.36	**0.50**	0.49	0.27	0.38	**0.43**
68076	Nowra	0.08	0.27	0.38	**0.18**	0.21	0.27	0.36	**0.22**	0.22	0.27	0.38	**0.20**	0.38	0.27	**0.38**	0.23
69018	Moruya Heads	0.41	0.27	**0.34**	0.23	0.35	0.27	0.44	**0.34**	0.45	0.27	0.57	**0.48**	0.25	**0.27**	0.39	0.17
70014	Canberra Airport	0.21	0.27	0.35	**0.22**	0.07	0.27	0.38	**0.13**	0.00	0.27	0.38	**0.07**	0.11	0.27	0.36	**0.10**
72161	Cabramurra	0.00	0.27	0.38	**0.11**	0.06	0.27	0.34	**0.14**	0.34	0.27	**0.39**	0.42	0.22	0.27	0.39	**0.19**
72150	Wagga Wagga	0.24	**0.27**	0.39	0.11	0.00	0.27	0.38	**0.07**	0.06	0.27	0.36	**0.08**	0.14	0.27	0.38	**0.13**
73054	Wyalong	0.21	0.27	0.47	**0.19**	0.10	0.27	0.38	**0.11**	0.17	0.27	0.40	**0.15**	0.17	**0.27**	0.55	0.30
74128	Deniliquin	0.28	**0.27**	0.44	0.16	0.03	0.27	0.36	**0.08**	0.03	0.27	0.40	**0.13**	0.19	0.27	0.44	**0.18**
76031	Mildura	0.26	**0.27**	0.41	0.13	0.13	0.27	0.42	**0.13**	0.15	0.27	0.37	**0.20**	0.37	0.27	0.60	**0.35**
78031	Nhill	0.31	0.27	0.58	**0.26**	0.00	0.27	0.37	**0.07**	0.16	0.27	0.32	**0.06**	0.16	0.27	0.38	**0.16**
80023	Kerang	0.17	0.27	0.55	**0.22**	0.21	0.27	0.45	**0.18**	0.21	0.27	0.40	**0.17**	0.21	0.27	0.51	**0.26**
82039	Rutherglen	0.10	0.27	0.40	**0.09**	0.10	0.27	0.42	**0.11**	0.00	0.27	0.37	**0.06**	0.18	0.27	0.48	**0.19**
84016	Gabo Island	0.29	**0.27**	0.47	0.16	0.31	**0.27**	0.40	0.26	0.25	**0.27**	0.41	0.52	0.45	0.27	**0.37**	**0.37**
84030	Orbost	0.20	0.27	0.37	**0.18**	0.08	0.27	0.37	**0.08**	0.14	0.27	0.36	**0.07**	0.25	0.27	0.39	**0.25**

Table 6.6b (cont.). Actual and modelled percentage frequencies of minimum temperatures more than 3 standard deviations from the mean

A – actual value; B – single Gaussian distribution; C – three-parameter gamma distribution; D – compound Gaussian distribution

Table 6.6b (cont.). Actual and modelled percentage frequencies of minimum temperatures more than 3 standard deviations from the mean

A – actual value; B – single Gaussian distribution; C – three-parameter gamma distribution; D – compound Gaussian distribution

Station number	Station name	Summer (Dec-Feb)				Autumn (Mar-May)				Winter (Jun-Aug)				Spring (Sep-Nov)			
		A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
85072	Sale	0.04	0.27	0.39	**0.11**	0.09	0.27	0.35	**0.09**	0.22	**0.27**	0.47	0.43	0.15	0.27	0.36	**0.11**
85096	Wilsons Prom.	1.13	0.27	0.45	**0.89**	0.66	0.27	0.38	**0.59**	1.06	0.27	0.47	**1.19**	1.27	0.27	0.53	**1.46**
86071	Melbourne RO	0.80	0.27	0.59	**0.77**	0.21	0.27	0.37	**0.26**	0.05	0.27	0.36	**0.15**	0.58	0.27	0.53	**0.57**
87031	Laverton	0.64	0.27	0.42	**0.52**	0.02	0.27	0.40	**0.10**	0.06	0.27	0.35	**0.05**	0.37	**0.27**	0.43	0.10
90015	Cape Otway	0.99	0.27	0.62	**0.90**	0.62	0.27	0.46	**0.57**	0.42	0.27	**0.43**	0.39	1.14	0.27	0.66	**1.19**
91057	Low Head	0.50	0.27	**0.41**	0.60	0.08	0.27	0.38	**0.09**	0.00	0.27	0.38	**0.02**	0.06	0.27	0.48	**0.22**
91104	Launceston AP	0.04	0.27	0.35	**0.08**	0.00	0.27	0.37	**0.07**	0.00	0.27	0.38	**0.09**	0.02	0.27	0.41	**0.09**
92045	Eddystone Point	0.33	0.27	0.57	**0.34**	0.03	0.27	0.41	**0.09**	0.06	0.27	0.34	**0.13**	0.21	0.27	0.44	**0.25**
94010	Cape Bruny	0.72	0.27	0.41	**0.53**	0.49	0.27	0.40	**0.54**	0.28	**0.27**	0.38	0.25	0.54	0.27	**0.38**	**0.38**
94029	Hobart RO	0.60	0.27	0.48	**0.51**	0.18	0.27	0.39	**0.18**	0.21	**0.27**	0.38	**0.15**	0.39	0.27	**0.39**	0.29
94069	Grove	0.30	**0.27**	0.39	0.22	0.16	0.27	0.39	**0.10**	0.30	**0.27**	0.45	0.21	0.14	0.27	0.37	**0.13**
96003	Butlers Gorge	0.29	**0.27**	0.42	0.39	0.12	0.27	0.40	**0.11**	0.12	0.27	0.38	**0.14**	0.25	**0.27**	0.38	0.28

Season	Maximum temperature extreme frequency simulated best by procedure: (%)			Minimum temperature extreme frequency simulated best by procedure: (%)		
	Single Gaussian	Gamma	Compound Gaussian	Single Gaussian	Gamma	Compound Gaussian
Spring	10	13	77	18	13	69
Summer	11	15	74	26	14	60
Autumn	12	14	74	14	9	77
Winter	11	20	69	19	8	73
Annual	11	15	74	19	11	70

Table 6.7. Summary of effectiveness of model distributions in simulating frequencies of temperatures more than 3 standard deviations from the mean

The results for maxima are similar to those from the goodness-of-fit tests, with the three-parameter gamma distribution performing better than the single Gaussian distribution, but less well than the compound Gaussian distribution. For minima, however, the three-parameter gamma distribution performs less well, on both measures used, than the single Gaussian distribution. Of particular interest in this context is the fact that, by definition, the gamma distribution is unimodal and skewed in one direction, and hence has a tendency to a low frequency of extremes at one end (relative to the single Gaussian distribution) and a high frequency at the other end. We have already seen in section 6.2.2.2 that some actual distributions in Australia (particularly those of winter minima in inland eastern Australia) have a low frequency of extremes at both ends of the distribution. The gamma distribution does not have the flexibility to accurately simulate such a distribution.

6.4.3. Conclusion

A detailed comparison of three models for the frequency distribution of daily maximum and minimum temperatures in Australia has established that the compound Gaussian distribution is the most effective, particularly with respect to the frequency of extreme high and low temperatures. The 'binormal' model of Toth and Szentimrey (1990) was not evaluated in detail, but the results they obtained for Budapest suggest that it is unlikely that it would perform better than the compound Gaussian model.

Accordingly, this distribution has been chosen for use in the further analysis of trends in the frequency of extreme temperatures in Australia, as described in Chapter 7.

6.5. Consequences of the compound Gaussian distribution

6.5.1. Physical considerations in the use of the distribution

It has long been postulated by some authors (e.g. Essenwanger, 1954, Bryson, 1966, Grace et al., 1991, Grace and Curran, 1993) that the frequency distribution of daily temperatures can be considered as the combination of a number of Gaussian distributions, each of them associated with a particular air mass.

Bryson, in particular, analysed the situation in some detail for Canada and the United States. He approached the problem from two directions; first finding the frequency of air-mass occurrence at each station by means of analysing the backward trajectories to find the source of the air at each station on each day, then decomposing the observed frequency distribution of daily maximum temperature at each station into four Gaussian sub-distributions and associating each of these sub-distributions with an air mass, by assuming that an air mass was found most frequently near its source region. He found that the weights of the sub-distributions of July maximum temperature at the stations he examined corresponded reasonably well with the air-mass frequencies found by trajectory analysis.

Bryson also found that interannual variability, as defined by changes in July mean maximum temperatures at Madison, Wisconsin, could be more readily explained by changes in the weights of the sub-distributions (implying a change in the relative frequency of air masses) than it could by changes in the mean or standard deviation of the sub-distributions. Similar findings were made in the case of the very cool January 1992 at Adelaide and Melbourne by Curran and Grace (1992), although they did not extend this study to a longer-term consideration of anomalously warm and cool months.

The relationship of sub-distributions with air masses is an intuitively attractive one (in particular, the maritime/continental split postulated by Grace et al. (1991)). Establishing it in an objective manner over all of Australia is much more difficult and would require an analysis of air mass origins (through synoptic analysis) that is too large to be within the scope of this thesis. Such air mass analyses have been carried out for other locations, for example the German 'Grosswetterlage' (Gerstengarbe et al., 1993) and the Lamb synoptic types for Britain (Lamb, 1950; Perry and Mayes, 1998), and for specific Australian sites over short periods (Thompson, 1973a) and an analysis of the frequency distributions of daily temperatures associated with those air mass classifications would be of considerable interest. The situation for Australia is further complicated by the fact that the temperature regime at a number of coastal sites is strongly influenced by mesoscale phenomena (for example, sea breezes) that may not necessarily correspond to the air mass that might be identified by a broader synoptic analysis.

As an example, an attempt was made to decompose the frequency of January maximum temperatures at Perth Airport into maritime and continental components, defining air of continental origin (which, at Perth, tends to be associated with a substantial surface synoptic-scale flow from the NE quadrant) using the following criteria:

- Mean sea-level pressure at 1500 at Perth Airport less than that at Southern Cross;
- Mean sea-level pressure at 1500 at Perth Airport greater than that at Geraldton;
- Daily rainfall at Perth Airport less than 2 mm.

The first two criteria define a north-easterly flow; the third excludes the (rare) situations where a north-easterly flow occurs in association with a low-pressure system (often a decaying tropical cyclone) and the air is effectively maritime air being recirculated over land.

The results of this analysis are shown in Fig. 6.5. The criteria appear to define a particular air mass fairly well, as they isolate a component which is associated with an approximately Gaussian frequency distribution of maximum temperature (no departure from normality at the 5% level was detected on any of the tests described earlier in this chapter). The remaining temperature observations, however, do not have a Gaussian distribution (departing from normality at the 1% level on all five tests), suggesting that, if one were to identify air masses with Gaussian distributions, more than the two or three distributions used earlier would be required. (This is consistent with the results obtained by Bryson, who used up to eight sub-distributions to model North American data).

In a study of this size working with more than three sub-distributions would rapidly become computationally unmanageable, and hence attempting to verify an association of the sub-distributions with air masses in Australia will not be pursued further here. Nevertheless, if one accepts the concept that the sub-distributions are associated with specific air masses, it has consequences for the way in which the frequency distribution of temperature might be expected to change with changes in the climate. In particular, it would be expected that, if warming occurs associated with the enhanced greenhouse effect, that there would be an increase in the mean of each sub-distribution (and possibly changes in the standard deviation and weighting as well, depending on whether synoptic changes occur), although that increase would not necessarily be the same for all sub-distributions – for example, Brinkmann (1993) found that different air masses would be expected to change in temperature by different amounts. On the other hand, the findings of Bryson (1966) and Curran and Grace (1992) suggest that abnormally warm months in the *present* climate are characterised by changes in the weights of the sub-distributions, rather than in their means.

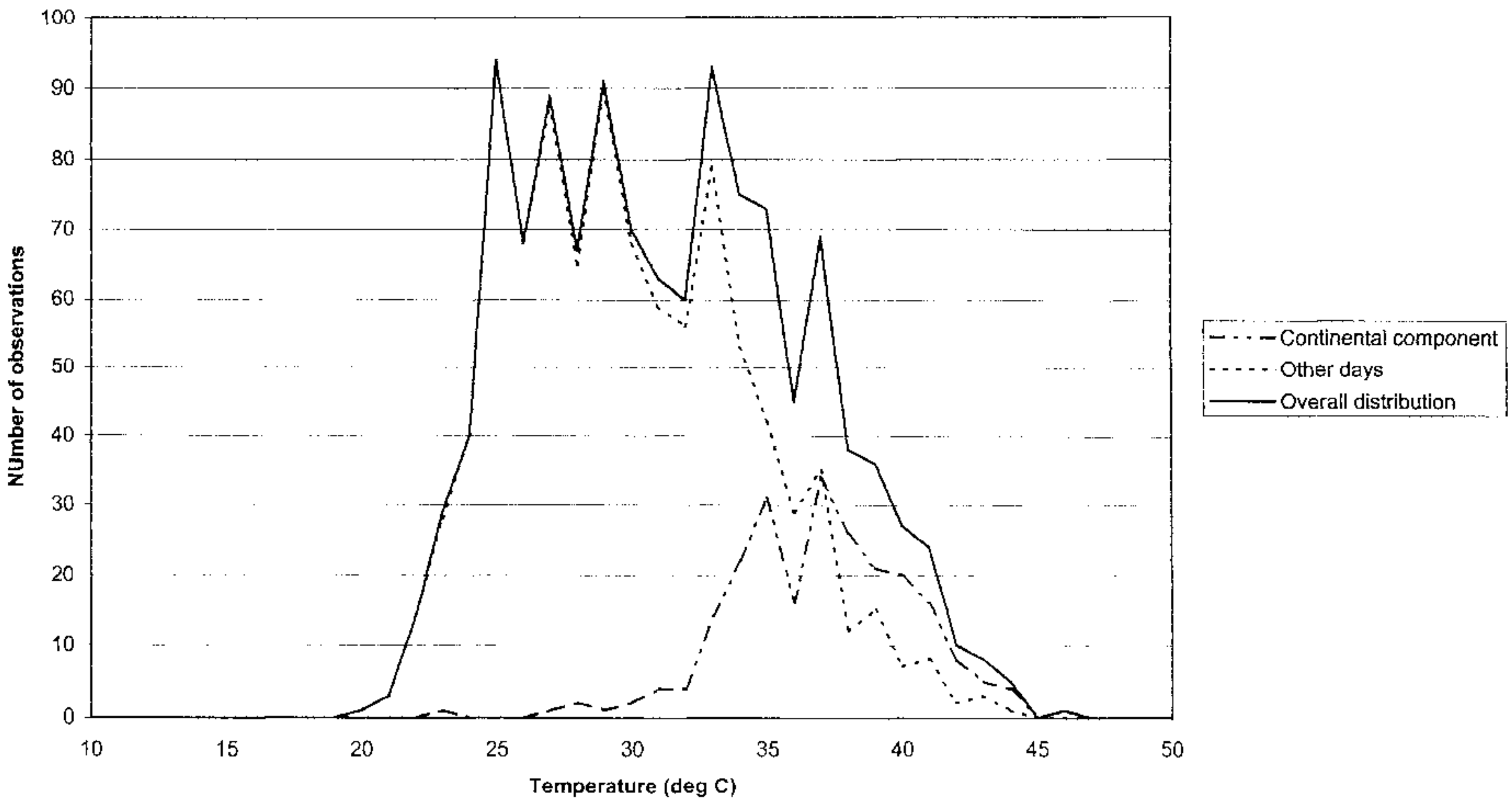
Accordingly, using abnormally warm months in the present climate as a surrogate for normal months in a warmer climate is an approach which should be used with caution. This approach is followed by Balling et al. (1990) who analyse changes in the frequency of extreme high maxima at Phoenix, Arizona.

6.5.2. The generation of artificial temperature series

A technique commonly used (e.g. Mearns et al., 1984) for estimating the impact of changes in the mean, standard deviation or autocorrelation of daily temperature on the frequency of various extreme indices (such as the frequency of threshold events or the frequency of occurrence of a number of consecutive days above or below a threshold) is to generate a synthetic temperature series, using a first-order autoregressive (AR(1)) model. This is based on the assumption that the conditional probability distribution of the temperature anomaly on the *t*-th day of a time series, $X(t)$, depends only on the temperature anomaly on the previous day, $X(t-1)$. This allows a synthetic time series to be constructed using the algorithm:

$$X(t) = \varphi X(t-1) + \varepsilon$$

Fig. 6.5. Decomposition of frequency distribution of January daily maximum temperatures at Perth Airport into air-mass linked sub-distributions



where φ is the first-order autocorrelation coefficient of the series $X(t)$ and ε is a random variable (adding 'white noise' to the process).

Mearns et al. (1984) use a normally distributed ε, which has a consequence of generating a normally distributed time series $X(t)$. (More generally, it is trivial to prove, by substituting $-X$ for X, that any symmetric distribution of ε will generate a symmetric distribution for $X(t)$)..

As we have seen earlier in this chapter, the assumption that daily maximum and minimum temperatures are normally distributed cannot be sustained in the Australian context. An obvious way around this difficulty (and one commonly found in the statistical literature) is to apply a transformation of some kind to the data to produce a normally distributed time series. Whilst this may be technically feasible, the concept of relating multiple sub-distributions to different air masses suggests that, in a statistical sense, the data may be drawn from multiple populations, raising into question the validity of the transformation approach.

A possible approach could be to have two processes; one to synthesise the appropriate sub-distribution which the day falls into, and then a second to generate a temperature based on this information. The generation of synthetic precipitation series is widely done in this way (Bruhn et al., 1980; Hutchinson, 1986; Wilks: 1992, 1999), using two separate models: one to generate a sequence of days with precipitation or no precipitation, and a second to generate the amount of precipitation on the wet days. This is a potentially interesting line of inquiry but has not been pursued further in this thesis.

6.5.3. Changes in extremes arising from changes in distribution parameters

Katz and Brown (1992) discuss, in detail, the relative impact of changes in the mean of a Gaussian distribution and changes in its variance on the expected frequency of extremes. They conclude that changes in the expected frequency of occurrences of temperatures above (or below) a given threshold becomes relatively more dependent on changes in the variance, and less dependent on changes in the mean, as the threshold of interest becomes more extreme. Neild et al. (1979) also found that changes in the occurrence of a critical event for agriculture (the length of the freeze-free season) was far more sensitive to changes in temperature variability than changes in the mean.

Their work is based on the assumption that daily temperatures are adequately represented by a single Gaussian distribution. It is therefore appropriate to generalise their results to the compound Gaussian distribution.

Following their definition, let us define the sensitivity of the probability of a threshold event, *P(T)*, to changes in a parameter, a, as the partial derivative of the probability with respect to a:

$$\frac{\partial P(T)}{\partial a} \tag{6.1}$$

where *P(T)* is the probability of a temperature above a threshold T (if high extremes are being considered) or below a threshold T (if low extremes are being considered).

Furthermore, we define the relative sensitivity as:

$$\frac{\left(\frac{\partial P(T)}{\partial a}\right)}{P(T)} \tag{6.2}$$

Katz and Brown show that, where μ is a location parameter and σ is a scale parameter of a distribution (in the specific case of the Gaussian distribution, the location and scale parameters are the mean and standard deviation respectively), the following relationship of the sensitivities will hold, independently of the form of the distribution:

$$\frac{\left(\frac{\partial P(T)}{\partial \sigma}\right)}{\left(\frac{\partial P(T)}{\partial \mu}\right)} = \frac{T-\mu}{\sigma} \tag{6.3}$$

Taking μ and σ as fixed, it follows that the magnitude of this ratio will increase as the difference between T and μ increases, that is, as the event under consideration becomes more extreme (at either end of the scale). Katz and Brown found that this implies that the sensitivity of the frequency of an event to changes in the scale parameter, relative to its sensitivity to changes in the location parameter, will increase as the event becomes more extreme, indicating in turn that, as an event becomes more extreme, changes in the variability of temperature play an increasingly important role, and changes in the mean a less important role, in that event's expected frequency.

The use of the general concept of the location and scale parameter of a population is useful for the development of a general theory. The model for the frequency distribution of daily temperature being used in this study, however, is a mixture of multiple distributions, and is governed by either five (in the two-component case) or eight (in the three-component case) independent parameters. We therefore examine the sensitivity of *P(T)* to changes in each of these parameters (or a combination thereof).

First, let *N(z)* be the cumulative Gaussian distribution function with z as a standardised variable:

$$N(z) = \int_{\infty}^{z} \frac{1}{\sqrt{2\pi}} \exp(\frac{-z^2}{2})dx \qquad (6.4)$$

$$\text{with: } z = \frac{x-\mu}{\sigma} \qquad (6.5)$$

where x is a variable and μ and σ are the mean and standard deviation respectively of the Gaussian distribution N.

Furthermore, define:

$$n(z) = N'(z) = \frac{1}{\sqrt{2\pi}} \exp(\frac{-z^2}{2}) \qquad (6.6)$$

We may then define the cumulative distribution for the two-component compound Gaussian distribution as follows:

$$F(T) = w_1 N(\frac{T-\mu_1}{\sigma_1}) + (1-w_1) N(\frac{T-\mu_2}{\sigma_2}) \tag{6.7}$$

where the two components have weights w_1 and w_2, means μ_1 and μ_2 and standard deviations σ_1 and σ_2 respectively.

Using the result from equation 6.3, the following relationships, analogous to those found by Katz and Brown (1992) for a single distribution, follow from the definition in 6.7:

$$\frac{(\frac{\partial F}{\partial \sigma_1})}{(\frac{\partial F}{\partial \mu_1})} = \frac{T-\mu_1}{\sigma_1} \tag{6.8}$$

$$\frac{(\frac{\partial F}{\partial \sigma_2})}{(\frac{\partial F}{\partial \mu_2})} = \frac{T-\mu_2}{\sigma_2} \tag{6.9}$$

These results imply that the sensitivity of the frequency of a temperature above or below a given threshold becomes more sensitive to the variability of that component, relative to the mean, as the threshold departs further from the mean of the component.

The simplicity of these results depends on the fact that $n(z)$ (or $F'(z)$ in the more general results of Katz and Brown) cancels out. The absence of such a cancellation involving $\partial F/\partial w$ makes it more complex to examine the sensitivity of the frequency of temperatures above or below a threshold to changes in component weights. (The interpretation of the results is also clouded by the fact that the weights are dimensionless, whereas the means and standard deviations are measured using the same units).

We may still develop a relationship involving the weights in some cases. In parts of the composite distribution which are only substantially contributed to by one component (as is usually the case in the two tails of the distribution), and assuming that $\mu_1 \leq \mu_2$, then, for low T, we have:

$$F(T) \approx w_1 N(\frac{T-\mu_1}{\sigma_1}) \tag{6.10}$$

and for high T:

$$F(T) \approx w_1 + (1-w_1)N(\frac{T-\mu_2}{\sigma_2}) \tag{6.11}$$

Using the fact that $N(z) = 1 - N(-z)$, we then have for low T:

$$\frac{\partial F}{\partial w_1} \approx N(\frac{T-\mu_1}{\sigma_1}) \tag{6.12}$$

and for high T:

$$\frac{\partial F}{\partial w_1} \approx N(\frac{\mu_2 - T}{\sigma_2}) \tag{6.13}$$

Using this and the fact that $n(z) = n(-z)$, we may obtain the following relationships, for low T:

$$\frac{(\frac{\partial F}{\partial \mu_1})}{(\frac{\partial F}{\partial w_1})} = \frac{-1}{\sigma_1} \frac{n(\frac{T-\mu_1}{\sigma_1})}{N(\frac{T-\mu_1}{\sigma_1})} \tag{6.14}$$

$$\frac{(\frac{\partial F}{\partial \sigma_1})}{(\frac{\partial F}{\partial w_1})} = \frac{-(\mu_1 - T)}{(\sigma_1)^2} \frac{n(\frac{T-\mu_1}{\sigma_1})}{N(\frac{T-\mu_1}{\sigma_1})} \tag{6.15}$$

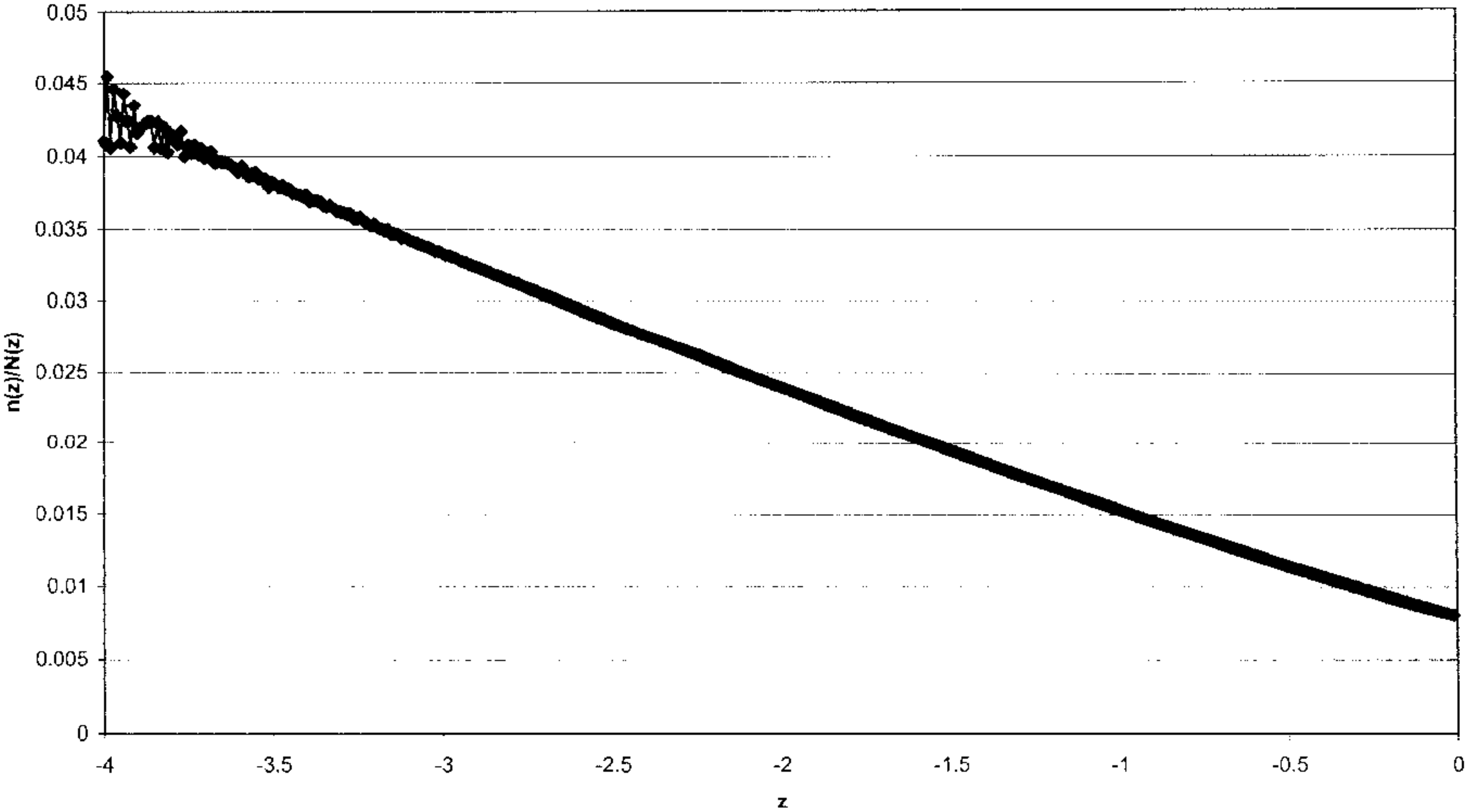
For high T we have:

$$\frac{(\frac{\partial F}{\partial \mu_2})}{(\frac{\partial F}{\partial w_1})} = \frac{-1}{\sigma_2} \frac{n(\frac{\mu_2 - T}{\sigma_2})}{N(\frac{\mu 2 - T}{\sigma_2})} \tag{6.16}$$

$$\frac{(\frac{\partial F}{\partial \sigma_2})}{(\frac{\partial F}{\partial w_1})} = \frac{-(\mu_2 - T)}{(\sigma_2)^2} \frac{n(\frac{\mu_2 - T}{\sigma_2})}{N(\frac{\mu_2 - T}{\sigma_2})} \tag{6.17}$$

Over the range $-4 < z < 0$, the ratio $n(z)/N(z)$ is approximately a linear function of z (Fig. 6.6), and hence of T (as z is a linear function of T). It hence follows that, as the departure of a threshold from a component mean increases, the sensitivity of the frequency of temperatures above or below that threshold to the weights decreases relative to the sensitivities to both the mean and standard deviation.

Fig. 6.6. n(z)/N(z), as defined in section 6.5



The following order of importance then follows as a threshold becomes more extreme:

1. Standard deviation
2. Mean
3. Component weight

in determining the frequency of temperatures above or below that threshold.

The generalisation to the three-component case is more complex, as the set of component weights w_1, w_2 and w_3 has two degrees of freedom, rather than one, and it is not possible to isolate a part of the overall distribution where the third component is dominant, as the distribution has only two tails. These two factors combine to prevent a generalisation of equations 6.10 to 6.17. The relationships of sensitivities to means and standard deviations shown in 6.8 and 6.9, however, do hold for a third component.

As a result of the difficulties in the theoretical treatment of the three-component case, the attempts to relate observed changes in extreme event frequency to changes in parameters of the distributions, described in Chapter 7, will concentrate on those stations and months where the frequency distribution has been shown to be adequately represented by two Gaussian components.

6.6. Summary

In this chapter, the compound Gaussian distribution has been developed as an appropriate frequency distribution for the representation of daily maximum and minimum temperatures. This model will be used further in Chapter 7, in order to assess changes over the 1957-96 period in the nature of the frequency distribution of daily maximum and minimum temperature, and to make conclusions from these changes concerning the potential attribution of such changes to physical causes.

Chapter 7

Observed Changes in the Frequency of Threshold Temperature Events at Australian Stations

7.1. Observed trends in frequency of threshold events at individual stations

7.1.1. Methods

Trends in the frequency of threshold events were considered in a number of ways. The following types of events were considered as possible threshold events for investigation:

(a) The frequency of temperatures above or below a percentile threshold

Events examined were the monthly frequency of daily maximum and minimum temperatures above the 90th and 95th percentiles, and below the 5th and 10th percentiles. In each case, the temperatures used were the deseasonalised anomalies as defined in Chapter 6.

The percentile thresholds were calculated separately for each of the 12 calendar months. As anomalies from a normal which varies seasonally, the absolute temperature corresponding to a given percentile threshold will vary through a month, particularly in spring and autumn.

(b) The frequency of temperatures above or below a fixed threshold

Events examined were the monthly frequency of daily maximum or minimum temperatures breaching the following thresholds:

- Maxima above 40, 35 and 30°C
- Minima above 20°C
- Maxima below 10 and 15°C
- Minima below 5, 2 and 0°C

In each case, the number of events per month was aggregated to generate four seasonal totals per year, for summer (December-February), autumn (March-May), winter (June-August) and spring (September-November). The number of events per season was then divided by the number of observations to generate the number of events per season as a proportion of all observations, in order to take missing observations into account.

Trends were calculated for each threshold and season over the 1957-96 period (although some stations were not open for the full period of record). At stations for which data are available prior to 1950, trends were also calculated for the full period of record at those stations.

In the case of fixed-threshold events, no trend was calculated if the event did not occur at least once in 20% of seasons, or if it occurred on every day in at least 20% of seasons. This prevents trends from being calculated if the event is rare or unknown at that station and season. (For example, at Thursday Island, where no temperature below 19.5°C has ever been observed between October and June, a trend in the frequency of summer or autumn minima above 20°C, or below 5° or 0°C, would obviously be meaningless).

Following the arguments of Nicholls (2001), it has not been considered appropriate to carry out significance testing on the trends, as the data from the 1957-1996 period are being viewed as a set of observations in itself and not as a sample from a larger statistical population. In any case, the magnitude of the observed trend is of greater importance than its statistical significance (Nicholls, 2001). As a benchmark, particular attention will be drawn in this section to trends exceeding 5 days/decade at the annual timescale. When the 10th and 90th percentile thresholds are being considered, an increasing trend of 5 days/decade represents an increase in frequency of 75% over the 1957-1996 period, whilst a similar decreasing trend represents a decrease in frequency of 43% over the same period.

As is discussed in more depth in Chapter 8, the percentile thresholds are most appropriate to any consideration of events on a national basis, as they occur with equal frequency over the long term at each station and in each season. A fixed threshold can also represent a different type of event at different stations: the frequency of winter maximum temperatures below 10°C is a indicator of extreme low maxima in many parts of Australia, but at the alpine site of Cabramurra it is an indicator of extreme high maxima (for the season).

It is, however, useful to consider fixed absolute thresholds at individual stations to which they are appropriate, not least because of the physical significance of some of the thresholds – for example, the importance of frost frequency in agriculture. Some discussion of the significance of such thresholds is worthwhile at this point. In some cases (such as frost) a specific threshold is critical. In other cases, while studies of the impacts of extreme events have focused on specific thresholds, these thresholds are themselves somewhat arbitrary choices. Australian examples of the impact of extreme high temperatures on crop yields and quality (e.g. Savin and Nicolas, 1999; Savin et al., 1996; Blumenthal et al., 1991) have found relationships between crop yield and quality and the occurrence of temperatures above a specific threshold, but in these cases the impact of high temperatures was gradual (i.e. there was a progressive change in yield with increasing temperature, rather than a sudden change at a specific threshold) and the choice of a specific threshold for analysis is somewhat arbitrary. Elsewhere, the impact of extreme high temperatures on wheat and corn yields in the United States has been the subject of much study (e.g. Mearns et al., 1991). However, Shaw (1983) 's discussion of climatic influences on corn yields suggests that the impact of temperature on yields is also one which changes gradually with an increase in the threshold used.

Current international research on indices of climate extremes (e.g. IPCC, 2001) uses a variety of thresholds (both fixed and non-fixed), many of which are also arbitrary in nature.

The major urban stations were included in this stage of the analysis. Whilst the observed trends from those stations cannot be taken as representative of broader climate change, the nature of the changes in the frequency of threshold exceedances and how they relate to changes in the frequency distribution are still of interest, whatever the underlying cause.

7.1.2. Results for the 1957-1996 period

The observed trends in the frequency of exceedances of high percentile thresholds are shown in Figs. 7.1a-h, and in Tables 7.1a-h. Those in the frequency of exceedances of fixed thresholds are shown in Figs. 7.2a-i, and in Tables 7.2a-i. All trends are shown in terms of days per decade, converting the proportion of threshold days to a number of days assuming a full set of observations for each season (and assuming a 28-day February).

The signs of the observed trends are summarised in Tables 7.3 and 7.4.

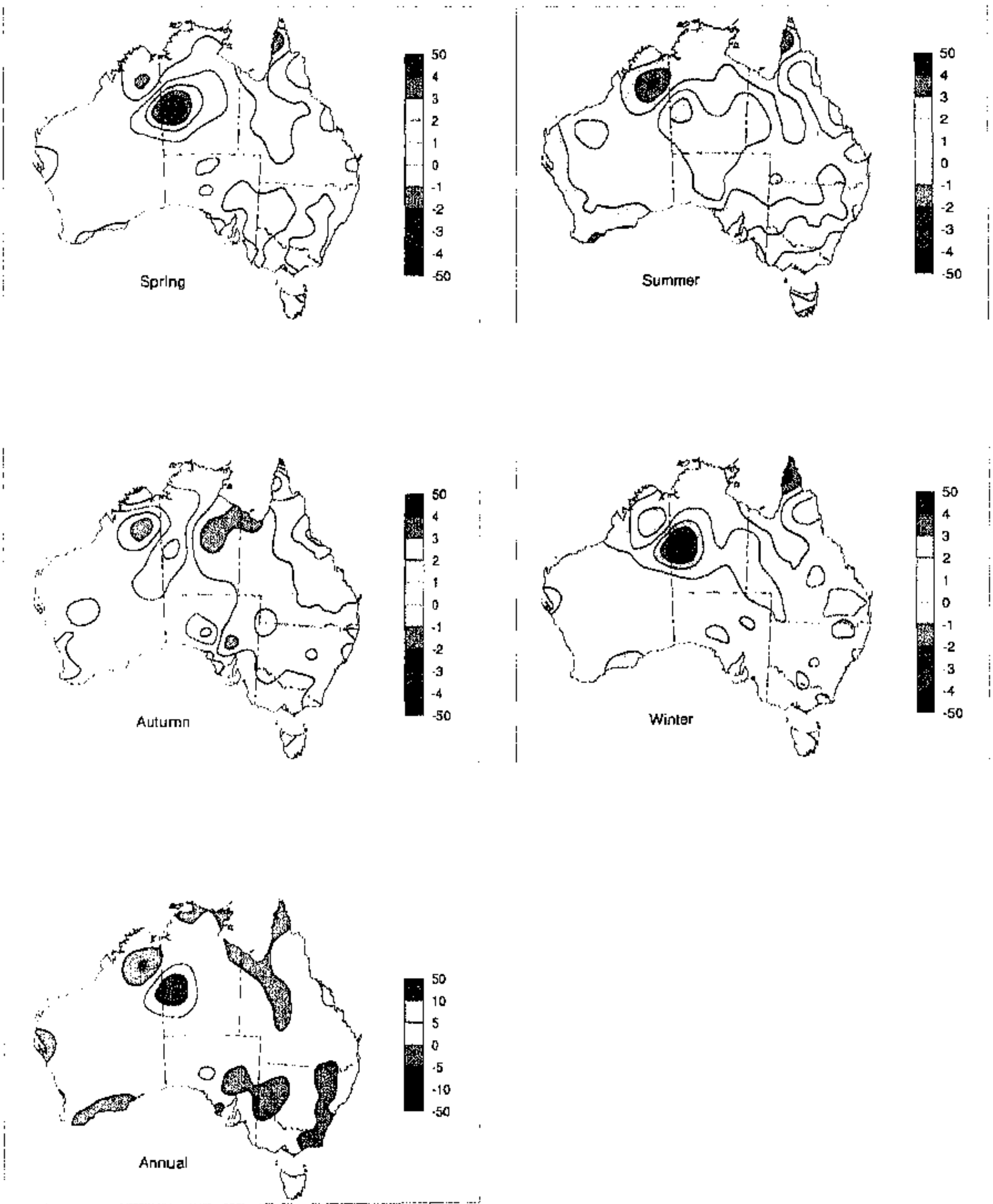


Fig. 7.1a. Trends, days/decade, in frequency of maxima above 95th percentile

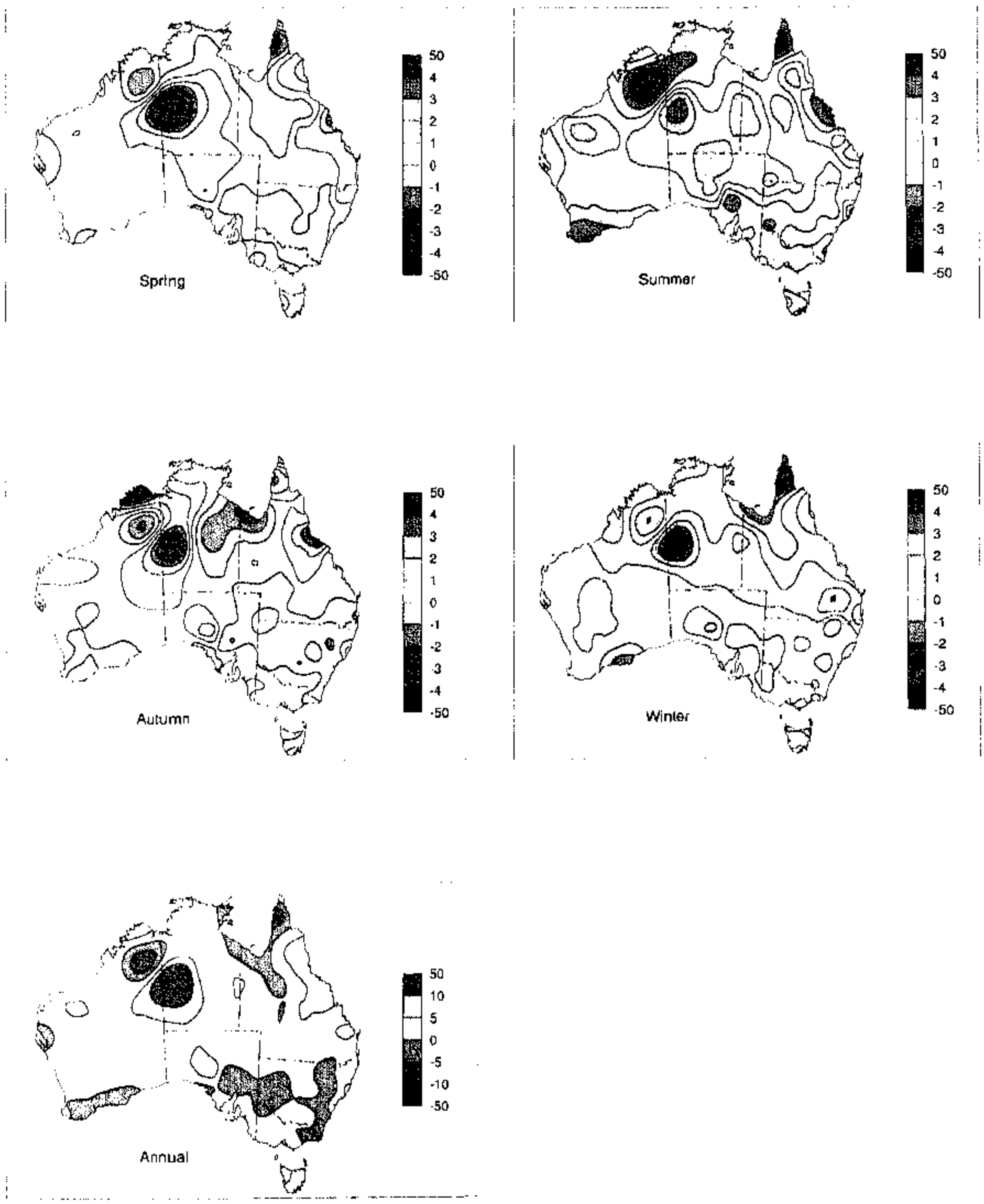


Fig. 7.1b. Trends, days/decade, in frequency of maxima above 90th percentile

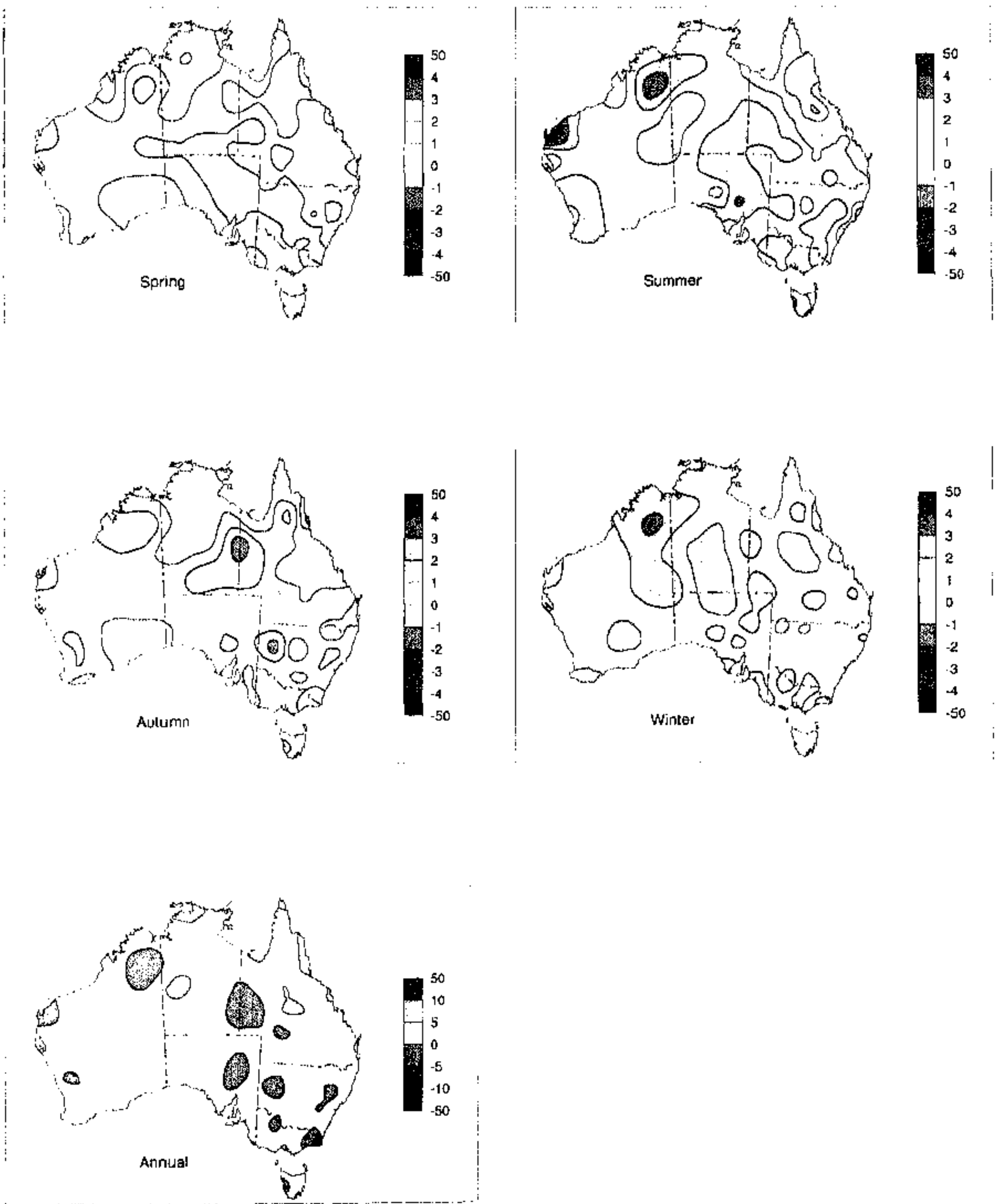


Fig. 7.1c. Trends, days/decade, in frequency of minima above 95th percentile

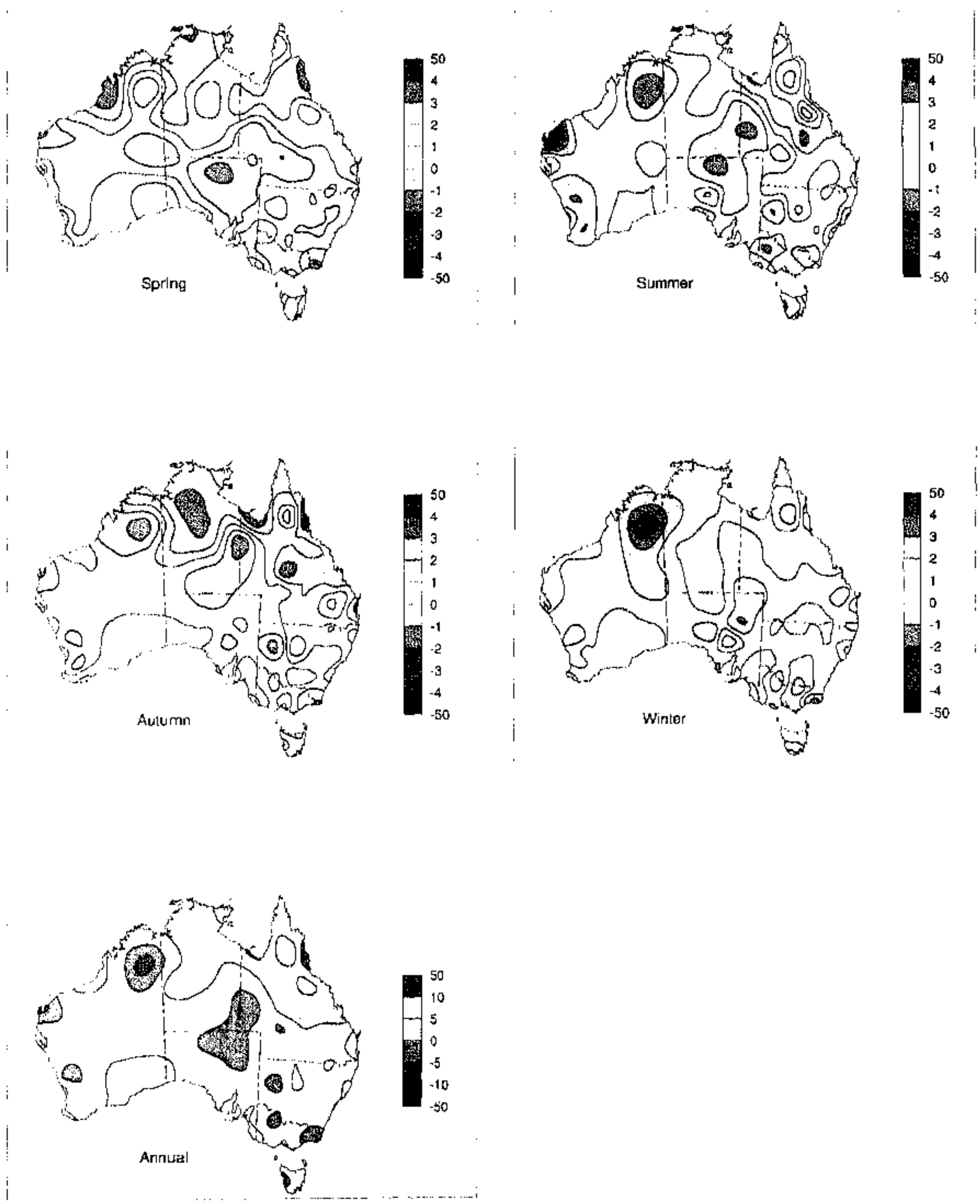


Fig. 7.1d. Trends, days/decade, in frequency of minima above 90th percentile

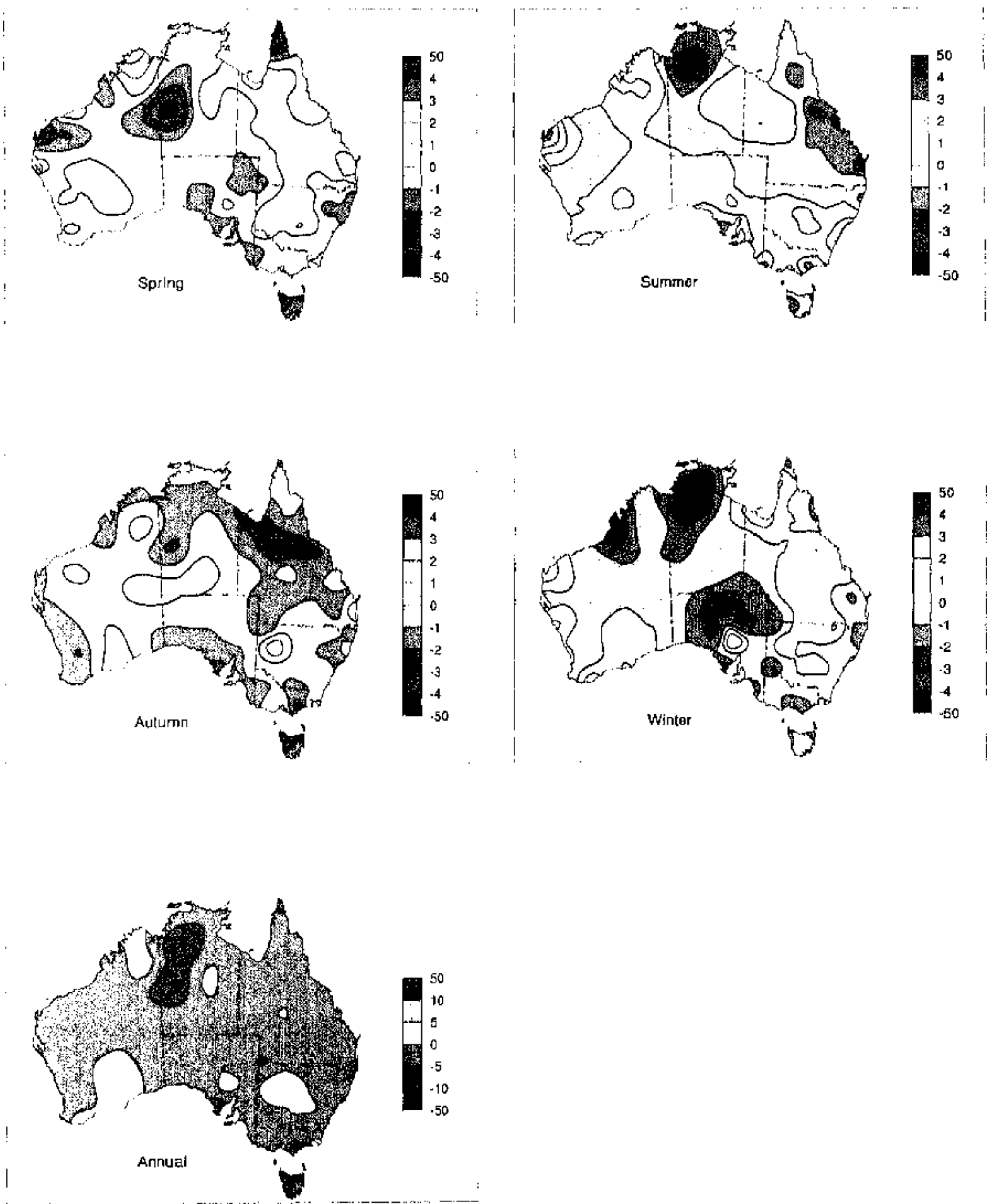


Fig. 7.1e. Trends, days/decade, in frequency of maxima below 10th percentile

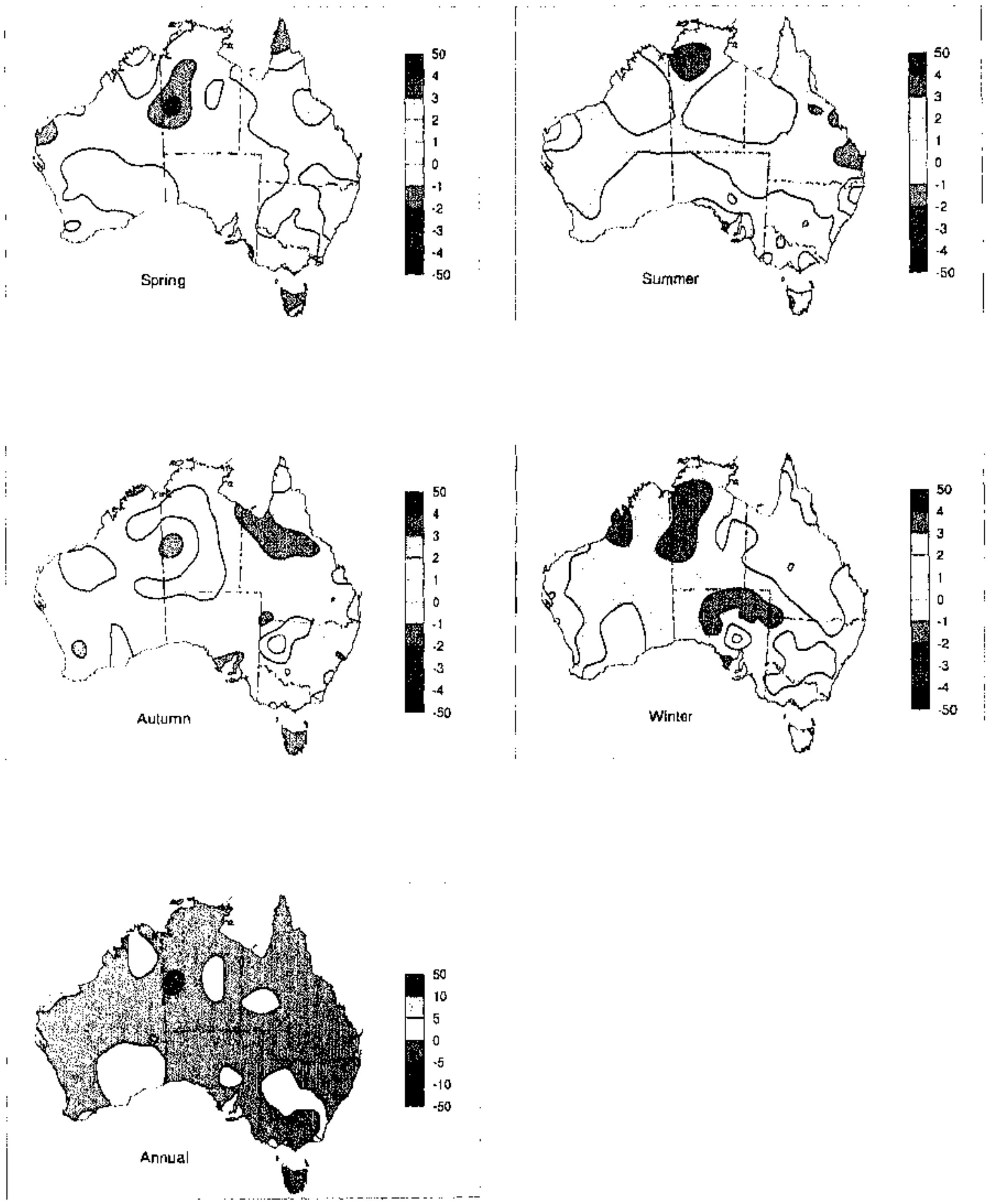


Fig. 7.1f. Trends, days/decade, in frequency of maxima below 5th percentile

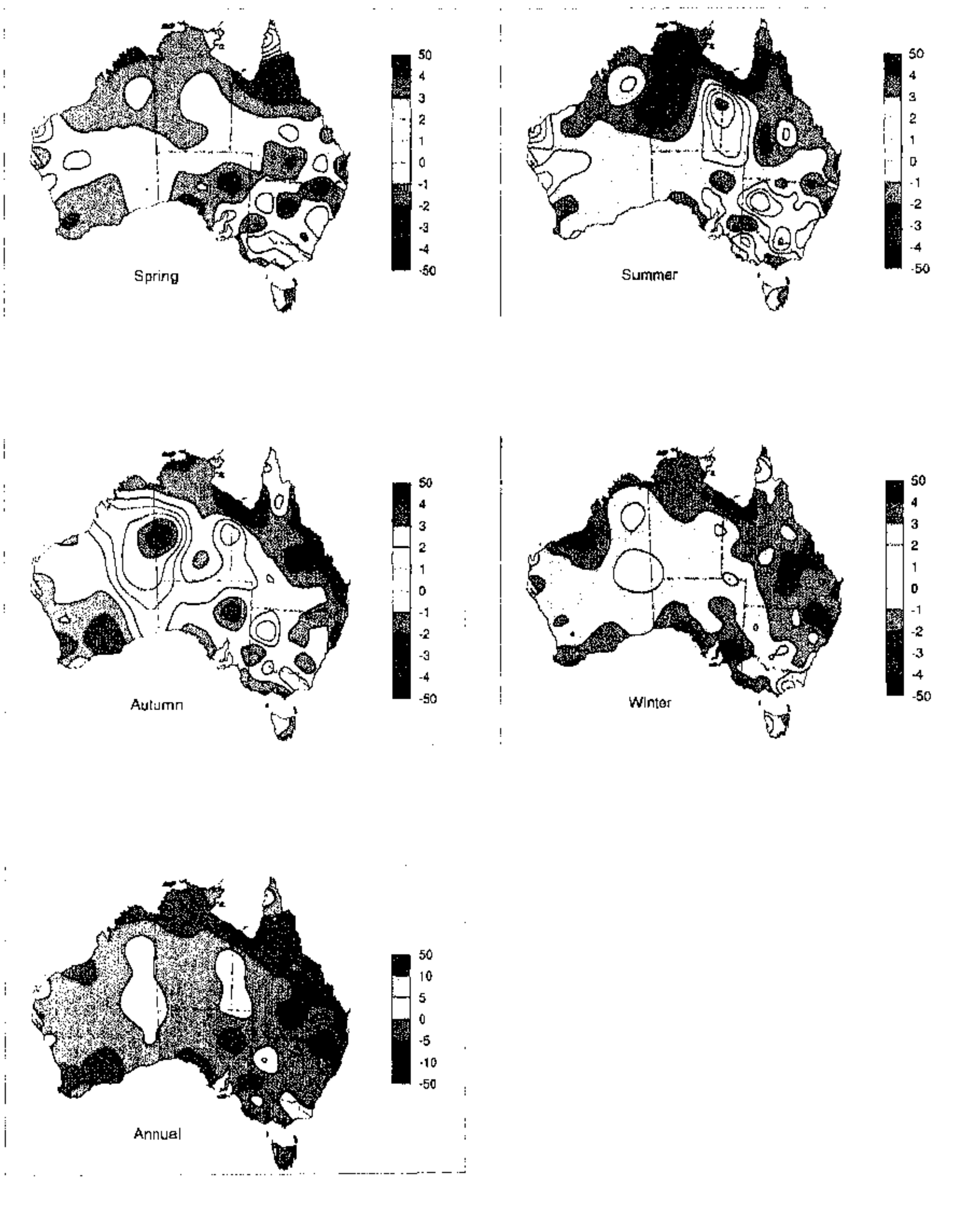


Fig. 7.1g. Trends, days/decade, in frequency of minima below 10th percentile

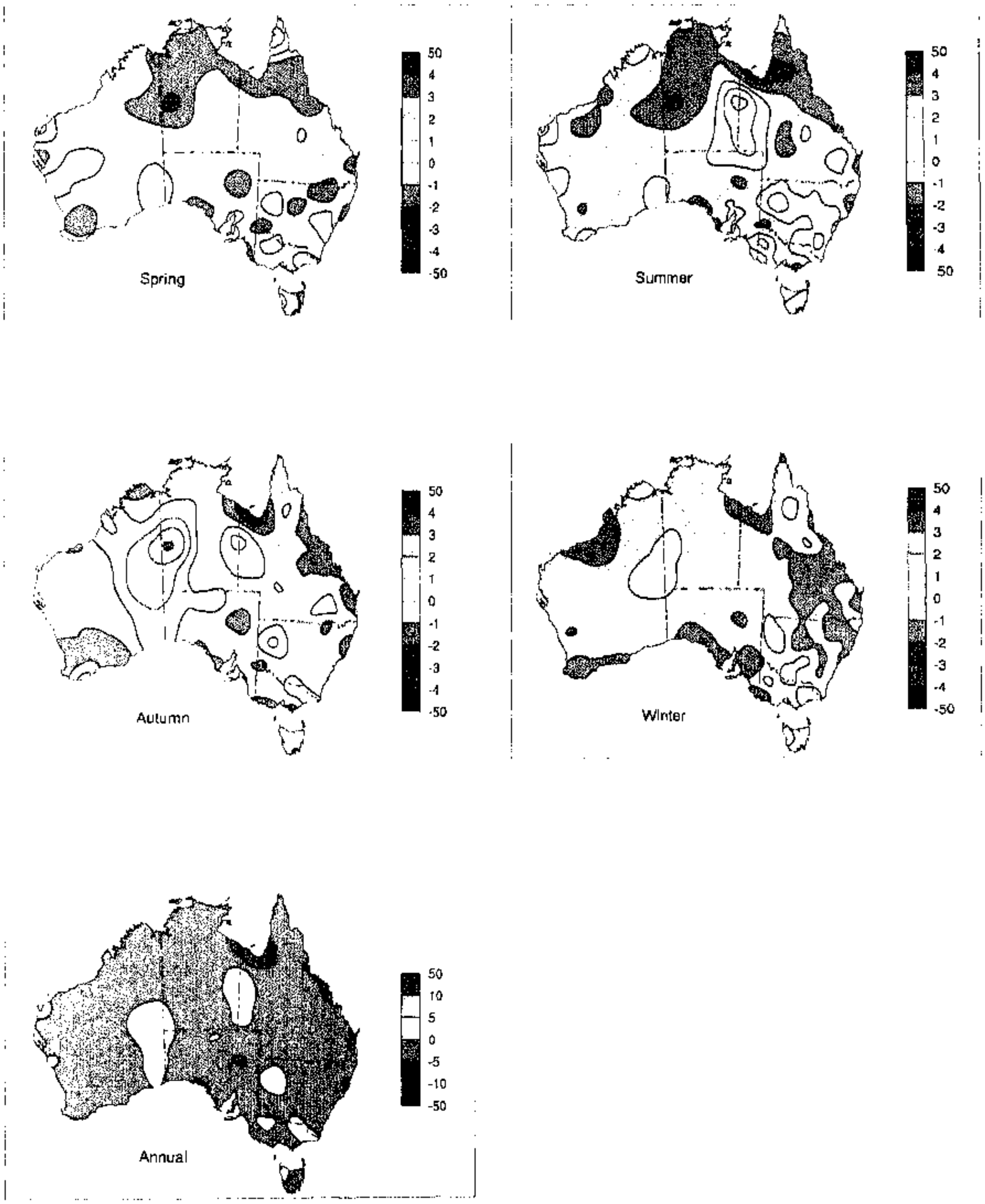


Fig. 7.1h. Trends, days/decade, in frequency of minima below 5th percentile

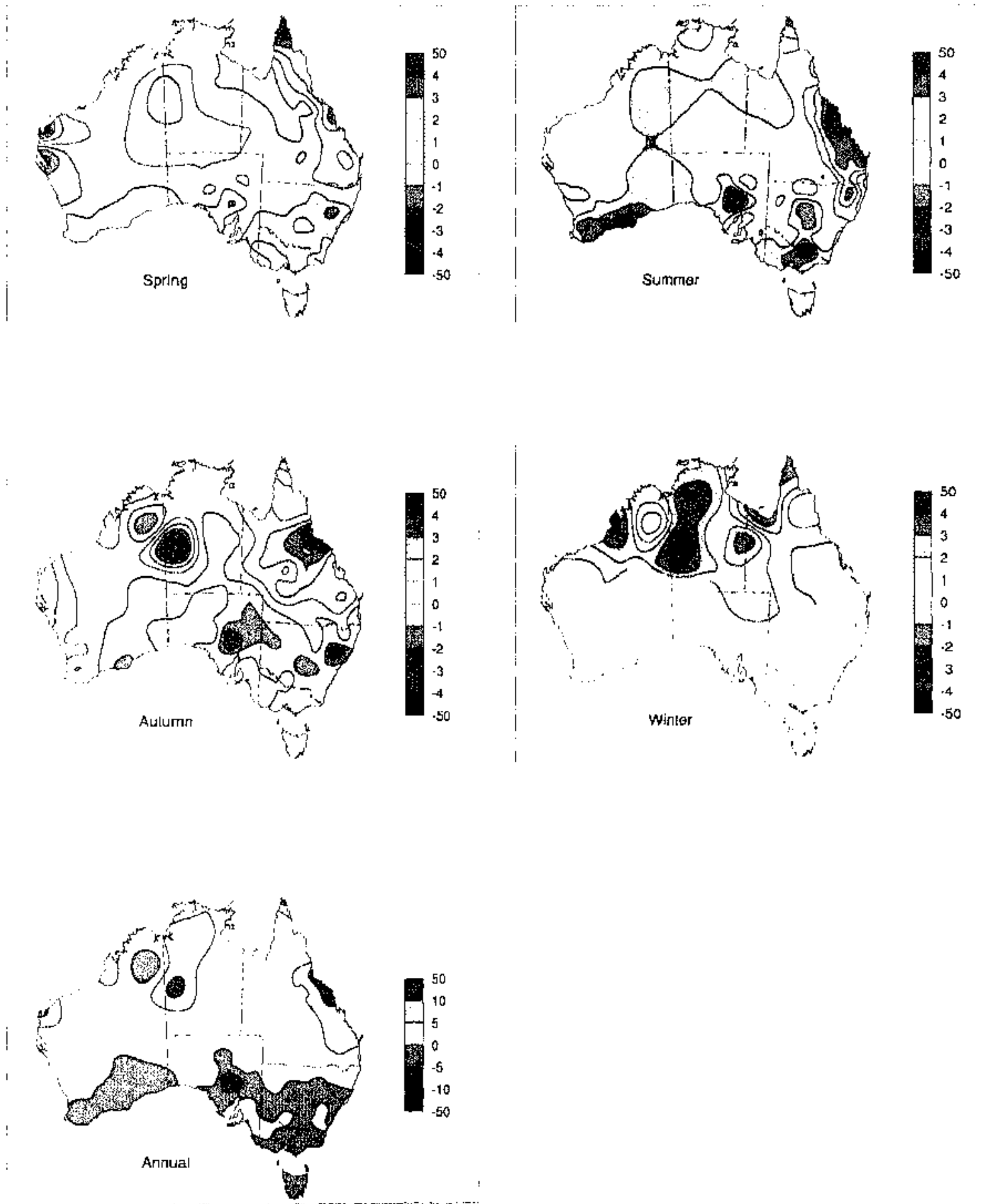


Fig. 7.2a. Trends, days/decade, in frequency of maxima above 30 degrees C

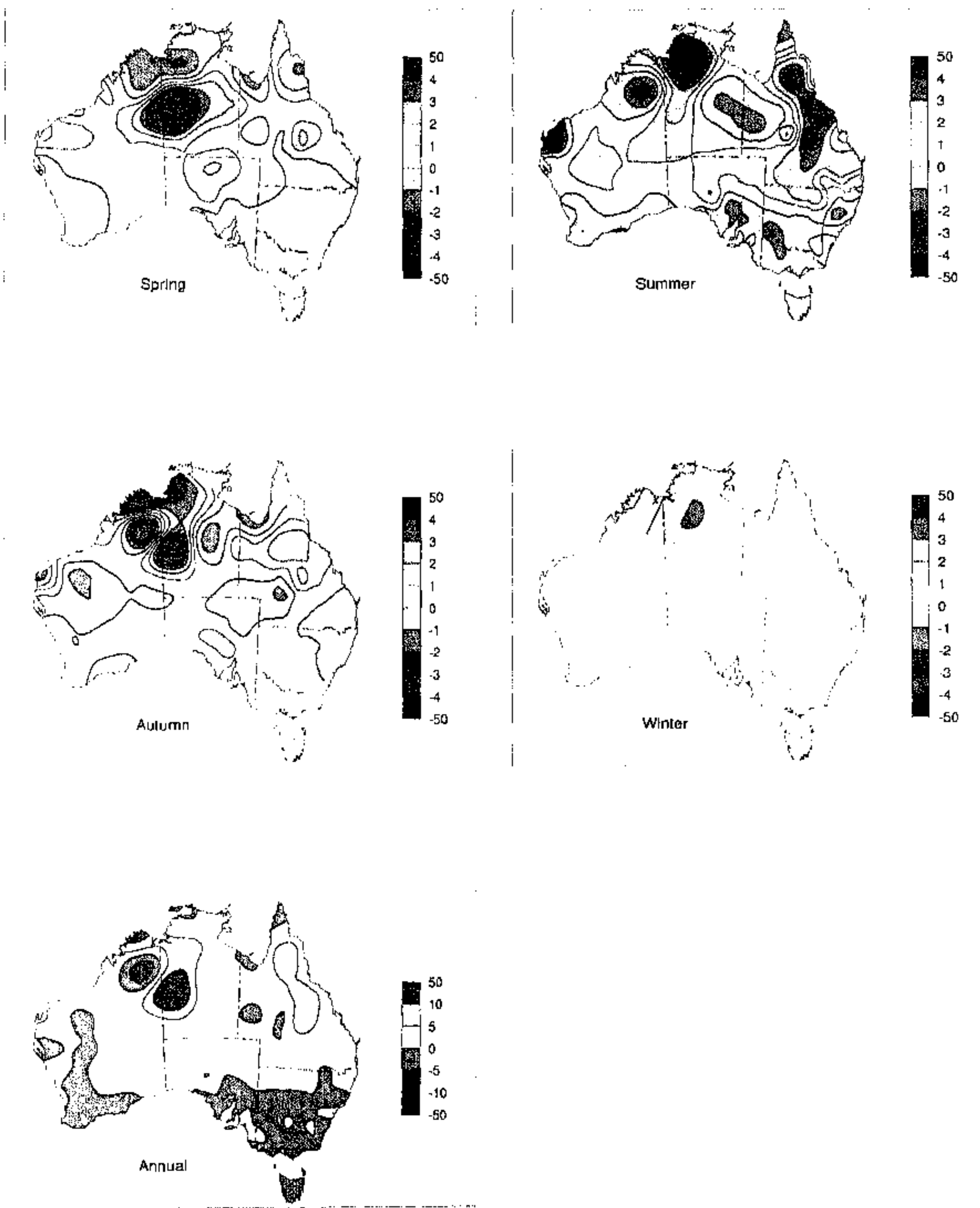


Fig. 7.2b. Trends, days/decade, in frequency of maxima above 35 degrees C

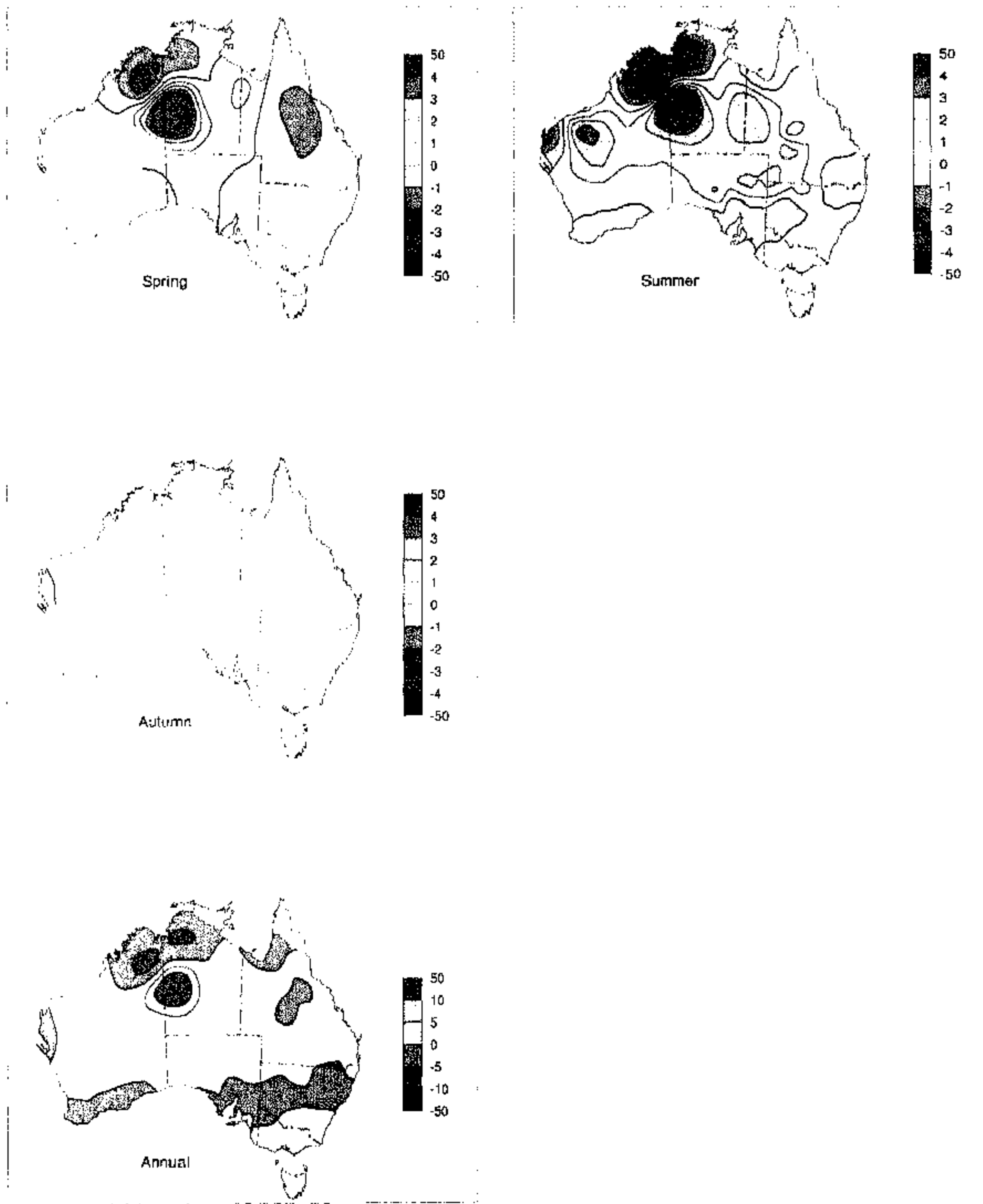


Fig. 7.2c. Trends, days/decade, in frequency of maxima above 40 degrees C

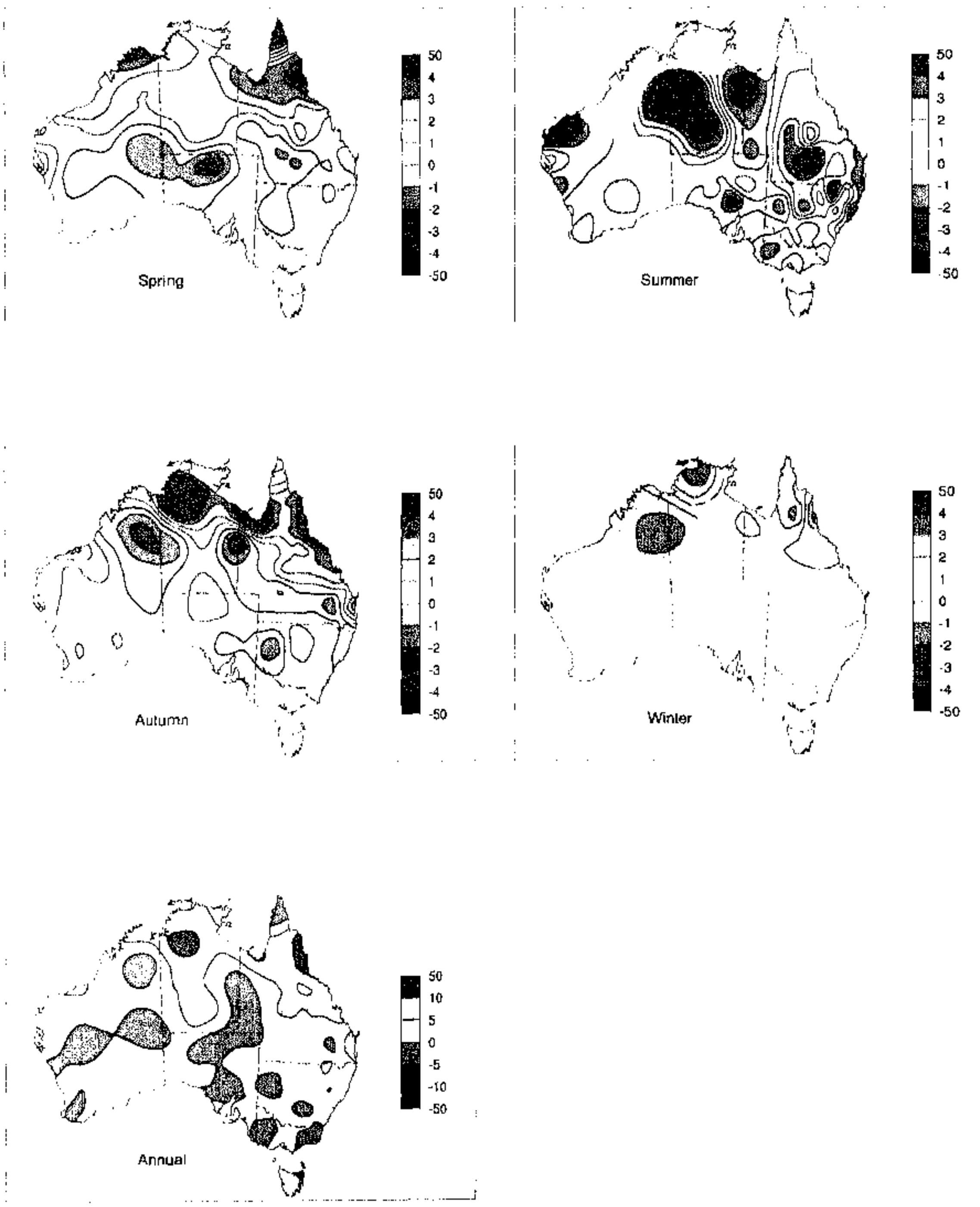


Fig. 7.2d. Trends, days/decade, in frequency of minima above 20 degrees C

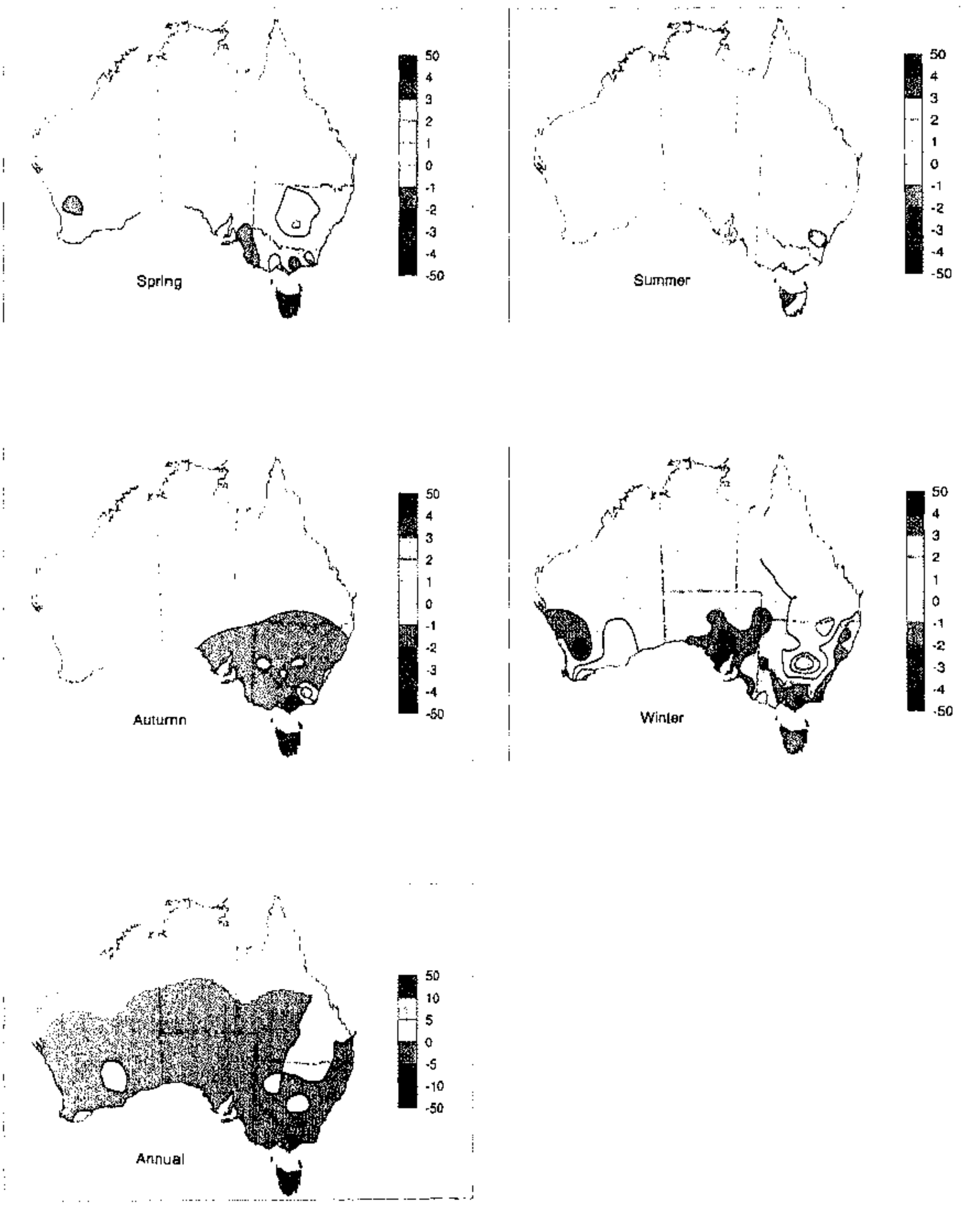


Fig. 7.2e. Trends, days/decade, in frequency of maxima below 15 degrees C

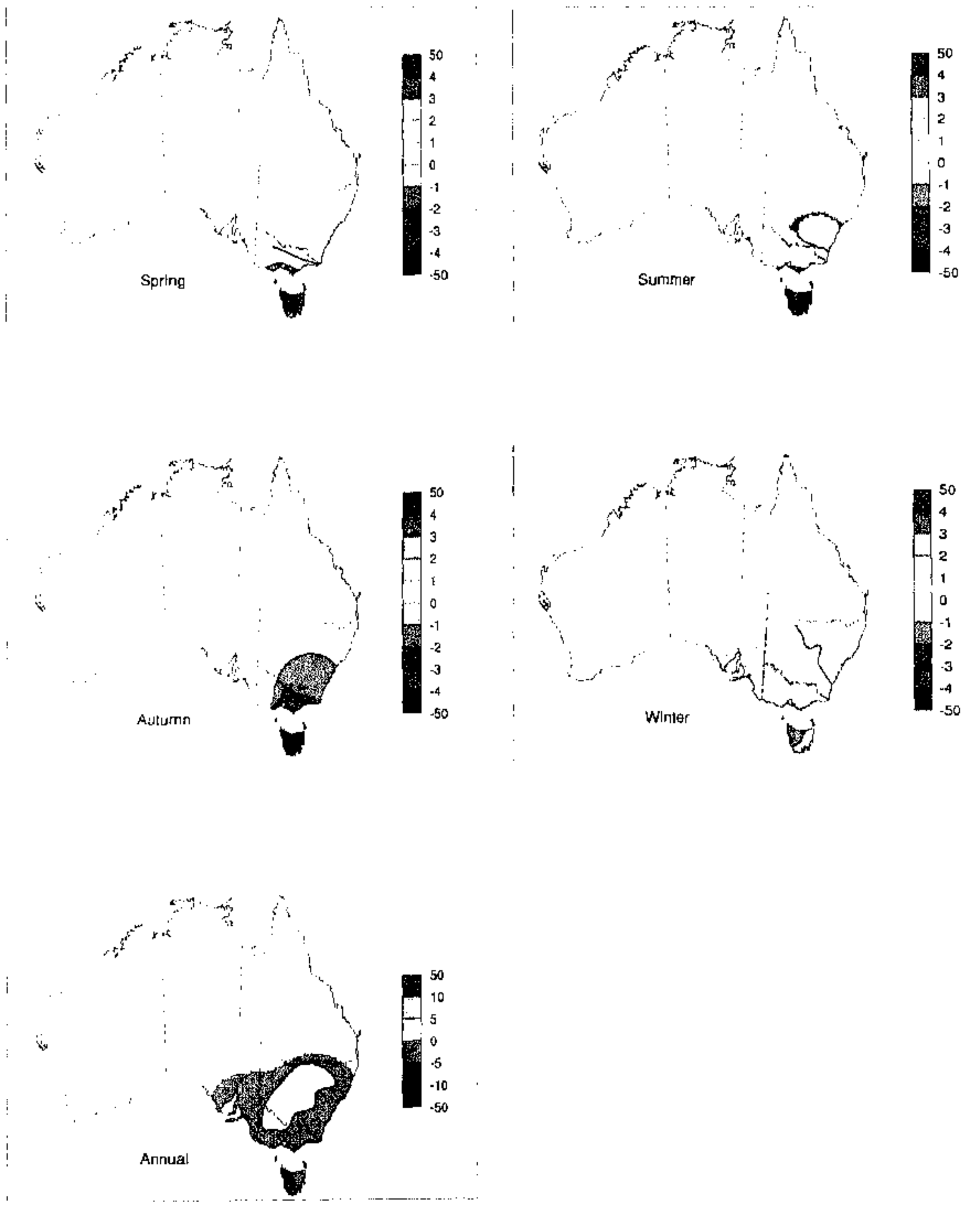


Fig. 7.2f. Trends, days/decade, in frequency of maxima below 10 degrees C

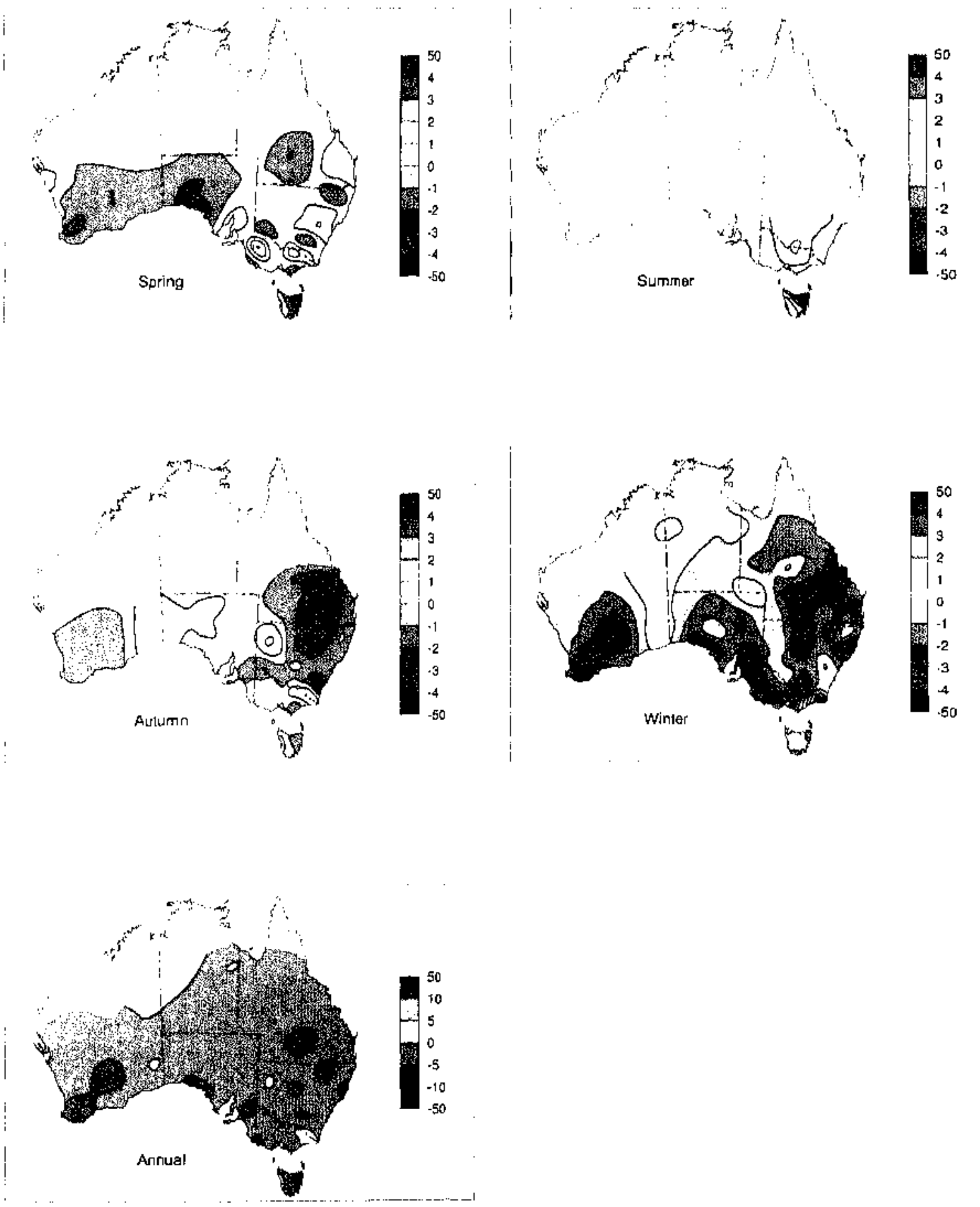


Fig. 7.2g. Trends, days/decade, in frequency of minima below 5 degrees C

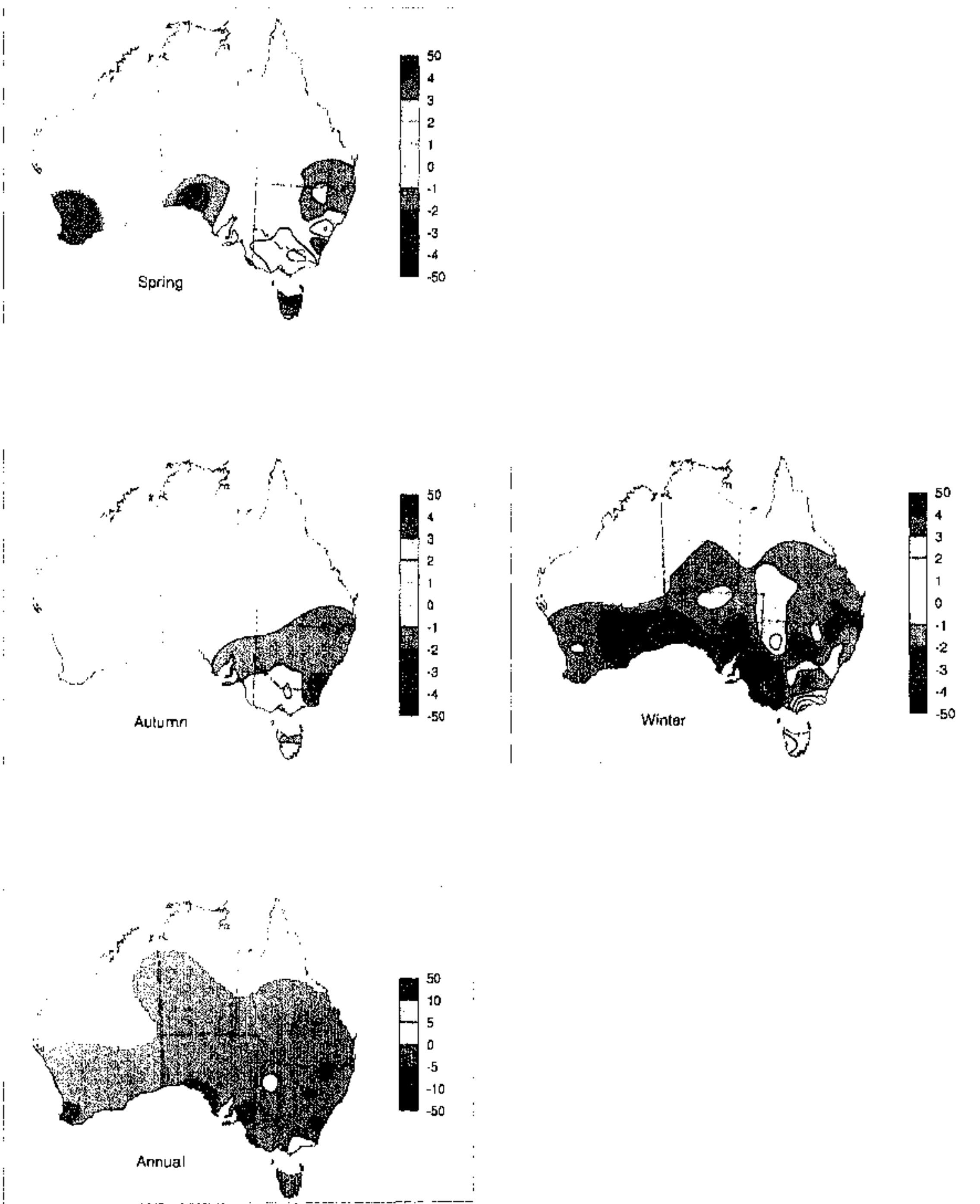


Fig. 7.2h. Trends, days/decade, in frequency of minima below 2 degrees C

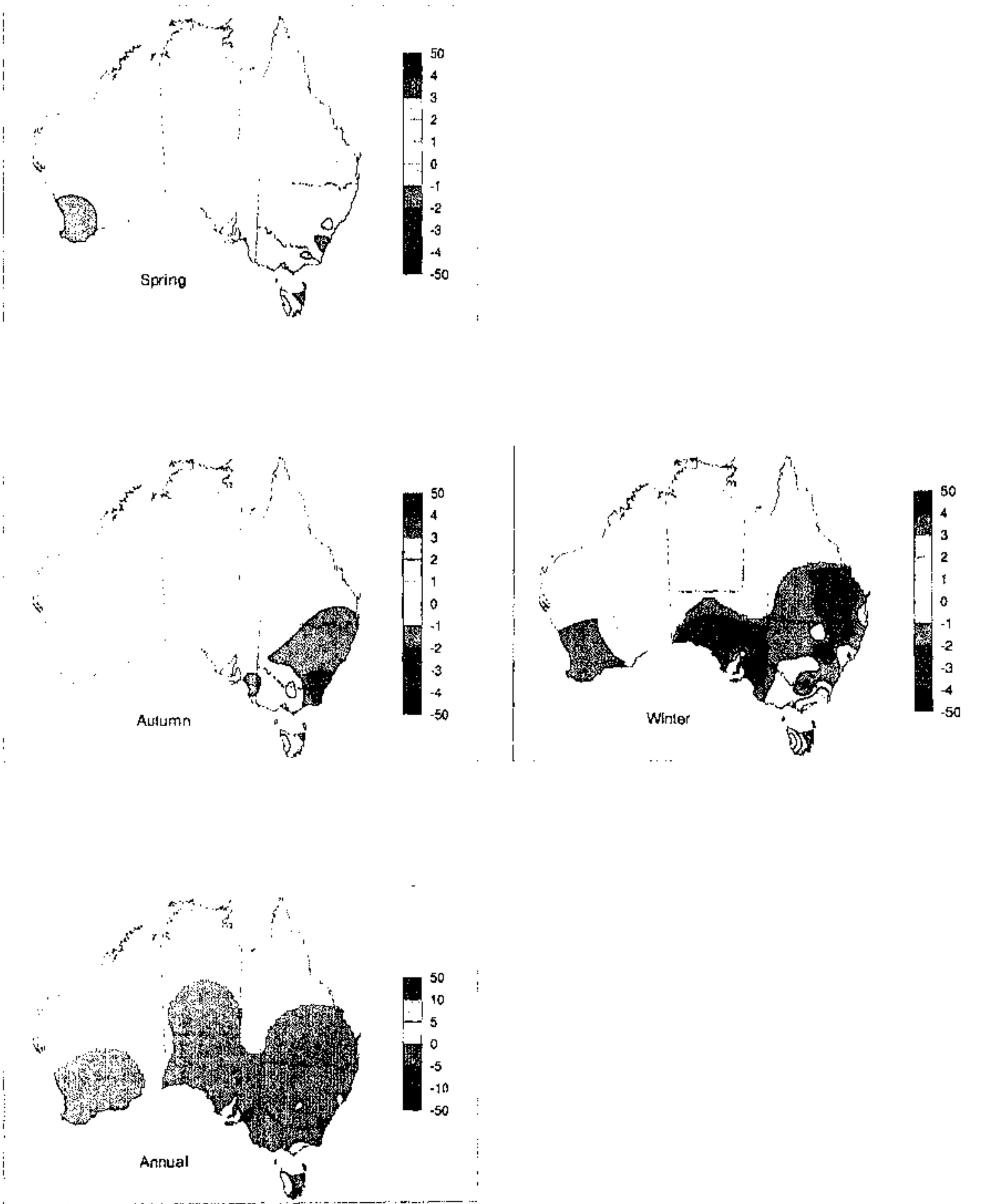


Fig. 7.2i. Trends, days/decade, in frequency of minima below 0 degrees C

Table 7.1a. Trends in frequency of maxima above 95th percentile, 1957-96

Station number	Station name	Trend (days/decade)				
		Spring	Summer	Autumn	Winter	Annual
1021	Kalumburu	-0.12	0.94	3.04	1.17	4.96
2012	Halls Creek	-0.72	-1.88	-1.25	-0.47	-4.11
3003	Broome	0.82	0.19	0.36	1.65	2.95
4032	Port Hedland	0.40	0.49	0.46	0.28	1.55
5007	Learmonth	0.70	-0.64	0.97	0.49	1.96
5026	Wittenoom	0.22	1.29	0.55	0.23	2.23
6011	Carnarvon	-0.37	-0.66	0.24	-0.18	-0.96
7045	Meekatharra	0.32	0.58	-0.06	0.51	1.27
8039	Dalwallinu	0.28	-0.10	-0.02	0.73	0.93
8051	Geraldton	0.11	-0.11	0.15	0.20	0.30
9021	Perth Airport	0.02	-0.12	-0.23	0.07	-0.38
9518	Cape Leeuwin	1.02	-0.06	0.00	0.18	1.24
9741	Albany	-0.25	-1.14	0.05	0.28	-1.15
9789	Esperance	-0.09	-1.02	0.02	-0.58	-1.66
10035	Cunderdin	0.62	0.02	0.30	0.38	1.30
10648	Wandering	0.52	-0.32	-0.10	0.36	0.56
11052	Forrest	0.16	0.43	0.34	0.66	1.47
12038	Kalgoorlie	0.66	0.20	0.15	0.66	1.62
13017	Giles	0.69	0.92	1.09	0.35	3.05
14015	Darwin Airport	-0.12	-0.40	0.24	0.21	-0.21
14825	Victoria River Downs*	0.25	-0.62	1.72	0.90	1.94
15135	Tennant Creek	1.84	0.31	-1.33	0.97	1.92
15548	Rabbit Flat*	4.54	2.11	2.10	4.82	13.79
15590	Alice Springs	0.70	1.42	0.00	0.99	3.10
16001	Woomera	-0.16	-0.67	-1.22	0.86	-1.22
16044	Tarcoola	0.97	1.56	1.95	1.14	5.58
17031	Marree	-0.09	0.32	-0.31	-0.03	-0.13
17043	Oodnadatta	0.98	1.20	0.42	0.11	1.93
18012	Ceduna	0.09	0.04	0.06	0.65	0.79
18070	Port Lincoln	-0.22	-0.33	-0.04	0.62	0.05
21046	Snowtown	0.43	-0.43	0.75	0.51	0.85
22801	Cape Borda	0.86	0.16	0.73	0.64	2.30
23090	Adelaide RO	0.24	0.17	0.39	0.69	1.39
23373	Nuriootpa	-0.20	0.03	0.84	0.12	0.79
26021	Mount Gambier	-0.13	0.00	0.47	0.37	0.62
26026	Robe	0.47	-0.37	0.95	0.06	1.07
27022	Thursday Island	1.39	1.59	-1.99	-0.78	0.47
27045	Weipa	-1.59	-1.63	2.09	-2.38	-3.32
28004	Palmerville	1.16	1.71	0.79	1.36	4.97
29004	Burketown	-0.35	-0.61	-1.45	-0.74	-2.91
30045	Richmond	-0.32	-0.45	0.26	-0.70	-0.93
31011	Cairns	1.71	0.43	1.10	1.12	4.35
32040	Townsville	0.45	1.79	2.56	0.44	5.13
33119	Mackay MO	1.91	2.65	0.74	0.91	6.25
34084	Charters Towers	0.00	1.59	1.14	0.28	3.08
36007	Barcaldine	0.50	0.58	0.54	1.23	2.89
36031	Longreach	-0.20	-0.64	-0.45	0.24	-0.85
37010	Camooweal	0.57	1.27	-0.42	1.40	2.75
38002	Birdsville	0.63	0.74	-0.11	1.38	2.62
38003	Boulia	-0.03	1.42	-0.02	0.94	2.16
39039	Gayndah	1.05	1.29	0.03	1.25	3.57
39083	Rockhampton	0.38	0.77	0.12	0.14	1.51

Table 7.1a (cont.). Trends in frequency of maxima above 95th percentile, 1957-96

Station number	Station name	Trend (days/decade)				
		Spring	Summer	Autumn	Winter	Annual
39128	Bundaberg	0.57	1.42	0.33	0.27	2.51
40004	Amberley	1.07	0.38	-0.03	1.06	2.67
40223	Brisbane Airport	-0.15	-0.25	-1.69	-0.48	-2.42
40264	Tewantin	1.80	0.44	-0.23	1.13	2.73
42023	Miles	0.14	0.43	0.11	1.70	2.45
43109	St. George	0.59	-0.63	-0.28	1.00	0.74
44021	Charleville	0.46	0.73	0.05	0.69	1.95
45017	Thargomindah	-0.29	0.16	-0.36	0.80	0.06
46037	Tibooburra	0.18	0.96	0.18	0.94	2.31
46043	Wilcannia	-0.79	-0.22	-0.49	0.31	-1.24
48027	Cobar	0.00	-0.04	-0.26	0.86	0.42
48239	Bourke	0.19	0.35	-0.91	0.88	0.42
52088	Walgett	0.20	-0.05	-0.28	0.44	0.07
53048	Moree	0.00	-0.35	-0.91	-0.97	-2.24
55024	Gunnedah Soil Cons	-0.37	-0.08	-0.96	0.84	-0.90
56017	Inverell PO	0.87	0.44	-0.32	-0.19	0.81
58012	Yamba	0.75	0.69	0.43	0.92	2.76
59040	Coffs Harbour	0.08	0.10	-0.41	0.24	0.02
60026	Port Macquarie	0.73	2.37	1.19	1.26	5.58
61078	Williamtown	0.49	0.51	-0.80	0.85	1.14
61089	Scone Soil Cons	0.31	-0.60	-0.57	0.80	-0.28
63005	Bathurst ARS	-0.31	0.41	-0.60	-0.09	-0.71
65012	Dubbo	-0.19	-0.04	0.05	0.47	0.26
66062	Sydney RO	0.06	-0.07	-0.55	0.44	-0.12
67105	Richmond	0.25	0.51	-0.27	0.45	0.95
68034	Jervis Bay	0.24	-0.15	-0.55	0.48	-0.08
68076	Nowra	0.01	-1.24	-0.45	-0.49	-2.08
69018	Moruya Heads	0.39	-0.40	-0.27	0.01	-0.31
70014	Canberra Airport	-0.56	-0.02	0.05	0.73	0.10
72150	Wagga Wagga	-0.48	0.48	0.37	0.12	0.38
72161	Cabramurra	-0.22	-0.17	-0.31	0.64	-0.01
73054	Wyalong	0.72	-0.02	-0.31	1.00	1.66
74128	Deniliquin	0.03	0.67	0.24	-0.25	0.67
76031	Mildura	-0.53	-0.20	-0.49	0.15	-1.18
78031	Nhill	-0.02	0.46	0.19	0.05	0.72
80023	Kerang	0.39	0.18	0.13	0.71	1.39
82039	Rutherglen	-0.15	0.04	0.53	0.08	0.32
84016	Gabo Island	-0.40	-0.27	-1.03	0.62	-1.04
84030	Orbost	-0.21	-0.42	-0.64	-0.92	-2.42
85072	Sale	-0.56	-0.12	0.22	0.93	0.40
85096	Wilsons Promontory	1.10	-0.20	0.25	0.73	1.84
86071	Melbourne RO	-0.07	-0.25	0.19	0.02	-0.22
87031	Laverton	0.24	-0.60	0.46	0.73	0.72
90015	Cape Otway	0.48	-0.15	0.07	0.42	0.56
91057	Low Head	0.11	-0.49	1.12	1.24	2.05
91104	Launceston AP	-0.46	-0.17	0.76	0.42	0.35
92045	Eddystone Point	0.25	0.27	1.03	2.10	3.61
94010	Cape Bruny	-0.22	-0.52	0.07	0.22	-0.45
94029	Hobart RO	0.42	0.11	0.41	0.71	1.58
94069	Grove	0.58	-0.38	0.52	0.67	1.28
96003	Butlers Gorge	1.15	0.67	1.08	0.28	3.29

* denotes station with less than 35 years of record in the 1957-96 period

Table 7.1b. Trends in frequency of maxima above 90th percentile, 1957-96

Station number	Station name	Trend (days/decade)				
		Spring	Summer	Autumn	Winter	Annual
1021	Kalumburu	-0.22	0.58	5.55	1.93	8.00
2012	Halls Creek	-1.19	-3.62	-1.69	-0.70	-6.90
3003	Broome	1.05	-0.05	0.52	2.68	4.02
4032	Port Hedland	0.15	0.39	0.44	0.68	1.53
5007	Learmonth	-0.06	-0.39	1.43	0.49	1.82
5026	Wittenoom	0.92	2.32	1.51	0.92	5.47
6011	Carnarvon	-0.89	-0.84	0.66	0.13	-0.99
7045	Meekatharra	0.48	0.51	0.02	1.09	2.01
8039	Dalwallinu	0.23	0.00	-0.03	1.02	1.21
8051	Geraldton	0.14	0.00	0.57	0.50	1.07
9021	Perth Airport	0.43	-0.23	0.29	0.40	0.72
9518	Cape Leeuwin	1.64	-1.27	-0.09	0.13	0.56
9741	Albany	-0.62	-2.21	0.99	0.47	-1.44
9789	Esperance	0.25	-0.99	-0.61	-1.42	-2.80
10035	Cunderdin	0.56	-0.16	0.00	1.10	1.48
10648	Wandering	0.62	-1.32	-0.16	0.54	-0.10
11052	Forrest	0.11	0.17	0.44	0.84	1.25
12038	Kalgoorlie	0.75	0.56	0.12	0.82	2.09
13017	Giles	1.04	1.50	1.63	0.36	4.67
14015	Darwin Airport	-0.05	-0.50	0.54	1.16	0.84
14825	Victoria River Downs*	0.12	-1.12	2.36	0.71	1.28
15135	Tennant Creek	2.12	0.29	-1.45	0.82	1.96
15548	Rabbit Flat*	7.10	3.22	5.29	4.74	21.00
15590	Alice Springs	1.42	1.79	0.04	1.32	4.61
16001	Woomera	-0.52	-1.50	-0.93	-0.51	-3.50
16044	Tarcoola	1.66	1.98	2.32	2.00	7.98
17031	Marree	-0.06	0.91	-0.10	0.05	0.82
17043	Oodnadatta	1.64	2.49	0.71	0.63	3.78
18012	Ceduna	-0.20	0.02	-0.37	0.20	-0.48
18070	Port Lincoln	0.48	-0.11	0.01	1.02	1.44
21046	Snowtown	0.19	-0.57	1.02	0.26	0.28
22801	Cape Borda	1.19	0.31	1.15	0.75	3.40
23090	Adelaide RO	0.05	-0.03	0.61	-0.05	0.42
23373	Nuriootpa	-0.07	0.19	0.87	0.47	1.40
26021	Mount Gambier	-0.43	0.12	0.53	0.23	0.24
26026	Robe	0.45	-0.35	1.40	0.61	1.82
27022	Thursday Island	2.49	3.07	-1.03	-1.06	3.97
27045	Weipa	-2.64	-3.17	2.96	-4.14	-7.33
28004	Palmerville	1.73	2.28	1.17	1.00	6.15
29004	Burketown	-0.66	0.08	-2.26	-1.53	-3.68
30045	Richmond	-0.65	-0.79	0.78	-0.78	-0.98
31011	Cairns	2.30	0.35	1.07	2.14	5.92
32040	Townsville	0.84	3.54	4.81	0.99	10.25
33119	Mackay MO	3.43	4.13	0.37	0.62	8.65
34084	Charters Towers	-0.47	3.09	2.76	0.89	6.23
36007	Barcaldine	1.36	0.84	1.24	1.39	4.84
36031	Longreach	-0.45	0.12	0.33	0.44	0.65
37010	Camooweal	0.63	2.24	-0.19	2.04	4.55
38002	Birdsville	0.85	1.15	-0.39	1.61	3.23
38003	Boulia	-0.02	2.15	1.00	1.27	4.23
39039	Gayndah	1.72	2.07	-0.04	2.05	5.74
39083	Rockhampton	1.27	0.91	0.56	0.61	3.41

Table 7.1b (cont.). Trends in frequency of maxima above 90th percentile, 1957-96

Station number	Station name	Trend (days/decade)				
		Spring	Summer	Autumn	Winter	Annual
39128	Bundaberg	0.74	2.55	0.91	0.65	4.78
40004	Amberley	2.11	0.49	-0.35	1.68	4.15
40223	Brisbane Airport	0.29	-0.57	-2.02	-1.56	-3.67
40264	Tewantin	1.64	1.40	-0.18	1.53	3.73
42023	Miles	0.55	0.03	-0.15	2.83	3.14
43109	St. George	0.70	-0.14	0.00	1.90	2.40
44021	Charleville	0.67	0.88	0.64	1.49	3.61
45017	Thargomindah	-0.09	0.49	-0.59	0.94	0.34
46037	Tibooburra	0.38	2.05	0.27	0.70	3.70
46043	Wilcannia	-0.76	-0.25	-0.96	-0.10	-2.17
48027	Cobar	-0.08	0.19	-0.76	1.28	0.44
48239	Bourke	0.09	0.92	-0.65	0.57	0.84
52088	Walgett	0.40	-0.22	-0.22	0.48	-0.01
53048	Moree	-0.62	-0.90	-0.60	-1.07	-3.21
55024	Gunnedah Soil Cons	-0.24	-0.36	-1.28	0.55	-1.86
56017	Inverell PO	1.51	0.63	-0.50	0.33	1.99
58012	Yamba	1.37	0.49	0.24	1.32	3.43
59040	Coffs Harbour	0.98	0.76	-0.36	0.74	2.00
60026	Port Macquarie	0.59	3.83	1.79	1.33	7.54
61078	Williamtown	1.09	1.12	-0.54	1.40	3.13
61089	Scone Soil Cons	-0.13	-0.88	-0.83	0.39	-1.82
63005	Bathurst ARS	-0.98	0.90	-0.43	-0.57	-1.27
65012	Dubbo	-0.08	-0.27	0.63	0.35	0.59
66062	Sydney RO	0.24	0.31	-0.36	0.22	0.38
67105	Richmond	0.28	0.65	-0.58	0.33	0.90
68034	Jervis Bay	-0.06	-0.02	-0.26	1.03	0.77
68076	Nowra	0.23	-1.23	-0.30	-0.05	-1.20
69018	Moruya Heads	0.33	-1.57	-1.35	-0.18	-2.89
70014	Canberra Airport	-1.24	0.38	0.61	0.18	-0.19
72150	Wagga Wagga	-0.59	0.84	0.37	0.53	1.02
72161	Cabramurra	-0.75	-0.66	0.27	1.69	0.72
73054	Wyalong	0.25	-0.55	-0.88	0.11	-0.06
74128	Deniliquin	-0.43	0.58	0.57	0.24	0.97
76031	Mildura	-0.48	-1.08	-0.11	-0.30	-2.08
78031	Nhill	0.09	-0.19	1.11	-0.42	0.72
80023	Kerang	-0.02	-0.09	0.54	0.83	1.37
82039	Rutherglen	-0.46	-0.42	0.83	0.24	-0.01
84016	Gabo Island	-0.83	-0.31	-0.23	1.52	0.14
84030	Orbost	-0.41	-0.73	-1.25	-1.01	-3.81
85072	Sale	-0.12	-0.60	0.78	1.54	1.42
85096	Wilsons Promontory	1.13	-0.37	0.72	1.37	2.90
86071	Melbourne RO	0.03	-0.44	0.52	-0.04	-0.07
87031	Laverton	0.14	-1.29	0.33	1.50	0.52
90015	Cape Otway	0.74	-0.26	0.05	0.95	1.49
91057	Low Head	0.29	-0.84	3.24	3.07	5.88
91104	Launceston AP	-0.03	-0.10	1.55	0.53	1.62
92045	Eddystone Point	0.23	-0.14	1.54	4.05	6.10
94010	Cape Bruny	-0.35	-0.75	0.33	0.38	-0.37
94029	Hobart RO	0.05	0.05	0.74	1.14	1.86
94069	Grove	0.35	-0.27	0.52	0.94	1.53
96003	Butlers Gorge	1.61	1.62	1.77	1.55	6.57

* denotes station with less than 35 years of record in the 1957-96 period

Table 7.1c. Trends in frequency of minima above 95th percentile, 1957-96

Station number	Station name	Trend (days/decade)				
		Spring	Summer	Autumn	Winter	Annual
1021	Kalumburu	1.49	0.60	1.17	-0.17	3.36
2012	Halls Creek	-0.31	-1.44	-0.58	-1.08	-3.17
3003	Broome	2.39	1.56	-0.31	0.05	3.77
4032	Port Hedland	0.53	0.12	0.79	0.94	2.33
5007	Learmonth	-0.48	-3.76	-1.23	1.29	-3.23
5026	Wittenoom	0.27	0.20	0.65	0.54	1.54
6011	Carnarvon	0.13	1.33	0.38	0.87	2.76
7045	Meekatharra	0.46	0.23	0.73	0.31	1.62
8039	Dalwallinu	0.48	-0.66	-0.14	0.11	-0.17
8051	Geraldton	0.66	-0.38	0.78	0.59	1.66
9021	Perth Airport	1.82	0.85	1.13	0.15	3.89
9518	Cape Leeuwin	1.71	-0.21	0.86	1.42	3.81
9741	Albany	0.01	-0.45	1.33	1.19	1.96
9789	Esperance	0.90	0.69	1.00	0.66	3.28
10035	Cunderdin	0.61	-0.64	-0.03	0.76	0.81
10648	Wandering	0.75	-0.62	-0.02	0.77	1.15
11052	Forrest	1.78	0.07	1.20	0.76	3.87
12038	Kalgoorlie	1.10	0.71	1.12	1.17	4.02
13017	Giles	-0.09	1.28	0.41	-0.45	1.20
14015	Darwin Airport	1.84	0.83	1.78	0.96	5.38
14825	Victoria River Downs*	1.86	-0.30	1.54	-0.20	2.94
15135	Tennant Creek	0.65	0.78	1.56	1.17	4.21
15548	Rabbit Flat*	1.43	1.56	1.59	0.68	5.27
15590	Alice Springs	-0.04	-0.09	-0.32	1.55	1.07
16001	Woomera	-0.60	-1.06	-0.23	1.15	-0.40
16044	Tarcoola	0.09	1.12	0.71	-0.21	1.71
17031	Marree	-0.62	-0.31	0.71	-0.29	-0.50
17043	Oodnadatta	-0.20	-0.80	0.54	1.48	0.95
18012	Ceduna	0.81	-0.27	0.35	0.27	1.11
18070	Port Lincoln	0.69	0.11	0.41	-0.34	0.92
21046	Snowtown	-0.03	0.13	0.50	0.43	0.91
22801	Cape Borda	-0.29	-0.16	0.26	0.40	0.32
23090	Adelaide RO	0.72	0.44	0.73	1.21	3.04
23373	Nuriootpa	0.56	0.66	1.26	0.78	3.29
26021	Mount Gambier	1.64	0.57	1.18	1.77	5.11
26026	Robe	1.18	0.10	1.25	2.04	4.43
27022	Thursday Island	1.89	0.78	1.69	0.86	5.39
27045	Weipa	0.27	1.92	1.79	0.67	4.60
28004	Palmerville	1.52	0.68	0.24	-0.13	2.36
29004	Burketown	0.53	1.42	1.81	0.91	4.77
30045	Richmond	1.52	1.14	0.70	1.52	4.96
31011	Cairns	2.46	0.85	3.32	1.68	8.24
32040	Townsville	1.12	1.97	1.19	0.94	5.19
33119	Mackay MO	1.10	1.54	1.31	1.16	5.18
34084	Charters Towers	0.63	0.11	1.08	0.87	2.80
36007	Barcaldine	0.62	1.45	1.28	0.96	4.63
36031	Longreach	1.33	0.96	1.97	1.01	5.21
37010	Camooweal	1.51	0.01	-1.22	-0.24	0.17
38002	Birdsville	0.38	0.31	0.14	-0.33	0.45
38003	Boulia	-0.51	-0.91	-0.55	0.17	-1.85
39039	Gayndah	0.90	1.21	0.24	-0.08	2.27
39083	Rockhampton	0.51	1.01	1.58	0.24	3.31

Table 7.1c (cont.). Trends in frequency of minima above 95[th] percentile, 1957-96

Station number	Station name	Trend (days/decade)				Annual
		Spring	Summer	Autumn	Winter	
39128	Bundaberg	0.63	1.53	0.98	0.35	3.41
40004	Amberley	0.44	0.65	1.32	0.02	2.49
40223	Brisbane Airport	1.01	1.16	1.56	0.76	4.49
40264	Tewantin	2.03	1.48	1.76	1.19	6.39
42023	Miles	0.47	0.50	0.31	0.39	1.52
43109	St. George	0.93	-0.17	0.67	0.62	1.86
44021	Charleville	0.28	0.98	0.99	-0.28	1.97
45017	Thargomindah	-0.12	-0.43	0.32	0.27	0.13
46037	Tibooburra	0.05	0.48	0.14	1.05	1.83
46043	Wilcannia	-0.63	-0.63	-1.08	0.74	1.49
48027	Cobar	-0.24	1.25	1.69	0.49	3.23
48239	Bourke	-0.07	0.87	0.79	0.99	2.55
52088	Walgett	0.11	0.29	0.43	0.07	0.69
53048	Moree	0.52	0.16	1.91	0.91	3.44
55024	Gunnedah Soil Cons	-0.24	-0.13	0.09	-0.02	0.42
56017	Inverell PO	0.19	0.24	1.17	0.31	1.98
58012	Yamba	1.27	0.87	0.10	0.24	2.59
59040	Coffs Harbour	0.05	0.85	0.07	-0.32	0.56
60026	Port Macquarie	0.72	2.75	0.32	1.00	4.83
61078	Williamtown	0.49	1.57	0.79	0.36	3.17
61089	Scone Soil Cons	-0.50	-0.68	-0.42	0.40	1.10
63005	Bathurst ARS	-0.18	-0.29	-0.12	0.08	0.88
65012	Dubbo	1.05	-0.12	0.48	0.56	2.00
66062	Sydney RO	0.69	1.94	0.97	0.11	3.62
67105	Richmond	0.59	1.17	0.16	-0.02	1.76
68034	Jervis Bay	0.31	1.03	0.75	0.64	3.05
68076	Nowra	0.22	1.10	0.41	0.70	2.36
69018	Moruya Heads	-0.19	0.54	-0.18	1.17	1.29
70014	Canberra Airport	-0.10	-0.04	0.43	0.11	0.16
72150	Wagga Wagga	0.22	0.14	1.37	0.80	2.49
72161	Cabramurra	-0.26	-0.65	-0.71	1.10	0.47
73054	Wyalong	-0.44	-0.33	0.70	0.91	1.30
74128	Deniliquin	0.00	0.14	0.91	0.52	1.54
76031	Mildura	0.71	0.49	0.49	0.60	2.1[illegible]
78031	Nhill	0.95	-0.99	0.82	0.52	1.56
80023	Kerang	0.20	-0.19	-0.02	-0.89	0.88
82039	Rutherglen	-0.03	0.10	0.37	1.75	2.30
84016	Gabo Island	-0.33	0.53	-0.86	-0.40	1.14
84030	Orbost	-0.42	-0.17	-0.43	-0.65	1.9[illegible]
85072	Sale	0.32	0.04	-0.30	0.35	0.3[illegible]
85096	Wilsons Promontory	1.47	0.25	0.67	0.92	3.33
86071	Melbourne RO	0.98	0.37	1.44	1.48	4.14
87031	Laverton	0.25	-0.01	0.08	0.76	0.98
90015	Cape Otway	0.66	-0.18	0.18	-0.24	0.49
91057	Low Head	-0.05	-0.26	1.25	0.69	1.66
91104	Launceston AP	1.46	0.37	0.99	0.43	3.02
92045	Eddystone Point	0.40	0.34	0.36	0.93	1.71
94010	Cape Bruny	0.69	0.22	0.98	0.80	2.60
94029	Hobart RO	1.00	0.24	0.41	0.03	1.61
94069	Grove	0.36	-0.39	0.05	-0.06	-0.06
96003	Butlers Gorge	0.17	-1.22	-0.54	0.26	-0.99

* denotes station with less than 35 years of record in the 1957-96 period

Table 7.1d. Trends in frequency of minima above 90th percentile, 1957-96

Station number	Station name	Trend (days/decade)				
		Spring	Summer	Autumn	Winter	Annual
1021	Kalumburu	2.44	0.15	2.15	0.12	5.10
2012	Halls Creek	-0.74	-1.69	-1.04	-2.36	-5.67
3003	Broome	3.87	1.33	-0.58	0.64	5.38
4032	Port Hedland	1.54	0.88	1.57	1.40	5.29
5007	Learmonth	-1.12	-6.18	-1.17	1.18	-5.92
5026	Wittenoom	0.20	0.38	0.78	0.64	2.06
6011	Carnarvon	1.01	1.50	0.21	1.45	4.30
7045	Meekatharra	0.46	0.24	0.50	0.49	1.53
8039	Dalwallinu	0.49	-0.89	-0.17	-0.53	-1.12
8051	Geraldton	1.19	-0.78	1.19	0.65	2.19
9021	Perth Airport	3.01	1.58	1.81	0.66	6.85
9518	Cape Leeuwin	2.83	-0.48	1.35	2.47	6.22
9741	Albany	1.33	-0.24	2.25	1.54	4.68
9789	Esperance	1.35	1.48	1.45	1.12	5.41
10035	Cunderdin	0.82	-0.69	0.23	1.12	1.49
10648	Wandering	0.74	-0.84	-0.39	0.68	0.54
11052	Forrest	2.84	0.94	1.46	1.07	6.46
12038	Kalgoorlie	1.53	0.84	1.17	1.76	5.11
13017	Giles	-0.56	1.05	0.36	-0.17	0.76
14015	Darwin Airport	2.99	1.83	2.35	0.89	7.93
14825	Victoria River Downs*	2.60	0.14	3.18	-0.11	5.51
15135	Tennant Creek	0.33	1.53	2.82	1.23	5.94
15548	Rabbit Flat*	2.65	0.58	2.07	0.59	6.02
15590	Alice Springs	1.59	-0.13	-0.34	1.55	2.74
16001	Woomera	-0.60	-0.54	-0.25	2.26	1.07
16044	Tarcoola	-0.24	1.91	1.08	-0.64	2.11
17031	Marree	-0.78	-0.24	1.10	-0.79	-0.65
17043	Oodnadatta	-1.25	-1.22	-0.03	1.41	-1.13
18012	Ceduna	1.41	-0.40	0.97	0.66	2.54
18070	Port Lincoln	0.85	0.40	0.00	0.03	1.42
21046	Snowtown	0.16	0.54	0.92	0.54	1.84
22801	Cape Borda	0.01	-0.61	0.23	0.77	0.53
23090	Adelaide RO	1.78	0.79	1.16	0.80	4.44
23373	Nuriootpa	1.06	0.48	1.75	1.50	4.89
26021	Mount Gambier	2.70	1.25	2.29	2.13	8.18
26026	Robe	1.87	0.13	1.99	3.09	6.80
27022	Thursday Island	3.14	1.33	2.81	2.04	9.59
27045	Weipa	0.21	2.38	2.48	1.20	6.19
28004	Palmerville	2.59	-0.13	0.32	-0.28	2.73
29004	Burketown	1.68	2.96	3.59	1.98	10.00
30045	Richmond	2.28	2.91	2.01	1.62	8.79
31011	Cairns	3.68	2.34	5.02	2.97	13.94
32040	Townsville	2.02	3.06	2.54	1.97	9.55
33119	Mackay MO	1.64	2.40	2.08	1.86	8.04
34084	Charters Towers	0.41	-0.14	1.65	1.27	3.36
36007	Barcaldine	1.56	3.12	2.39	0.57	7.93
36031	Longreach	1.13	1.60	3.59	1.64	7.90
37010	Camooweal	2.74	-0.19	-1.42	0.19	1.57
38002	Birdsville	0.01	0.20	0.31	-0.73	-0.05
38003	Boulia	-0.78	-1.05	0.09	0.72	-1.00
39039	Gayndah	1.57	1.63	0.86	-0.37	3.65
39083	Rockhampton	1.15	1.84	2.85	0.85	6.75

Table 7.1d (cont.). Trends in frequency of minima above 90th percentile, 1957-96

Station number	Station name	Trend (days/decade)				
		Spring	Summer	Autumn	Winter	Annual
39128	Bundaberg	1.26	1.90	1.60	0.31	4.89
40004	Amberley	0.76	0.97	1.44	1.13	4.44
40223	Brisbane Airport	1.25	2.76	2.45	0.60	6.99
40264	Tewantin	3.00	1.83	3.96	2.66	11.29
42023	Miles	0.90	0.66	-0.03	0.08	1.40
43109	St. George	0.33	0.62	1.15	1.35	3.43
44021	Charleville	-0.35	1.70	1.85	0.97	4.15
45017	Thargomindah	-0.62	-0.10	0.98	0.60	0.96
46037	Tibooburra	0.28	1.39	0.47	0.96	3.42
46043	Wilcannia	-0.46	-0.80	-1.03	0.93	1.11
48027	Cobar	0.42	2.11	2.55	0.32	5.50
48239	Bourke	0.41	1.58	1.87	1.17	5.01
52088	Walgett	-0.06	0.67	1.22	0.61	2.19
53048	Moree	1.31	1.30	2.08	1.42	5.04
55024	Gunnedah Soil Cons	-0.18	0.60	1.12	1.07	2.51
56017	Inverell PO	0.14	0.36	1.62	0.40	2.58
58012	Yamba	1.33	1.33	0.56	-0.02	3.28
59040	Coffs Harbour	0.40	1.67	1.00	1.02	4.02
60026	Port Macquarie	0.86	3.53	1.66	2.64	8.49
61078	Williamtown	0.59	2.52	1.47	0.94	5.53
61089	Scone Soil Cons	-0.14	-0.11	-0.03	0.49	0.51
63005	Bathurst ARS	-0.46	-0.10	0.60	0.39	0.43
65012	Dubbo	0.67	0.75	0.68	0.88	3.05
66062	Sydney RO	1.02	2.97	1.87	0.66	6.32
67105	Richmond	0.67	2.03	0.80	0.12	3.48
68034	Jervis Bay	0.25	1.26	1.18	1.01	4.14
68076	Nowra	0.29	1.21	0.96	1.07	3.48
69018	Moruya Heads	-0.45	0.30	-0.13	0.61	0.33
70014	Canberra Airport	0.45	0.15	0.91	0.44	1.93
72150	Wagga Wagga	0.74	0.72	1.99	1.38	4.69
72161	Cabramurra	-0.70	-0.72	0.45	1.39	0.33
73054	Wyalong	-0.08	0.31	0.80	1.55	2.79
74128	Deniliquin	-0.12	0.35	1.29	0.97	2.47
76031	Mildura	1.89	0.44	0.55	1.25	3.99
78031	Nhill	0.67	-1.07	0.94	1.05	1.89
80023	Kerang	0.50	-0.68	-0.55	-0.86	1.61
82039	Rutherglen	0.26	-0.47	0.39	2.80	3.11
84016	Gabo Island	-1.09	0.27	-1.20	0.81	3.01
84030	Orbost	-1.16	0.03	-0.84	-1.67	4.02
85072	Sale	0.23	0.05	-0.48	0.80	0.35
85096	Wilsons Promontory	2.00	0.45	0.97	2.33	5.79
86071	Melbourne RO	1.64	0.80	2.66	2.12	6.92
87031	Laverton	-0.08	0.88	-0.07	0.44	0.98
90015	Cape Otway	0.99	-0.53	0.76	-0.35	1.49
91057	Low Head	-0.41	0.02	1.64	0.32	1.66
91104	Launceston AP	1.83	0.60	1.26	0.67	3.95
92045	Eddystone Point	1.26	-0.61	0.50	1.22	2.04
94010	Cape Bruny	0.79	0.62	1.77	0.91	4.02
94029	Hobart RO	1.51	0.49	0.61	-0.82	1.59
94069	Grove	0.75	-0.09	0.01	-0.69	-0.07
96003	Butlers Gorge	0.03	-1.38	-0.54	0.01	-1.59

* denotes station with less than 35 years of record in the 1957-96 period

Table 7.1e. Trends in frequency of maxima below 10th percentile, 1957-96

Station number	Station name	Trend (days/decade)				
		Spring	Summer	Autumn	Winter	Annual
1021	Kalumburu	2.39	0.33	-1.30	-0.84	0.82
2012	Halls Creek	0.08	0.70	0.21	-0.33	0.70
3003	Broome	-1.23	0.95	-1.37	-2.68	-4.48
4032	Port Hedland	0.59	-0.62	-0.67	-0.43	-1.01
5007	Learmonth	-3.30	3.57	-1.24	1.76	-0.20
5026	Wittenoom	-1.78	-0.02	0.13	-0.26	-1.35
6011	Carnarvon	-0.09	0.67	-1.05	-0.26	-0.80
7045	Meekatharra	0.15	-0.54	-0.66	-0.34	-1.35
8039	Dalwallinu	0.11	-0.01	-1.18	-0.52	-1.47
8051	Geraldton	-0.55	-0.78	-1.64	1.01	-2.05
9021	Perth Airport	-0.54	0.04	-1.26	0.36	-1.51
9518	Cape Leeuwin	-0.70	0.93	-1.06	-0.59	-1.24
9741	Albany	-0.55	1.58	-1.47	1.36	1.44
9789	Esperance	-0.28	0.51	0.37	0.02	0.75
10035	Cunderdin	-0.83	0.00	-2.09	-0.82	-3.53
10648	Wandering	0.24	0.34	-1.46	-0.33	-1.37
11052	Forrest	-0.19	0.64	-1.08	-0.17	-0.80
12038	Kalgoorlie	0.18	1.03	-0.03	0.46	1.57
13017	Giles	-0.66	0.03	0.25	-0.42	-0.88
14015	Darwin Airport	-0.23	-1.12	-0.73	-1.87	-3.58
14825	Victoria River Downs*	-1.12	-2.87	-1.58	-3.09	-7.68
15135	Tennant Creek	0.30	0.53	-0.26	-0.39	0.31
15548	Rabbit Flat*	-4.31	-0.80	-2.04	-1.50	-9.18
15590	Alice Springs	-0.30	-0.27	0.31	-0.36	-0.68
16001	Woomera	0.09	1.14	-0.98	1.64	2.34
16044	Tarcoola	-1.30	0.29	-1.13	-1.95	-4.10
17031	Marree	-1.17	-0.25	-0.71	-1.92	-3.93
17043	Oodnadatta	-0.71	0.33	-0.55	-2.44	-3.13
18012	Ceduna	-1.04	-0.24	-1.27	-1.24	-3.84
18070	Port Lincoln	-1.76	-1.90	-2.68	-2.19	-8.68
21046	Snowtown	-1.24	-0.42	-1.38	-0.58	-2.75
22801	Cape Borda	-2.24	-2.23	-1.71	-0.86	-7.12
23090	Adelaide RO	-1.24	-0.73	-1.39	-0.78	-4.10
23373	Nuriootpa	-0.62	0.11	-0.96	-0.76	-2.20
26021	Mount Gambier	-1.29	-1.26	-1.51	-0.21	-4.06
26026	Robe	-1.75	0.89	-1.31	-1.72	-3.96
27022	Thursday Island	-2.62	-0.51	-1.23	-2.44	-6.81
27045	Weipa	-3.48	-0.92	-0.55	0.67	-4.26
28004	Palmerville	0.24	-1.25	-1.03	-0.26	-2.28
29004	Burketown	1.17	0.14	-2.42	1.39	-1.00
30045	Richmond	0.27	0.50	-3.07	0.05	-2.15
31011	Cairns	-0.44	-0.01	-1.32	-1.28	-3.03
32040	Townsville	-0.38	-0.42	-1.56	0.24	-2.23
33119	Mackay MO	0.10	-2.15	-1.71	-0.01	-4.02
34084	Charters Towers	-0.59	-2.24	-2.59	0.86	-4.54
36007	Barcaldine	0.45	-1.22	-1.15	0.81	-0.86
36031	Longreach	0.36	0.05	-0.47	0.35	0.15
37010	Camooweal	-0.84	0.15	-1.32	-0.65	-2.69
38002	Birdsville	-1.03	-0.81	-0.96	-1.43	-4.34
38003	Boulia	-0.01	0.93	-0.83	-0.49	-0.68
39039	Gayndah	-0.51	-1.71	-0.92	-1.25	-4.23
39083	Rockhampton	0.46	-1.80	-0.51	0.26	-1.55

Table 7.1e (cont.). Trends in frequency of maxima below 10th percentile, 1957-96

Station number	Station name	Trend (days/decade)				
		Spring	Summer	Autumn	Winter	Annual
39128	Bundaberg	0.05	-2.09	-0.91	-0.42	3.13
40004	Amberley	-0.17	-0.51	-0.48	-1.08	2.28
40223	Brisbane Airport	0.54	-0.02	0.71	0.43	1.76
40264	Tewantin	-0.46	-3.71	1.02	-0.22	3.44
42023	Miles	0.54	-1.25	-1.82	-0.42	2.97
43109	St. George	-0.39	-0.35	-0.20	0.46	0.88
44021	Charleville	0.66	-0.47	-0.99	0.33	0.52
45017	Thargomindah	0.18	-0.30	-1.62	0.73	0.81
46037	Tibooburra	-0.95	-0.36	-1.57	-1.54	4.29
46043	Wilcannia	0.59	0.54	1.38	0.59	3.16
48027	Cobar	0.34	1.06	-0.13	-0.18	1.20
48239	Bourke	0.22	-0.68	-0.27	0.50	0.12
52088	Walgett	0.08	-0.62	-0.49	0.39	0.66
53048	Moree	-0.52	-0.49	-0.14	1.07	0.17
55024	Gunnedah Soil Cons	-1.78	-0.04	-1.50	-0.44	3.41
56017	Inverell PO	-0.45	0.02	-0.99	-0.62	2.21
58012	Yamba	-1.66	-1.05	-1.59	-1.99	6.28
59040	Coffs Harbour	-1.36	-1.26	-0.77	-1.52	4.97
60026	Port Macquarie	-1.59	0.66	-0.62	-0.92	2.22
61078	Williamtown	-1.04	-1.37	-2.04	-1.19	5.53
61089	Scone Soil Cons	-0.65	0.88	-1.07	-0.35	0.98
63005	Bathurst ARS	-0.18	0.64	-0.72	-0.03	0.54
65012	Dubbo	0.18	0.36	-0.95	-0.27	0.62
66062	Sydney RO	-0.43	-1.46	-0.47	-0.15	2.48
67105	Richmond	-0.65	-0.38	-0.51	-0.88	2.43
68034	Jervis Bay	-0.05	-0.23	-1.50	1.56	3.44
68076	Nowra	-0.48	-1.01	0.13	0.13	1.29
69018	Moruya Heads	0.15	0.18	0.73	-0.50	0.84
70014	Canberra Airport	-0.37	0.13	0.56	0.07	0.91
72150	Wagga Wagga	-1.38	0.18	0.82	0.75	2.80
72161	Cabramurra	-0.47	0.11	-1.12	0.84	2.47
73054	Wyalong	0.74	1.28	-0.60	0.78	1.60
74128	Deniliquin	-0.51	0.21	-0.98	0.34	1.69
76031	Mildura	0.56	0.61	-0.61	-1.47	1.01
78031	Nhill	-1.15	0.13	-1.21	0.42	2.98
80023	Kerang	-0.57	0.81	-0.99	0.44	0.91
82039	Rutherglen	-0.14	0.86	-1.61	0.28	1.46
84016	Gabo Island	0.00	-0.06	0.31	0.58	0.12
84030	Orbost	0.21	-0.13	-0.09	0.41	0.68
85072	Sale	-1.21	-1.85	-3.06	-1.46	7.88
85096	Wilsons Promontory	0.11	1.20	-0.37	-1.29	0.67
86071	Melbourne RO	-0.73	0.19	-0.45	-1.18	2.33
87031	Laverton	-0.02	0.95	-0.22	-1.33	0.55
90015	Cape Otway	-0.16	1.08	-0.12	-0.87	0.21
91057	Low Head	-2.22	-0.13	-2.83	-1.15	6.97
91104	Launceston AP	-1.09	0.42	-1.30	0.20	1.12
92045	Eddystone Point	-2.77	-2.56	-2.81	-2.70	-11.06
94010	Cape Bruny	-0.75	-0.23	-1.64	-0.87	-3.51
94029	Hobart RO	-0.63	-0.01	-0.93	-0.58	2.31
94069	Grove	-0.33	0.15	-0.74	0.12	-0.85
96003	Butlers Gorge	-2.72	-2.34	-2.92	-1.76	-9.37

* denotes station with less than 35 years of record in the 1957-96 period

Table 7.1f. Trends in frequency of maxima below 5th percentile, 1957-96

Station number	Station name	Trend (days/decade)				
		Spring	Summer	Autumn	Winter	Annual
1021	Kalumburu	1.35	-0.11	-1.09	-0.33	-0.03
2012	Halls Creek	0.25	0.52	0.25	-0.20	0.86
3003	Broome	-0.75	0.25	-0.24	-1.59	-2.38
4032	Port Hedland	0.14	-0.19	-0.02	0.13	0.11
5007	Learmonth	-1.71	1.84	-0.55	1.02	0.07
5026	Wittenoom	-0.71	-0.01	0.30	-0.42	-0.32
6011	Carnarvon	-0.38	-0.35	-0.69	0.02	-1.47
7045	Meekatharra	0.31	-0.43	-0.26	-0.28	-0.66
8039	Dalwallinu	0.02	-0.22	-0.75	-0.08	-0.85
8051	Geraldton	-0.27	-0.51	-0.89	0.96	-0.77
9021	Perth Airport	-0.30	0.54	-0.59	0.60	0.19
9518	Cape Leeuwin	-0.28	0.94	-0.92	-0.53	-0.70
9741	Albany	-0.70	0.89	-0.85	0.46	0.21
9789	Esperance	-0.35	0.13	0.05	0.07	0.04
10035	Cunderdin	-0.38	-0.38	-1.25	-0.81	-2.75
10648	Wandering	0.17	0.36	-0.73	-0.10	-0.45
11052	Forrest	0.39	0.46	-0.50	-0.35	0.18
12038	Kalgoorlie	0.17	0.35	-0.08	0.40	0.82
13017	Giles	-0.25	-0.03	0.03	-0.14	-0.35
14015	Darwin Airport	0.08	-0.53	-0.34	-0.70	-1.30
14825	Victoria River Downs*	-1.11	-1.66	0.25	-1.51	-3.93
15135	Tennant Creek	0.03	0.58	0.18	-0.04	0.67
15548	Rabbit Flat*	-2.12	-0.09	-1.21	-1.90	-5.81
15590	Alice Springs	-0.32	0.01	0.27	-0.18	-0.28
16001	Woomera	-0.41	1.07	-0.09	1.07	1.92
16044	Tarcoola	-0.49	0.56	-0.80	-1.14	-1.98
17031	Marree	-0.62	-0.58	-0.59	-0.83	-2.56
17043	Oodnadatta	-0.63	-0.08	-0.12	-1.18	-1.79
18012	Ceduna	-0.47	-0.42	-0.40	-0.53	-1.88
18070	Port Lincoln	-0.99	-1.31	-1.35	-1.54	-5.16
21046	Snowtown	-0.63	-0.27	-1.19	-0.38	-2.21
22801	Cape Borda	-1.26	-1.35	-1.22	-0.67	-4.53
23090	Adelaide RO	-0.76	-0.37	-0.83	-0.14	-2.13
23373	Nuriootpa	-0.57	-0.07	-0.51	-0.47	-1.59
26021	Mount Gambier	-0.82	-0.37	-0.86	-0.22	-2.24
26026	Robe	-1.29	0.71	-0.64	-0.74	-1.74
27022	Thursday Island	-1.28	-0.49	-0.36	-1.36	-3.61
27045	Weipa	-1.79	-0.22	0.37	0.08	-1.50
28004	Palmerville	0.08	-0.69	-0.35	0.19	-0.80
29004	Burketown	0.32	0.10	-1.43	0.51	-0.97
30045	Richmond	0.29	0.42	-1.59	0.52	-0.34
31011	Cairns	0.20	0.21	-0.83	-1.08	-1.47
32040	Townsville	-0.11	0.05	-0.57	0.63	-0.03
33119	Mackay MO	0.09	-1.16	-0.68	0.40	-1.48
34084	Charters Towers	-0.45	-1.01	-1.35	0.62	-2.11
36007	Barcaldine	0.09	-0.58	-0.46	0.79	-0.01
36031	Longreach	0.34	-0.13	-0.33	0.04	-0.04
37010	Camooweal	-0.39	0.12	-0.70	-0.25	-1.29
38002	Birdsville	-0.47	-0.27	-0.46	-0.90	-2.16
38003	Boulia	0.07	0.68	-0.37	0.43	0.62
39039	Gayndah	0.16	-1.20	-0.62	-0.91	-2.55
39083	Rockhampton	0.37	-0.86	0.23	-0.24	-0.44

Table 7.1f (cont.). Trends in frequency of maxima below 5th percentile, 1957-96

Station number	Station name	Trend (days/decade)				
		Spring	Summer	Autumn	Winter	Annual
39128	Bundaberg	0.34	-1.53	-0.03	-0.31	1.46
40004	Amberley	0.05	-0.25	0.17	-0.39	-0.42
40223	Brisbane Airport	0.33	0.05	0.33	0.07	0.88
40264	Tewantin	0.65	-2.24	0.93	-0.73	1.49
42023	Miles	0.41	-1.02	-0.92	-0.12	1.66
43109	St. George	-0.44	-0.23	-0.08	0.37	0.65
44021	Charleville	0.11	-0.14	-0.62	0.25	0.50
45017	Thargomindah	0.04	-0.42	-0.71	0.42	0.46
46037	Tibooburra	-0.32	-0.09	-0.92	-1.19	2.40
46043	Wilcannia	0.26	0.22	1.49	0.42	2.40
48027	Cobar	0.01	0.49	-0.31	-0.24	0.03
48239	Bourke	0.03	-0.59	0.39	-0.27	0.51
52088	Walgett	0.19	-0.41	-0.23	-0.05	0.62
53048	Moree	-0.33	-0.24	-0.14	0.66	0.09
55024	Gunnedah Soil Cons	-0.88	-0.14	-0.66	-0.48	2.02
56017	Inverell PO	-0.45	0.20	-0.52	-0.43	1.25
58012	Yamba	-0.78	-0.13	-1.01	-0.90	2.86
59040	Coffs Harbour	-0.59	-0.49	-0.30	-1.05	2.51
60026	Port Macquarie	-0.62	0.67	-0.16	-0.52	0.37
61078	Williamtown	-0.45	-0.83	-1.15	-0.96	3.42
61089	Scone Soil Cons	-0.23	0.06	-1.02	-0.05	1.09
63005	Bathurst ARS	0.03	0.17	-0.54	0.40	0.08
65012	Dubbo	0.26	-0.26	-0.56	0.16	0.34
66062	Sydney RO	-0.28	-0.74	-0.18	-0.10	1.30
67105	Richmond	-0.29	0.08	0.08	-0.30	0.43
68034	Jervis Bay	-0.10	-0.70	0.57	0.80	2.15
68076	Nowra	0.12	-0.01	0.66	0.55	1.34
69018	Moruya Heads	0.31	0.39	-0.10	0.01	0.53
70014	Canberra Airport	0.04	0.37	-0.17	0.11	0.02
72150	Wagga Wagga	-0.85	0.11	-0.65	0.19	1.64
72161	Cabramurra	-0.38	0.36	-0.50	-0.58	1.19
73054	Wyalong	0.08	0.94	0.47	0.74	1.13
74128	Deniliquin	-0.85	0.62	0.09	0.30	0.14
76031	Mildura	0.30	0.38	0.37	-0.43	0.20
78031	Nhill	-0.66	0.18	-0.44	0.22	0.86
80023	Kerang	-0.22	-0.17	-0.48	0.24	0.56
82039	Rutherglen	-0.74	0.10	-0.93	0.11	1.91
84016	Gabo Island	-0.36	0.05	0.58	-0.18	0.19
84030	Orbost	0.32	0.04	0.22	-0.64	0.27
85072	Sale	-0.71	-0.66	-1.20	-0.66	3.22
85096	Wilsons Promontory	-0.46	0.34	-0.48	-0.64	1.56
86071	Melbourne RO	-0.68	0.22	-0.31	-0.37	1.19
87031	Laverton	-0.47	0.73	-0.09	-0.68	0.50
90015	Cape Otway	-0.08	0.94	0.05	-0.29	0.59
91057	Low Head	-1.82	0.30	-1.76	-0.80	4.50
91104	Launceston AP	-0.82	0.28	-1.22	-0.08	1.50
92045	Eddystone Point	-1.26	-1.44	-1.93	-2.05	-0.80
94010	Cape Bruny	-0.38	-0.46	-1.14	-1.56	-3.56
94029	Hobart RO	-0.56	0.12	-0.74	-0.34	-1.64
94069	Grove	-0.42	0.10	-0.72	0.13	-0.97
96003	Butlers Gorge	-1.84	-1.76	-1.79	-0.79	-0.23

* denotes station with less than 35 years of record in the 1957-96 period

Table 7.1g. Trends in frequency of minima below 10^{th} percentile, 1957-96

Station number	Station name	Trend (days/decade)				
		Spring	Summer	Autumn	Winter	Annual
1021	Kalumburu	-2.39	-1.62	-1.78	-1.24	-7.44
2012	Halls Creek	-0.74	-0.17	1.70	0.20	1.05
3003	Broome	-1.80	-1.26	1.26	-1.62	-3.60
4032	Port Hedland	-1.34	-0.72	-1.24	-3.23	-6.70
5007	Learmonth	1.62	2.82	-0.60	0.31	3.47
5026	Wittenoom	-0.96	-1.17	-0.49	-1.22	-3.95
6011	Carnarvon	-1.73	-0.60	-1.30	-1.27	-4.97
7045	Meekatharra	0.10	0.27	-0.80	-0.29	-0.78
8039	Dalwallinu	-1.20	-0.92	-1.22	-1.11	-4.14
8051	Geraldton	0.23	1.52	-1.19	-0.24	0.30
9021	Perth Airport	-1.38	-1.30	-2.81	-0.48	-5.87
9518	Cape Leeuwin	-1.63	-1.18	-1.86	-1.81	-6.45
9741	Albany	-1.05	0.14	-0.18	-2.21	-3.23
9789	Esperance	-1.49	-0.62	-2.61	-1.56	-6.27
10035	Cunderdin	-1.75	-1.13	-1.94	0.01	-4.80
10648	Wandering	-2.22	-0.94	-2.37	-1.16	-6.85
11052	Forrest	-0.06	-0.08	0.61	-0.82	-0.38
12038	Kalgoorlie	-1.51	-0.67	-2.20	-0.93	-5.32
13017	Giles	-0.88	-0.72	2.49	0.42	1.12
14015	Darwin Airport	-1.37	-1.94	-2.14	-1.54	-6.75
14825	Victoria River Downs*	-1.84	-2.84	-0.99	-1.29	-6.10
15135	Tennant Creek	-0.27	-1.77	-0.78	-0.97	-3.70
15548	Rabbit Flat*	-1.38	-3.88	4.39	-0.79	-1.16
15590	Alice Springs	-1.13	-0.91	-1.10	-0.71	-3.90
16001	Woomera	-1.30	0.39	-0.96	-0.27	-2.62
16044	Tarcoola	-1.13	-0.38	-0.57	-0.99	-2.97
17031	Marree	-2.69	-1.76	-2.55	-1.66	-8.52
17043	Oodnadatta	-0.68	-0.16	0.48	-0.77	-0.88
18012	Ceduna	-2.75	-1.65	-1.55	-2.63	-8.32
18070	Port Lincoln	-1.28	-1.47	-1.35	-2.01	-6.57
21046	Snowtown	0.29	0.31	-0.17	-1.96	-1.01
22801	Cape Borda	-0.81	0.30	-0.28	-2.04	-2.67
23090	Adelaide RO	-0.54	0.55	0.35	-1.62	-0.97
23373	Nuriootpa	-1.15	-2.10	-1.20	-3.02	-7.69
26021	Mount Gambier	-1.14	-1.26	-1.18	-2.76	-6.11
26026	Robe	-2.26	-0.47	-1.63	-1.35	-5.76
27022	Thursday Island	-0.58	-0.43	-1.07	-3.26	-5.51
27045	Weipa	2.66	-1.72	0.06	0.84	1.50
28004	Palmerville	-3.69	-1.87	-0.07	-1.02	-7.16
29004	Burketown	-2.37	-4.32	-5.91	-3.10	-14.43
30045	Richmond	-1.72	-1.32	-1.55	-1.62	-5.83
31011	Cairns	-2.12	-2.30	-2.71	-1.78	-8.93
32040	Townsville	-2.43	-2.12	-3.38	-1.61	-9.69
33119	Mackay MO	-0.94	-1.80	-2.91	-2.37	-8.10
34084	Charters Towers	-1.90	-1.23	-1.53	-0.81	-5.30
36007	Barcaldine	0.29	-0.13	-2.55	-2.29	-4.84
36031	Longreach	-0.01	-2.12	-1.37	-0.71	-4.10
37010	Camooweal	-1.14	2.83	1.22	-0.12	2.54
38002	Birdsville	-0.24	1.39	0.32	0.06	1.50
38003	Boulia	-0.44	1.56	-0.03	-1.16	-0.24
39039	Gayndah	-0.98	-0.71	-2.39	-1.01	-5.11
39083	Rockhampton	-1.18	-1.78	-2.31	-2.30	-7.68

Table 7.1g (cont.). Trends in frequency of minima below 10^{th} percentile, 1957-96

Station number	Station name	Trend (days/decade) Spring	Summer	Autumn	Winter	Annual
39128	Bundaberg	-0.34	-1.89	-2.31	1.86	6.17
40004	Amberley	-0.76	-0.97	-1.44	-1.13	4.33
40223	Brisbane Airport	-1.85	-2.52	-2.98	-2.60	10.12
40264	Tewantin	-3.12	-2.56	-3.70	-3.03	13.45
42023	Miles	0.29	-0.67	-0.92	1.40	2.20
43109	St. George	-0.47	-0.75	-0.64	1.19	3.25
44021	Charleville	-2.03	-1.04	-0.91	-2.30	6.25
45017	Thargomindah	-1.26	-2.12	-0.33	-1.48	-4.84
46037	Tibooburra	-0.94	-0.42	-0.17	0.41	2.03
46043	Wilcannia	0.59	2.96	1.86	0.07	4.91
48027	Cobar	-2.67	1.09	-0.87	1.73	4.42
48239	Bourke	-0.76	-0.86	-0.70	-1.69	4.31
52088	Walgett	-1.16	-0.10	-1.14	0.77	3.01
53048	Moree	-2.75	-2.17	-2.01	3.39	10.29
55024	Gunnedah Soil Cons	-0.72	-0.15	-0.62	1.40	3.36
56017	Inverell PO	-1.70	-1.23	-0.98	2.77	6.62
58012	Yamba	-1.07	-0.89	-1.34	0.97	4.30
59040	Coffs Harbour	-1.34	-2.21	-2.90	-2.70	9.20
60026	Port Macquarie	-2.86	-2.61	-3.34	2.49	10.89
61078	Williamtown	-0.35	0.12	-1.88	1.89	3.87
61089	Scone Soil Cons	1.11	0.65	-0.14	-0.40	0.55
63005	Bathurst ARS	0.26	0.98	-0.80	1.63	0.99
65012	Dubbo	-0.17	-0.06	-1.10	1.72	2.97
66062	Sydney RO	-0.30	-1.04	-0.96	0.87	3.15
67105	Richmond	1.34	-0.32	-0.07	0.84	0.31
68034	Jervis Bay	-0.47	0.12	-0.69	0.27	1.66
68076	Nowra	0.88	-0.57	-0.87	0.17	0.46
69018	Moruya Heads	-0.70	0.18	-0.65	1.08	0.02
70014	Canberra Airport	-1.62	-1.13	-1.92	2.68	6.98
72150	Wagga Wagga	-1.00	1.52	-1.15	0.94	1.15
72161	Cabramurra	-0.10	0.50	-0.40	0.55	0.56
73054	Wyalong	-0.44	0.63	0.80	0.09	1.61
74128	Deniliquin	-0.01	-0.37	0.53	0.11	1.15
76031	Mildura	-1.75	-1.53	1.72	1.17	6.09
78031	Nhill	0.57	1.31	-0.90	0.35	0.60
80023	Kerang	0.44	-0.59	0.48	0.72	0.09
82039	Rutherglen	0.69	2.34	0.84	0.99	2.95
84016	Gabo Island	0.27	0.16	-0.41	0.40	0.21
84030	Orbost	0.54	-0.61	1.33	0.85	1.96
85072	Sale	-0.45	-1.48	-0.82	1.73	0.39
85096	Wilsons Promontory	-1.40	-1.94	-3.64	-1.95	9.34
86071	Melbourne RO	-1.47	-1.18	-1.19	-1.44	5.08
87031	Laverton	0.23	-1.08	-1.53	-0.92	-2.75
90015	Cape Otway	-1.93	1.51	-2.27	-0.97	-4.12
91057	Low Head	-0.59	1.37	-0.15	-0.52	0.12
91104	Launceston AP	-1.95	-2.73	-1.09	-1.38	-6.84
92045	Eddystone Point	-1.80	-1.04	-1.94	-1.48	6.99
94010	Cape Bruny	-1.53	-0.97	-1.57	-0.39	-4.85
94029	Hobart RO	-1.35	-1.23	-1.77	-0.71	-5.10
94069	Grove	-0.74	-0.22	-1.40	-1.00	-3.46
96003	Butlers Gorge	-0.11	0.00	-0.31	0.78	0.09

* denotes station with less than 35 years of record in the 1957-96 period

Table 7.1h. Trends in frequency of minima below 5th percentile, 1957-96

Station number	Station name	Trend (days/decade)				
		Spring	Summer	Autumn	Winter	Annual
1021	Kalumburu	-0.93	0.28	-1.45	0.22	-2.11
2012	Halls Creek	-0.95	-0.71	0.25	-0.42	-1.90
3003	Broome	-0.95	-1.01	1.04	-1.27	-2.24
4032	Port Hedland	-0.66	-0.76	-1.15	-1.56	-4.24
5007	Learmonth	1.25	1.30	-0.49	-0.11	1.69
5026	Wittenoom	-0.87	-1.10	-0.34	-0.85	-3.15
6011	Carnarvon	-1.26	-0.62	-0.95	-0.26	-3.07
7045	Meekatharra	0.35	-0.20	-0.56	-0.18	-0.65
8039	Dalwallinu	-0.28	-0.39	-1.01	-1.03	-2.56
8051	Geraldton	0.42	0.50	-0.51	-0.32	0.10
9021	Perth Airport	-0.73	-0.65	-1.61	-0.13	-3.12
9518	Cape Leeuwin	-0.74	-0.81	-1.26	-1.19	-3.93
9741	Albany	-0.96	0.41	0.23	-1.43	-1.68
9789	Esperance	-0.82	-0.39	-1.48	-1.25	-3.88
10035	Cunderdin	-1.15	-1.04	-1.23	-0.39	-3.96
10648	Wandering	-1.44	-0.67	-1.39	-1.30	-4.86
11052	Forrest	0.34	0.15	0.67	-0.61	0.35
12038	Kalgoorlie	-0.86	-0.94	-1.05	-0.33	-3.29
13017	Giles	-0.23	-0.64	1.47	0.17	0.69
14015	Darwin Airport	-0.96	-1.25	-1.01	-0.67	-3.74
14825	Victoria River Downs*	-1.63	-1.48	0.23	-0.41	-2.37
15135	Tennant Creek	-0.60	-1.03	-0.65	-0.83	-3.23
15548	Rabbit Flat*	-2.11	-2.07	2.91	0.11	-0.66
15590	Alice Springs	-0.64	-0.30	-0.59	-0.36	-1.91
16001	Woomera	-0.75	-0.07	-0.25	-0.09	-1.52
16044	Tarcoola	-0.18	-0.50	-0.81	-0.82	-2.30
17031	Marree	-1.53	-1.10	-1.61	-1.10	-5.28
17043	Oodnadatta	-0.44	0.01	0.24	-0.30	-0.30
18012	Ceduna	-1.60	-1.27	-1.04	-1.83	-5.47
18070	Port Lincoln	-0.73	-1.01	-1.25	-1.50	-4.83
21046	Snowtown	0.27	0.27	-0.24	-1.18	-0.63
22801	Cape Borda	-0.51	-0.04	-0.52	-1.12	-2.35
23090	Adelaide RO	-0.30	0.22	0.69	-1.22	-0.54
23373	Nuriootpa	-0.94	-1.03	-1.08	-2.27	-5.54
26021	Mount Gambier	-0.88	-0.95	-1.08	-2.19	-4.87
26026	Robe	-1.74	-0.20	-0.59	-0.97	-3.54
27022	Thursday Island	-0.23	-0.30	-0.30	-1.53	-2.44
27045	Weipa	1.69	-1.07	-0.09	-0.39	-0.12
28004	Palmerville	-1.73	-2.01	-0.07	0.17	-4.05
29004	Burketown	-1.68	-2.49	-2.92	-1.76	-8.47
30045	Richmond	-0.59	-0.50	-0.68	-1.03	-2.61
31011	Cairns	-1.06	-1.14	-1.49	-1.04	-4.77
32040	Townsville	-0.99	-1.34	-1.71	-1.44	-5.51
33119	Mackay MO	-0.81	-1.16	-1.80	-1.70	-5.56
34084	Charters Towers	-1.41	-1.31	-1.08	-0.04	-3.69
36007	Barcaldine	0.06	0.06	-0.92	-1.75	-2.64
36031	Longreach	-0.55	-1.24	-0.59	-1.03	-3.20
37010	Camooweal	-0.63	2.01	0.97	-0.21	2.07
38002	Birdsville	-0.26	1.14	-0.44	-0.50	-0.19
38003	Boulia	-0.42	0.88	0.39	-0.71	0.04
39039	Gayndah	-0.70	0.25	-1.26	-0.38	-2.16
39083	Rockhampton	-0.74	-0.92	-1.05	-1.47	-4.24

Table 7.1h (cont.). Trends in frequency of minima below 5th percentile, 1957-96

Station number	Station name	Trend (days/decade)				
		Spring	Summer	Autumn	Winter	Annual
39128	Bundaberg	-0.58	-1.03	-1.02	-1.13	3.68
40004	Amberley	-0.43	-0.11	-0.40	0.45	1.43
40223	Brisbane Airport	-0.94	-1.56	-1.44	1.35	5.55
40264	Tewantin	-2.68	-1.84	-1.77	2.16	9.00
42023	Miles	-0.34	0.23	0.22	1.12	0.91
43109	St. George	-0.56	-0.50	0.00	0.89	1.98
44021	Charleville	-0.92	-0.56	-0.49	1.47	3.58
45017	Thargomindah	-0.58	-1.37	-0.09	0.83	2.23
46037	Tibooburra	-0.58	-0.12	-0.20	0.07	0.84
46043	Wilcannia	0.64	1.50	1.07	0.46	3.48
48027	Cobar	-1.46	0.54	-0.39	1.44	2.81
48239	Bourke	-0.55	-0.36	-0.68	1.05	2.92
52088	Walgett	-1.18	0.04	-0.61	0.56	2.41
53048	Moree	-1.80	-0.58	-1.39	1.85	[illegible]
55024	Gunnedah Soil Cons	-0.92	-0.46	-0.46	1.12	3.16
56017	Inverell PO	-0.88	-0.60	-0.23	1.87	[illegible]
58012	Yamba	-0.79	-0.48	-0.46	0.41	2.13
59040	Coffs Harbour	-0.77	-1.64	-1.68	1.69	5.81
60026	Port Macquarie	-1.36	-1.53	-1.74	1.41	[illegible]
61078	Williamtown	-1.58	-0.16	-0.78	2.06	[illegible]
61089	Scone Soil Cons	0.43	0.68	-0.46	0.04	[illegible]
63005	Bathurst ARS	0.15	0.97	-0.71	1.28	0.81
65012	Dubbo	0.01	0.48	-0.77	1.02	1.30
66062	Sydney RO	-0.24	-0.49	-0.46	0.42	1.89
67105	Richmond	0.97	0.04	0.44	0.46	0.11
68034	Jervis Bay	-0.17	0.38	0.05	0.40	0.56
68076	Nowra	0.85	0.18	0.08	0.03	1.05
69018	Moruya Heads	-0.51	0.38	-0.75	0.01	[illegible]
70014	Canberra Airport	-0.67	-0.57	1.29	1.52	3.92
72150	Wagga Wagga	-0.58	0.72	-0.61	0.81	1.03
72161	Cabramurra	-0.08	-0.02	-0.07	0.06	0.20
73054	Wyalong	-0.17	-0.35	-0.52	0.14	[illegible]
74128	Deniliquin	-0.18	-0.46	-0.20	0.28	[illegible]
76031	Mildura	-1.27	-1.07	-1.07	0.75	[illegible]
78031	Nhill	-0.01	1.26	0.43	0.00	[illegible]
80023	Kerang	0.27	-0.16	0.08	0.08	0.22
82039	Rutherglen	-0.18	1.07	0.86	0.10	[illegible]
84016	Gabo Island	0.12	0.03	0.11	0.37	[illegible]
84030	Orbost	0.26	0.37	0.88	0.64	2.01
85072	Sale	0.36	-1.04	-0.59	0.63	0.24
85096	Wilsons Promontory	-0.91	-1.23	-1.85	0.94	5.15
86071	Melbourne RO	-0.83	-0.56	-0.66	-0.82	2.80
87031	Laverton	0.20	-0.68	-0.68	-0.26	0.97
90015	Cape Otway	-0.90	0.55	-1.50	-0.75	2.95
91057	Low Head	-0.78	1.47	0.07	-0.08	0.63
91104	Launceston AP	-1.24	-1.41	-0.62	-0.74	3.77
92045	Eddystone Point	-1.31	-0.46	-0.90	-0.52	3.76
94010	Cape Bruny	-1.22	-0.61	-1.05	-0.55	-3.76
94029	Hobart RO	-1.27	-0.69	-1.16	-0.33	-3.47
94069	Grove	-0.76	-0.08	-0.99	-0.60	-2.55
96003	Butlers Gorge	0.42	-0.02	-0.26	0.48	0.62

* denotes station with less than 35 years of record in the 1957-96 period

Table 7.2a. Trends in frequency of maxima above 30°C, 1957-96

Station number	Station name	Trend (days/decade)					Mean annual days >30°C
		Spring	Summer	Autumn	Winter	Annual	
1021	Kalumburu		0.28	1.52	1.58	3.11	339.9
2012	Halls Creek		-0.22	-1.23	-0.27	-2.25	279.9
3003	Broome	0.40	0.14	1.47	4.27	6.27	273.2
4032	Port Hedland	0.14		0.56	1.62	2.46	263.9
5007	Learmonth	4.38		2.78		10.78	212.7
5026	Wittenoom	1.38		0.52	0.74	1.87	234.2
6011	Carnarvon	-1.99	0.53	2.56		1.14	94.3
7045	Meekatharra	0.11	0.45	0.84		0.54	168.8
8039	Dalwallinu	-0.11	-0.15	0.75		0.42	120.4
8051	Geraldton	-0.08	-0.02	1.88		1.76	81.1
9021	Perth Airport	0.02	0.93	1.33		1.82	72.0
9518	Cape Leeuwin		0.20			0.26	3.5
9741	Albany		-1.86	0.73		-1.99	18.3
9789	Esperance	-0.26	-3.25	-1.05		-4.59	37.4
10035	Cunderdin	0.36	0.29	1.30		1.66	97.7
10648	Wandering	-0.57	-1.62	0.12		-2.00	75.8
11052	Forrest	-0.16	-0.42	0.08		-0.30	98.2
12038	Kalgoorlie	0.03	-0.02	-0.23		-0.39	103.9
13017	Giles	1.65	0.02	-0.29		1.59	182.9
14015	Darwin Airport		1.19	1.01	2.56	4.50	320.2
14825	Victoria R. Downs*			0.35	3.81	8.39	305.5
15135	Tennant Creek	0.26		-0.41	1.36	1.40	234.4
15548	Rabbit Flat*	2.26	-0.11	5.17	4.68	10.91	259.3
15590	Alice Springs	1.52	0.48	-0.09		2.67	172.6
16001	Woomera	-0.97	-3.41	-2.78		-8.75	117.1
16044	Tarcoola	0.93	0.29	0.49		2.34	129.2
17031	Marree	0.84	0.89	-1.27		0.46	164.0
17043	Oodnadatta	0.90	0.22	0.22		0.05	165.1
18012	Ceduna	-0.13	-0.13	-0.31		-0.66	60.7
18070	Port Lincoln	-0.10	0.03	-0.23		-0.28	21.1
21046	Snowtown	0.55	1.67	0.14		0.60	71.5
22801	Cape Borda		-0.46			-0.34	9.6
23090	Adelaide RO	0.06	0.95	0.33		1.06	50.5
23373	Nuriootpa	-0.11	-0.10	0.74		0.62	48.8
26021	Mt Gambier	-0.22	-0.19	0.25		-0.37	25.0
26026	Robe		-0.35			-0.14	7.0
27022	Thursday Island	4.97	3.72	3.47		12.42	128.1
27045	Weipa		2.12	1.23	-1.40	2.91	322.4
28004	Palmerville		0.68	0.81	1.79	3.21	318.5
29004	Burketown	-0.84	-0.51	1.58	-1.81	0.38	285.2
30045	Richmond	-0.17	-0.26	2.95	0.06	3.10	261.6
31011	Cairns	2.38	-0.18	1.39		3.61	142.4
32040	Townsville	2.42	3.14	7.75		13.42	142.7
33119	Mackay MO	3.54	6.74	1.42		12.13	57.8
34084	Charters Towers	0.16	2.25	3.91	0.03	6.88	192.5
36007	Barcaldine	-0.04	0.42	2.65		2.33	196.9
36031	Longreach	-0.29		0.97	-0.12	0.38	217.1
37010	Camooweal	0.28		0.19	3.35	3.88	259.5
38002	Birdsville	0.89	0.19	-0.59	1.34	2.01	197.4
38003	Boulia	0.87		1.81	1.22	3.40	215.9

Table 7.2a (cont.). Trends in frequency of maxima above 30°C, 1957-96

Station number	Station name	Trend (days/decade)					Mean annual days > 30°C
		Spring	Summer	Autumn	Winter	Annual	
39039	Gayndah	2.67	2.85	1.94		7.25	134.1
39083	Rockhampton	1.30	3.78	0.97		5.82	131.9
39128	Bundaberg	0.64	4.99	1.17		6.38	49.6
40004	Amberley	1.97	1.70	-0.16		3.43	90.4
40223	Brisbane Airport	0.24	-1.33	-1.05		-2.05	36.5
40264	Tewantin	1.65	4.27	-0.36		5.13	35.1
42023	Miles	1.47	3.27	1.55		5.95	127.9
43109	St. George	1.39	0.27	0.02		2.12	148.3
44021	Charleville	0.08	0.47	0.93		2.35	155.3
45017	Thargomindah	0.32	0.91	2.52		4.06	164.7
46037	Tibooburra	0.83	0.91	-0.96		0.98	145.3
46043	Wilcannia	0.38	0.84	-1.02		0.31	128.6
48027	Cobar	-0.04	-1.40	-0.74		-2.17	108.2
48239	Bourke	0.69	1.45	-0.26		2.23	141.7
52088	Walgett	-0.17	0.65	0.42		0.08	136.2
53048	Moree	0.71	0.80	-0.51		1.14	115.5
55024	Gunnedah Soil Cons	0.03	1.59	-1.42		-0.49	88.0
56017	Inverell PO	0.61	3.36	0.20		3.49	60.6
58012	Yamba		0.19			1.01	6.3
59040	Coffs Harbour	0.22	0.66			0.41	13.1
61078	Williamtown	0.43	1.02	-0.42		1.22	36.5
61089	Scone Soil Cons	-1.30	1.16	-2.82		-3.63	66.0
63005	Bathurst ARS		1.26			0.86	29.4
65012	Dubbo	-0.81	0.15	-0.13		-1.11	87.3
66062	Sydney RO	-0.42	-0.03	-0.55		1.00	15.0
67105	Richmond	-0.23	-0.14	0.75		0.46	55.0
68034	Jervis Bay		0.33			-0.48	6.8
68076	Nowra	0.14	0.07	0.42		0.01	23.1
69018	Moruya Heads		0.08			0.05	6.5
70014	Canberra Airport		0.50			0.15	29.4
72150	Wagga Wagga	-0.67	1.14	-0.16		-0.07	64.2
73054	Wyalong	0.28	-1.22	-1.82		-1.34	80.2
74128	Deniliquin	-0.29	0.28	0.63		0.65	70.0
76031	Mildura	-0.82	0.21	-0.51		1.39	81.7
78031	Nhill	0.14	-0.24	0.97		1.02	52.3
80023	Kerang	-0.08	0.15	-0.17		-0.21	68.6
82039	Rutherglen	-0.08	-3.65	-1.05		-4.74	62.2
84030	Orbost	0.25	-0.65	-0.77		-1.67	25.3
85072	Sale	-0.27	-0.58	-0.60		-1.56	19.5
85096	Wilsons Promontory		-0.26			-0.45	5.4
86071	Melbourne RO	-0.03	-1.32	-0.14		-1.69	30.5
87031	Laverton	0.11	-1.90	-0.63		-2.61	27.9
90015	Cape Otway		-0.30			-0.21	8.8
91104	Launceston AP		-0.53			-0.54	3.6
94029	Hobart RO		0.03			0.11	6.2
94069	Grove		-0.66			-0.33	7.0

Stations not listed failed to meet the criteria for a trend to be calculated (see text) in any season or annually.

Table 7.2b. Trends in frequency of maxima above 35°C, 1957-96

Station number	Station name	Trend (days/decade)					Mean annual days > 35°C
		Spring	Summer	Autumn	Winter	Annual	
1021	Kalumburu	-1.33	1.98	9.55	1.02	11.90	139.7
2012	Halls Creek	-0.51	-1.74	-3.29		-6.18	165.5
3003	Broome	1.08	-0.40	1.47		2.00	55.4
4032	Port Hedland	-0.14	0.71	0.89		1.29	136.8
5007	Learmonth	2.55	-6.26	3.61		6.08	114.7
5026	Wittenoom	1.49	0.53	-1.04		-0.02	161.8
6011	Carnarvon	-0.32	0.19	-0.42		-0.55	29.5
7045	Meekatharra	0.19	1.66	-0.74		-0.05	99.6
8039	Dalwallinu	-0.27	-0.26	0.06		-0.35	55.6
8051	Geraldton	-0.19	0.06	0.86		0.70	37.0
9021	Perth Airport		0.83	0.26		0.53	26.5
9741	Albany		-0.85			-1.16	5.4
9789	Esperance	0.05	-1.06	-0.61		-1.68	13.7
10035	Cunderdin	-0.52	-0.25	0.12		0.93	41.9
10648	Wandering		-0.71	0.31		-0.77	26.0
11052	Forrest	0.25	-0.07	0.64		0.77	40.4
12038	Kalgoorlie	-0.02	0.64	0.34		0.64	41.3
13017	Giles	0.72	1.19	0.02		2.08	102.6
14015	Darwin Airport	-0.03				0.14	9.9
14825	Victoria R. Downs*	-1.60	5.46	3.36	-0.92	7.33	174.6
15135	Tennant Creek	3.19	-0.72	-1.42		1.10	130.0
15548	Rabbit Flat*	9.17	2.41	5.98		17.55	163.7
15590	Alice Springs	0.79	0.71	0.49		2.24	89.1
16001	Woomera	-0.20	-1.19	1.17		-1.38	53.1
16044	Tarcoola	1.24	1.63	1.26		4.41	64.3
17031	Marree	0.55	0.59	-0.12		0.86	94.6
17043	Oodnadatta	2.03	1.12	-0.08		1.08	94.8
18012	Ceduna	-0.20	-0.38	0.07		-0.66	29.2
18070	Port Lincoln		-0.40			-0.33	5.8
21046	Snowtown	-0.07	-1.20			-0.84	31.5
23090	Adelaide RO		-0.22			-0.05	16.5
23373	Nuriootpa		0.19			0.68	15.0
26021	Mt Gambier		-0.24			-0.11	7.8
27045	Weipa	1.56	-1.38			-0.89	56.0
28004	Palmerville	2.75	4.60			8.40	92.6
29004	Burketown	-1.28	0.68	-1.33		-0.49	106.7
30045	Richmond	0.44	0.25	2.70		4.07	145.7
31011	Cairns		0.57			0.79	3.6
32040	Townsville					1.07	3.6
34084	Charters Towers	0.70	5.46			7.38	48.5
36007	Barcaldine	2.08	4.63	1.96		8.22	87.4
36031	Longreach	0.27	0.03	0.40		0.67	116.6
37010	Camooweal	1.53	-0.90	1.48		2.99	158.2
38002	Birdsville	0.66	1.67	-0.62		1.56	122.6
38003	Boulia	-0.42	-1.12	0.47		-0.61	133.1
39039	Gayndah	0.76	2.96			4.15	20.4
39083	Rockhampton	0.50	0.93			1.67	16.2
40004	Amberley		0.43			1.52	11.5
40264	Tewantin					0.12	2.6

Table 7.2b (cont.). Trends in frequency of maxima above 35°C, 1957-96

Station number	Station name	Trend (days/decade)					Mean annual days > 35°C
		Spring	Summer	Autumn	Winter	Annual	
42023	Miles	-0.09	2.57	-0.20		1.74	31.2
43109	St. George	-0.20	0.76	-0.66		0.30	54.4
44021	Charleville	-0.33	3.17	0.53		3.81	63.5
45017	Thargomindah	0.02	1.97	-0.97		0.46	91.2
46037	Tibooburra	0.75	1.60	0.21		2.42	71.6
46043	Wilcannia	-0.83	0.41	0.26		-0.08	62.2
48027	Cobar	-0.72	0.53			-0.21	39.7
48239	Bourke	-0.25	2.59	0.03		2.49	62.0
52088	Walgett	-0.72	2.28	0.00		0.42	55.1
53048	Moree	-0.84	0.40			-0.46	28.5
55024	Gunnedah Soil Cons		-0.41			-1.07	19.1
56017	Inverell PO					0.70	5.3
61078	Williamtown		0.68			0.44	8.4
61089	Scone Soil Cons		-1.45			-1.61	16.1
65012	Dubbo		0.23			-0.16	24.9
66062	Sydney RO		0.18			0.16	3.3
67105	Richmond		0.60			0.78	12.0
68076	Nowra		-1.39			-1.81	6.8
70014	Canberra Airport		0.21			0.11	4.7
72150	Wagga Wagga		0.29			0.03	18.2
73054	Wyalong		-0.54			-0.43	26.0
74128	Deniliquin		-0.35			0.28	23.1
76031	Mildura	-0.59	-1.38	0.19		-2.13	33.1
78031	Nhill		-0.32			0.22	17.0
80023	Kerang		-1.35			-0.85	22.4
82039	Rutherglen		-1.01			-0.68	16.1
84030	Orbost		-0.34			-0.86	7.0
85072	Sale		0.14			-0.24	4.7
86071	Melbourne RO		-0.71			-0.68	9.1
87031	Laverton		-0.97			-0.81	9.0
90015	Cape Otway					0.04	2.2

Stations not listed failed to meet the criteria for a trend to be calculated (see text) in any season or annually.

Table 7.2c. Trends in frequency of maxima above 40°C, 1957-96

Station number	Station name	Trend (days/decade)					Mean annual days > 40°C
		Spring	Summer	Autumn	Winter	Annual	
1021	Kalumburu					-0.72	3.2
2012	Halls Creek	-1.89	-3.61			-5.52	35.6
3003	Broome					0.31	2.7
4032	Port Hedland	0.01	-0.08	0.86		0.57	29.8
5007	Learmonth		-2.98	-0.07		-0.46	27.7
5026	Wittenoom	0.35	3.19			2.61	57.8
6011	Carnarvon		-0.73			-0.79	7.7
7045	Meekatharra		1.83			1.92	27.8
8039	Dalwallinu		0.02			0.10	11.3
8051	Geraldton		0.35			0.13	10.2
9021	Perth Airport		0.33			0.05	4.0
9789	Esperance		-0.72			-1.06	4.3
10035	Cunderdin		0.14			0.32	8.2
10648	Wandering		-0.39			-0.28	3.9
11052	Forrest	-0.07	0.27			0.19	11.3
12038	Kalgoorlie		0.22			0.30	8.4
13017	Giles		1.54			2.62	18.2
14825	Victoria R. Downs*	-1.12	-2.39			-4.17	27.8
15135	Tennant Creek	0.48	1.01			1.64	20.5
15548	Rabbit Flat*	6.51	7.97			16.44	53.0
15590	Alice Springs		1.97			2.46	15.6
16001	Woomera		-0.16			-0.36	12.4
16044	Tarcoola	0.21	1.74			2.75	20.2
17031	Marree	-0.82	1.89			1.31	35.0
17043	Oodnadatta	0.65	1.61			1.14	31.7
18012	Ceduna		0.05			-0.07	8.6
21046	Snowtown		-0.89			-1.16	6.7
23090	Adelaide RO					0.08	2.0
29004	Burketown		-0.73			-0.52	5.2
30045	Richmond	-1.07	0.76			0.22	26.2
36007	Barcaldine		0.73			0.77	9.0
36031	Longreach	-1.02	-0.35			-1.35	23.0
37010	Camooweal	1.11	2.54			3.20	38.8
38002	Birdsville	0.12	1.64			1.42	44.9
38003	Boulia	0.07	2.46			2.45	34.1
43109	St. George		-0.22			0.14	5.0
44021	Charleville					0.72	5.7
45017	Thargomindah	-0.90	1.94			0.32	23.9
46037	Tibooburra	-0.58	1.91			1.48	17.4
46043	Wilcannia		-0.58			-1.17	16.7
48027	Cobar		0.14			-0.21	5.5
48239	Bourke		1.03			0.98	10.8
52088	Walgett		0.01			-0.27	8.2
74128	Deniliquin		0.33			0.45	3.4
76031	Mildura		-0.55			-0.82	6.2
78031	Nhill		0.21			0.08	2.6
80023	Kerang PO		0.12			0.13	3.8

Stations not listed failed to meet the criteria for a trend to be calculated (see text) in any season or annually.

Table 7.2d. Trends in frequency of minima above 20°C, 1957-96

Station number	Station name	Trend (days/decade)					Mean annual days > 20°C
		Spring	Summer	Autumn	Winter	Annual	
1021	Kalumburu	4.55		1.62	0.05	7.74	232.2
2012	Halls Creek	1.13		-1.90	-1.34	-1.81	221.1
3003	Broome	2.20		-0.30	-0.39	1.90	218.1
4032	Port Hedland	2.74		3.23		6.38	170.7
5007	Learmonth	-0.14	-5.03	1.27		2.97	129.9
5026	Wittenoom	0.85		1.03		1.56	190.6
6011	Carnarvon	2.34	1.10	1.60		5.25	122.7
7045	Meekatharra	-0.49	-0.13	0.50		-1.36	120.0
8039	Dalwallinu		0.80	0.38		1.06	28.5
8051	Geraldton		-1.50	1.07		-0.69	36.8
9021	Perth Airport		1.32			2.64	20.2
9518	Cape Leeuwin		0.04			0.01	6.4
9789	Esperance		0.60			0.86	4.2
10035	Cunderdin		0.21	0.03		0.19	15.1
10648	Wandering		-0.55			-0.43	4.7
11052	Forrest		0.64			1.39	8.4
12038	Kalgoorlie	0.35	1.25	0.92		2.26	28.1
13017	Giles	-1.42	0.65	-0.17		-0.78	121.9
14015	Darwin Airport				3.16	4.98	316.5
14825	Victoria R. Downs*	2.03		5.76		11.54	187.5
15135	Tennant Creek	1.27		1.47		4.95	200.0
15548	Rabbit Flat*	1.58	5.82	-1.46		4.61	133.3
15590	Alice Springs	1.57	4.44	1.02		7.40	68.6
16001	Woomera	0.55	-2.30	-0.39		-2.35	49.3
16044	Tarcoola	-0.36	0.05	0.58		0.83	36.1
17031	Marree	0.45	1.23	0.71		3.10	70.1
17043	Oodnadatta	-2.47	0.28	1.56		-2.47	89.5
18012	Ceduna		-0.57			-0.06	11.8
18070	Port Lincoln		0.05			0.23	4.7
21046	Snowtown		0.21			-0.05	11.9
22801	Cape Borda		-0.14			0.08	7.2
23090	Adelaide RO	0.48	0.34	0.91		1.57	22.8
23373	Nuriootpa		0.37			0.80	6.9
27045	Weipa	-3.40		0.12	-0.45	-3.53	276.0
28004	Palmerville	4.18		2.93	-0.62	9.20	187.6
29004	Burketown	3.99		6.22	0.95		213.7
30045	Richmond	2.61	1.55	1.07		5.18	138.6
31011	Cairns	4.72		5.57	3.56	14.41	224.6
32040	Townsville	3.93		5.36	1.55	11.54	208.5
33119	Mackay MO	0.88	1.15	3.72		6.30	179.5
34084	Charters Towers	1.88	1.50	2.39		5.60	144.1
36007	Barcaldine	2.02	0.01	1.71		4.63	140.1
36031	Longreach	0.53	3.41	2.13		6.94	117.4
37010	Camooweal	2.12	-2.40	-2.28		-1.76	168.4
38002	Birdsville	0.61	-1.14	-0.50		-1.36	117.3
38003	Boulia	-0.41	-0.64	-0.29		-1.38	153.9

Table 7.2d (cont.). Trends in frequency of minima above 20°C, 1957-96

Station number	Station name	Trend (days/decade)					Mean annual days > 20°C
		Spring	Summer	Autumn	Winter	Annual	
39039	Gayndah	1.39	2.87	0.71		4.80	72.2
39083	Rockhampton	0.81	1.94	2.56		5.63	126.1
39128	Bundaberg	1.07	3.39	1.32		4.85	99.8
40004	Amberley	0.04	3.17	0.37		3.59	39.0
40223	Brisbane Airport	1.20	5.07	2.10		8.45	65.3
40264	Tewantin	1.57	3.07	4.21		9.74	97.5
42023	Miles	-0.01	1.35	-1.30		-0.61	52.1
43109	St. George	0.65	1.95	0.18		3.70	86.5
44021	Charleville	-1.01	5.43	-0.44		4.70	86.2
45017	Thargomindah	-0.79	3.23	-0.52		1.37	111.5
46037	Tibooburra	0.11	0.95	0.18		0.88	86.9
46043	Wilcannia	-0.21	-1.10	-1.33		-1.78	54.4
48027	Cobar	0.05	3.34	1.26		4.82	46.3
48239	Bourke	0.12	2.51	1.22		4.34	69.5
52088	Walgett	0.44	0.79	0.95		1.07	56.7
53048	Moree	1.16	4.93	0.58		6.40	47.5
55024	Gunnedah Soil Cons		0.89			0.67	31.4
56017	Inverell PO		0.09			0.11	4.9
58012	Yamba	0.64	3.63	-0.49		3.74	64.7
59040	Coff's Harbour	0.22	2.91	-0.43		2.55	41.2
60026	Port Macquarie		5.44	-0.28		4.71	25.3
61078	Williamtown		3.07			2.44	18.6
61089	Scone Soil Cons		0.15			0.08	15.0
65012	Dubbo		1.14			1.54	16.2
66062	Sydney RO		3.49	0.03		3.45	34.5
67105	Richmond		1.40			1.32	10.1
68034	Jervis Bay		0.41			0.55	12.2
68076	Nowra		0.70			0.44	4.3
69018	Moruya Heads		0.01			-0.06	4.6
72150	Wagga Wagga		0.04			0.27	13.6
73054	Wyalong		-0.37			-0.66	22.8
74128	Deniliquin		0.09			1.08	15.9
76031	Mildura		0.35			1.14	16.9
78031	Nhill		-1.16			-0.54	7.2
80023	Kerang		-0.82			-0.21	14.4
82039	Rutherglen		-0.14			0.07	7.0
84030	Orbost		-0.24			-0.41	2.4
86071	Melbourne RO		0.24			0.47	6.6
87031	Laverton					-0.03	3.5

Stations not listed failed to meet the criteria for a trend to be calculated (see text) in any season or annually.

Table 7.2e. Trends in frequency of maxima below 15°C, 1957-96

Station number	Station name	Trend (days/decade)					Mean annual days < 15°C
		Spring	Summer	Autumn	Winter	Annual	
7045	Meekatharra				-0.82	-0.89	6.2
8039	Dalwallinu				-1.24	-1.27	14.7
9021	Perth Airport				0.33	0.22	5.2
9518	Cape Leeuwin				-1.47	-2.16	13.4
9741	Albany	-0.93			2.04	0.84	36.4
9789	Esperance	-0.42			0.31	-0.39	18.3
10035	Cunderdin	-1.08			-2.73	-4.25	28.4
10648	Wandering	-0.36		-0.31	-0.53	-1.27	37.4
11052	Forrest				-0.44	-0.59	10.8
12038	Kalgoorlie				0.18	0.06	23.4
13017	Giles				-0.19	-0.37	4.2
15590	Alice Springs				-0.17	-0.10	8.7
16001	Woomera				-2.37	-3.02	17.6
16044	Tarcoola				-0.98	-1.20	6.7
17031	Marree				-0.71	-0.59	3.5
18012	Ceduna				-1.29	-1.80	12.2
18070	Port Lincoln	-0.80			-2.70	-3.90	22.5
21046	Snowtown	-0.68			-1.91	-3.06	35.2
22801	Cape Borda	-1.25		-1.30	-0.19	-2.74	97.9
23090	Adelaide RO	-0.88		-1.48	-1.68	-4.03	47.6
23373	Nuriootpa	-1.23		-1.62	-0.13	-2.97	92.4
26021	Mt Gambier	-1.87		-1.78	0.14	-3.46	109.2
26026	Robe	-1.93		-1.26	-2.58	-4.59	75.9
42023	Miles				0.22	0.12	5.3
43109	St. George				0.69	0.81	6.5
44021	Charleville				0.11	0.06	6.0
45017	Thargomindah				0.05	-0.23	4.2
46037	Tibooburra				-1.11	-1.95	13.6
46043	Wilcannia				-0.16	0.60	12.0
48027	Cobar			-1.46	-0.11	-1.56	37.1
48239	Bourke				0.41	0.41	9.2
52088	Walgett				0.91	0.65	15.5
53048	Moree				1.47	1.29	15.0
55024	Gunnedah Soil Cons				0.19	-1.29	27.0
56017	Inverell PO	-0.42			-0.85	-2.18	30.6
60026	Port Macquarie				-0.68	-0.65	3.0
61078	Williamtown				-1.75	-1.84	10.9
61089	Scone Soil Cons				-1.05	-1.35	29.4
63005	Bathurst ARS	-0.63		-1.33	0.73	-1.10	109.6
65012	Dubbo	0.14		-1.12	0.06	-0.89	44.9
66062	Sydney RO				-1.01	-1.32	11.3
67105	Richmond				-0.73	-1.15	13.4
68034	Jervis Bay	-0.62			-2.45	-3.06	41.4
68076	Nowra	-0.21		-0.62	-0.95	-1.93	32.4
69018	Moruya Heads	-0.35			-1.75	-1.99	20.3
70014	Canberra Airport	-0.21		-2.47	-0.23	-3.01	114.0
72150	Wagga Wagga	-0.76		-2.01	-0.08	-2.78	83.8
72161	Cabramurra	0.14	0.02	1.25		1.25	240.9
73054	Wyalong	0.90		-0.95	2.71	2.22	60.2
74128	Deniliquin	-0.26		-0.87	0.01	-1.31	63.2

Table 7.2e (cont.). Trends in frequency of maxima below 15°C, 1957-96

Station number	Station name	Trend (days/decade)					Mean annual days < 15°C
		Spring	Summer	Autumn	Winter	Annual	
76031	Mildura			-0.98	-1.03	-1.94	42.4
78031	Nhill	-1.00		-1.48	-0.22	-2.50	79.7
80023	Kerang	-0.09		-1.67	-1.22	-2.66	60.4
82039	Rutherglen	-0.58		-1.52	-1.19	-3.31	93.9
84016	Gabo Island	-0.19		-1.45	-3.28	-5.22	80.3
84030	Orbost	0.02		-0.50	-0.51	-0.81	61.3
85072	Sale	-2.38		-3.49	-2.82	-8.69	86.7
85096	Wilsons Promontory	1.12	0.34	-1.06	-0.75	-0.04	159.1
86071	Melbourne RO	-0.34		-1.69	-1.38	-3.36	79.7
87031	Laverton	0.51		-1.64	-1.23	-2.21	90.2
90015	Cape Otway	-0.12		-1.59	-0.67	-2.51	144.9
91057	Low Head	-2.38		-4.79	-3.21	-10.54	131.1
91104	Launceston AP	-0.94		-1.95	0.01	-1.96	151.6
92045	Eddystone Point	-6.93		-3.63	-4.35	-16.19	135.4
94010	Cape Bruny	-1.80	-0.53	-0.77	-0.69	-3.68	201.0
94029	Hobart RO	-0.92	0.11	-2.31	-1.96	-5.23	135.6
94069	Grove	-0.56	-0.11	-2.05	-1.03	-3.62	138.7
96003	Butlers Gorge	-3.65	-1.31	-3.45		-7.72	250.9

Stations not listed failed to meet the criteria for a trend to be calculated (see text) in any season or annually.

Table 7.2f. Trends in frequency of maxima below 10°C, 1957-96

Station number	Station name	Trend (days/decade)					Mean annual days < 10°C
		Spring	Summer	Autumn	Winter	Annual	
23373	Nuriootpa				-0.27	0.48	3.2
63005	Bathurst ARS				0.58	-0.29	23.8
65012	Dubbo				0.06	0.00	2.8
70014	Canberra Airport				-0.04	-0.70	17.7
72150	Wagga Wagga				-0.80	-1.05	9.0
72161	Cabramurra	0.35	0.00	-1.85	-0.65	-2.19	160.0
73054	Wyalong					0.58	3.3
74128	Deniliquin					0.46	2.1
82039	Rutherglen				-0.37	-0.74	9.3
85072	Sale				-0.29	-0.43	2.0
85096	Wilsons Promontory				-0.23	-0.32	5.1
87031	Laverton				-0.55	-0.56	2.7
91057	Low Head				-1.36	-1.54	6.0
91104	Launceston AP				-0.60	-0.54	22.0
94010	Cape Bruny	-0.35			-0.68	-2.18	25.8
94029	Hobart RO				-0.99	-1.95	18.3
94069	Grove	-0.20			-0.54	-1.08	23.0
96003	Butlers Gorge	-4.35	-2.72	-4.78	-1.31	-12.59	144.0

Stations not listed failed to meet the criteria for a trend to be calculated (see text) in any season or annually.

Table 7.2g. Trends in frequency of minima below 5°C, 1957-96

Station number	Station name	Trend (days/decade)					Mean annual days < 5°C
		Spring	Summer	Autumn	Winter	Annual	
7045	Meekatharra				-0.87	-0.81	12.6
8039	Dalwallinu	-1.34			-1.04	-2.66	28.1
8051	Geraldton	0.01			-0.54	-0.57	7.4
9021	Perth Airport	-0.56			-0.78	-2.45	16.1
9741	Albany	-1.38			-5.41	-7.37	25.8
9789	Esperance				-1.44	-2.53	6.5
10035	Cunderdin	-1.70			-2.16	-3.99	46.7
10648	Wandering	-2.43		-1.55	-2.90	-6.90	95.3
11052	Forrest	-1.23		0.82	0.44	-0.20	63.2
12038	Kalgoorlie	-1.96		-1.74	-2.82	-6.50	62.5
13017	Giles				0.19	-0.13	18.6
15548	Rabbit Flat*				0.96	0.75	29.0
15590	Alice Springs	-0.80		-0.85	-0.62	-2.29	66.3
16001	Woomera				-1.23	-4.39	30.4
16044	Tarcoola	-1.81		0.09	-0.65	-2.33	61.2
17031	Marree			-0.75	-2.10	-3.48	46.6
17043	Oodnadatta			0.12	-1.24	-1.17	39.9
18012	Ceduna	-3.06		-0.78	-3.84	-7.83	62.1
18070	Port Lincoln				-1.30	-1.48	3.6
21046	Snowtown	0.65		-0.72	-2.30	-1.61	60.6
22801	Cape Borda				-0.65	-0.74	2.4
23090	Adelaide RO	-0.50			-3.69	-4.08	21.1
23373	Nuriootpa	-0.21		-1.23	-4.74	-6.87	86.3
26021	Mt Gambier	-1.42	-0.90	-0.81	-4.26	-7.15	72.6
26026	Robe	-1.26			-1.01	-2.08	12.3
30045	Richmond				-1.46	-2.10	14.5
36007	Barcaldine				-1.48	-2.24	16.7
36031	Longreach				-0.16	-0.59	28.3
37010	Camooweal				-0.02	-0.18	9.9
38002	Birdsville				0.71	-0.27	25.9
38003	Boulia				-1.19	-1.11	12.6
39039	Gayndah				-1.91	-2.85	30.2
39083	Rockhampton				-2.90	-3.23	11.2
39128	Bundaberg				-1.29	-1.27	5.5
40004	Amberley	0.24		-1.41	-1.59	-2.66	54.3
40223	Brisbane Airport				-3.73	-3.71	15.2
42023	Miles	0.57		-2.39	-2.76	-4.20	67.0
43109	St. George				-1.01	-2.86	37.0
44021	Charleville	-1.71		-2.01	-3.65	-7.85	66.9
45017	Thargomindah				-1.99	-2.77	38.1
46037	Tibooburra				-0.27	-0.82	37.4
46043	Wilcannia	-0.20		0.84	-0.61	-0.14	51.7
48027	Cobar	-0.87		-1.82	-3.05	-5.74	54.0
48239	Bourke				-2.38	-3.29	45.2
52088	Walgett	-0.41		-2.32	-1.88	-4.10	72.3
53048	Moree	-1.26		-3.89	-3.14	-8.30	70.5
55024	Gunnedah Soil Cons	-0.43		-1.30	-2.14	-3.89	50.2

Table 7.2g (cont.). Trends in frequency of minima below 5°C, 1957-96

Station number	Station name	Trend (days/decade)					Mean annual days < 5°C
		Spring	Summer	Autumn	Winter	Annual	
56017	Inverell PO	-1.55		-1.43	-0.44	-3.45	134.3
59040	Coffs Harbour				-2.64	-4.12	23.3
60026	Port Macquarie				-5.93	-7.96	27.2
61078	Williamtown	-0.87			-2.09	-3.21	29.4
61089	Scone Soil Cons	0.69		-1.42	-2.73	-3.31	57.8
63005	Bathurst ARS	1.08		-1.24	0.20	0.59	152.9
65012	Dubbo	0.63		-2.25	-1.13	-2.77	95.5
67105	Richmond	0.33		-1.11	-1.29	-2.33	71.6
68076	Nowra	0.47			0.18	0.05	27.9
69018	Moruya Heads	-0.86			-0.79	-1.98	28.9
70014	Canberra Airport	-1.90		-3.47	-0.66	-6.35	151.1
72150	Wagga Wagga	-2.40		-1.83	-1.84	-6.02	111.8
72161	Cabramurra	0.70	-0.37	0.93		0.67	216.2
73054	Wyalong	0.02		-0.90	-1.76	-4.15	81.4
74128	Deniliquin	-0.55		-1.68	-0.79	-3.42	88.7
76031	Mildura	-1.23		-1.66	-0.90	-3.77	73.8
78031	Nhill	2.06		-0.61	-2.49	-0.11	101.9
80023	Kerang	-0.92		-0.59	-0.96	-3.12	68.8
82039	Rutherglen	1.89	0.93	0.69	-3.58	0.17	143.0
84016	Gabo Island					-0.74	2.8
84030	Orbost	-0.10		0.09	4.03	4.19	64.9
85072	Sale	-1.47		-1.80	0.35	-2.89	87.0
86071	Melbourne RO	-0.75		-0.54	-3.34	-4.63	23.7
87031	Laverton	-0.51		-0.60	-2.26	-3.63	72.3
90015	Cape Otway	-0.74			-1.00	-2.39	8.9
91057	Low Head	-1.42		-0.58	0.35	-1.46	39.8
91104	Launceston AP	-4.83	-3.57	-2.99	-1.63	-12.23	154.7
92045	Eddystone Point	-1.20		-1.27	-1.56	-4.01	29.9
94010	Cape Bruny	-1.09		-0.34	-3.90	-5.31	41.4
94029	Hobart RO	-1.35		-1.07	-0.31	-2.79	66.0
94069	Grove	-2.12	-0.28	-1.11	0.49	-3.16	156.6
96003	Butlers Gorge	0.52	0.73	0.55	-0.27	1.51	252.5

Stations not listed failed to meet the criteria for a trend to be calculated (see text) in any season or annually.

Table 7.2h. Trends in frequency of minima below 2°C, 1957-96

Station number	Station name	Trend (days/decade)					Mean annual days < 2°C
		Spring	Summer	Autumn	Winter	Annual	
8039	Dalwallinu				-1.10	-1.42	3.4
10035	Cunderdin				-0.91	-1.91	9.2
10648	Wandering	-2.97		-0.81	-1.51	-5.17	40.7
11052	Forrest				-2.09	-1.74	16.6
12038	Kalgoorlie				-2.30	-3.21	19.9
15548	Rabbit Flat*				-0.59	-0.53	9.4
15590	Alice Springs				-1.32	-2.76	33.4
16044	Tarcoola				-1.88	-2.10	21.5
17031	Marree				-2.55	-2.54	12.3
17043	Oodnadatta				-0.91	-0.68	10.4
18012	Ceduna	-2.13			-4.27	-7.35	21.9
21046	Snowtown	-0.02			-2.12	-2.26	15.4
23373	Nuriootpa	-0.57		-1.08	-5.68	-7.34	36.0
26021	Mt Gambier	-1.08		-0.91	-3.38	-5.36	18.7
36031	Longreach				-1.26	-1.38	8.2
39039	Gayndah				-1.31	-1.54	7.6
40004	Amberley				-2.11	-2.36	25.2
42023	Miles				-2.10	-3.48	33.8
43109	St. George				-1.21	-1.37	9.0
44021	Charleville				-1.64	-2.91	28.1
45017	Thargomindah				-0.64	-0.76	8.2
46037	Tibooburra				-0.34	-0.24	7.9
46043	Wilcannia				0.11	0.44	13.0
48027	Cobar				-3.49	-3.76	15.5
48239	Bourke				-1.88	-1.77	9.9
52088	Walgett				-0.60	-1.43	29.3
53048	Moree	-0.91			-3.78	-6.39	32.0
55024	Gunnedah Soil Cons				-2.22	-2.90	14.7
56017	Inverell PO	-1.46		-1.26	-1.28	-3.97	91.6
59040	Coffs Harbour				-2.01	-2.32	5.8
61078	Williamtown				-1.76	-1.88	5.6
61089	Scone Soil Cons				-0.66	-1.08	18.8
63005	Bathurst ARS	0.90		-1.66	-0.82	-1.39	88.9
65012	Dubbo	-1.33		-1.95	-2.05	-5.30	51.7
67105	Richmond				-0.49	-0.88	31.6
70014	Canberra Airport	-1.97		-2.80	-1.54	-6.40	93.7
72150	Wagga Wagga	-0.45		-0.84	-2.60	-3.86	51.9
72161	Cabramurra	0.71	-0.29	-1.77	-1.07	-2.44	150.9
73054	Wyalong	-0.14			-0.62	-2.75	29.3
74128	Deniliquin	0.42			0.02	0.12	29.3
76031	Mildura	-0.55		-1.03	-2.77	-4.34	24.9
78031	Nhill	0.29		-0.72	-1.53	-1.85	37.8
80023	Kerang				-3.49	-3.88	16.1
82039	Rutherglen	1.08		-0.18	-2.08	-0.97	75.4
84030	Orbost				1.05	1.37	16.1
85072	Sale	0.67		-0.43	2.41	2.64	27.1
86071	Melbourne RO				-1.40	-1.51	3.8
87031	Laverton	0.40			-1.70	-2.48	19.8

Table 7.2h (cont.). Trends in frequency of minima below 2°C, 1957-96

Station number	Station name	Trend (days/decade)					Mean annual days < 2°C
		Spring	Summer	Autumn	Winter	Annual	
91057	Low Head				-0.77	-0.78	4.4
91104	Launceston AP	-3.34		-1.05	-0.86	-5.36	73.8
92045	Eddystone Point				-0.78	-1.11	3.6
94010	Cape Bruny				-0.86	-1.12	4.3
94029	Hobart RO				-0.50	-1.34	11.1
94069	Grove	-0.97		-0.71	-0.40	-2.25	79.0
96003	Butlers Gorge	-1.64	-0.13	-0.97	0.98	-0.97	152.5

Stations not listed failed to meet the criteria for a trend to be calculated (see text) in any season or annually.

Table 7.2i. Trends in frequency of minima below 0°C, 1957-96

Station number	Station name	Trend (days/decade)					Mean annual days < 0°C
		Spring	Summer	Autumn	Winter	Annual	
10648	Wandering	-1.10			-1.77	-3.41	14.5
12038	Kalgoorlie				-0.88	-1.09	5.1
15590	Alice Springs				-0.77	-0.96	14.6
16044	Tarcoola					-0.96	4.3
18012	Ceduna				-2.74	-3.75	6.5
21046	Snowtown				-1.00	-0.91	3.0
23373	Nuriootpa				-5.08	-5.54	15.4
26021	Mt Gambier					-2.46	4.8
40004	Amberley				-0.57	-0.63	10.3
42023	Miles				-3.04	-3.19	17.1
44021	Charleville				-1.89	-2.17	12.6
52088	Walgett				-0.67	-0.66	10.7
53048	Moree				-3.84	-4.76	13.0
55024	Gunnedah Soil Cons				-1.39	-1.60	3.0
56017	Inverell PO	-0.43		-1.30	-2.36	-4.06	59.7
61089	Scone Soil Cons				-0.25	-0.16	4.4
63005	Bathurst ARS	0.06		-1.65	-2.02	-3.49	54.8
65012	Dubbo	-0.45			-2.79	-3.55	23.2
67105	Richmond				-0.86	-0.94	12.7
70014	Canberra Airport	-1.44		-2.77	-1.48	-5.70	63.0
72150	Wagga Wagga	-0.58			-2.01	-3.19	24.4
72161	Cabramurra	0.01		-2.04	0.36	-1.96	97.4
73054	Wyalong				-0.21	-0.23	8.0
74128	Deniliquin				-0.50	-0.48	8.1
76031	Mildura				-1.24	-1.32	5.8
78031	Nhill	-0.16		-0.99	-1.18	-2.30	13.7
80023	Kerang					-0.44	3.1
82039	Rutherglen	-0.14		-0.16	-2.27	-2.45	39.5
84030	Orbost					0.04	2.7
85072	Sale				1.12	0.91	7.6
87031	Laverton				-0.31	-0.72	4.9
91104	Launceston AP	-1.36		-0.92	-1.85	-3.76	34.9
94069	Grove	-0.39		-0.60	-1.06	-2.18	37.0
96003	Butlers Gorge	0.34	-0.29	0.36	1.87	2.72	81.7

Stations not listed failed to meet the criteria for a trend to be calculated (see text) in any season or annually.

Table 7.3. Percentage of stations with upward trends of percentile threshold event frequency, 1957-96

Threshold	Season	State							
		WA	NT	SA	Qld	NSW	Vic	Tas	Aus
5% minimum	Spring	21	0	8	8	24	45	14	18
	Summer	26	0	25	25	44	45	14	29
	Autumn	26	40	17	14	8	36	14	18
	Winter	11	20	0	4	24	23	14	12
	Annual	21	0	0	8	16	36	29	16
10% minimum	Spring	16	0	8	12	20	55	0	17
	Summer	21	0	33	12	40	36	21	25
	Autumn	21	20	17	12	4	27	0	14
	Winter	21	0	0	8	16	27	14	14
	Annual	21	0	0	12	20	36	14	17
90% minimum	Spring	84	100	67	88	64	73	86	78
	Summer	58	80	67	79	84	64	57	72
	Autumn	74	80	83	92	84	55	86	81
	Winter	84	80	83	88	96	64	71	84
	Annual	84	100	83	92	92	73	71	86
95% minimum	Spring	84	80	58	92	60	73	86	76
	Summer	58	60	58	87	68	55	57	67
	Autumn	68	80	92	92	80	64	86	81
	Winter	84	80	75	79	84	64	86	80
	Annual	84	100	83	96	80	73	71	84
5% maximum	Spring	42	40	0	71	40	18	0	38
	Summer	53	40	25	29	52	82	57	47
	Autumn	21	60	0	21	20	27	0	19
	Winter	42	0	8	58	32	18	14	33
	Annual	42	20	8	12	24	36	0	22
10% maximum	Spring	37	20	8	50	28	32	0	31
	Summer	71	20	42	21	52	73	29	46
	Autumn	21	20	0	8	8	9	0	10
	Winter	32	0	8	50	24	9	29	27
	Annual	26	20	8	8	12	9	0	13
90% maximum	Spring	74	80	58	71	52	45	71	37
	Summer	42	60	58	83	56	0	29	48
	Autumn	74	80	75	58	32	73	100	38
	Winter	89	100	83	79	80	64	100	17
	Annual	74	100	83	83	60	64	86	25
95% maximum	Spring	74	80	58	71	68	36	71	66
	Summer	48	60	67	75	44	27	43	53
	Autumn	74	80	75	54	28	73	100	60
	Winter	84	100	92	79	80	91	100	85
	Annual	74	80	83	79	60	64	86	73

Table 7.4. Percentage of stations with upward trends of fixed threshold event frequency, 1957-96

Threshold	Season	State							
		WA	NT	SA	Qld	NSW	Vic	Tas	Aus
Max > 30°C	Spring	60	100	50	82	56	37		63
	Summer	50	67	50	81	74	20	33	60
	Autumn	78	60	60	83	18	12		57
	Winter	80	100		67				78
	Annual	68	100	50	96	61	10	33	66
Max > 35°C	Spring	47	60	50	69	17	0		51
	Summer	50	75	40	83	71	12		59
	Autumn	71	75	60	56	88	100		68
	Winter	100	0						50
	Annual	56	100	40	85	56	78		60
Max > 40°C	Spring	50	67	67	50	0			53
	Summer	60	75	67	67	83	67		67
	Autumn	50							50
	Winter								
	Annual	65	75	57	80	50	67		66
Max < 15°C	Spring	0		0		27	30	0	15
	Summer					100	100	25	50
	Autumn	0		0		12	0	0	3
	Winter	33	0	9	100	36	0	17	27
	Annual	25	0	0	75	26	0	0	18
Max < 10°C	Spring					100		0	25
	Summer					50		0	25
	Autumn					0		0	0
	Winter			0		40	0	0	12
	Annual			0		36	0	0	14
Min > 20°C	Spring	70	100	60	78	88			78
	Summer	69	100	70	83	91	33		77
	Autumn	77	75	80	74	60			73
	Winter	33	100		60				56
	Annual	72	100	60	78	86	43		75
Min < 5°C	Spring	12	0	14	67	39	22	14	26
	Summer			0		0	100	33	33
	Autumn	33	0	29	0	13	22	14	18
	Winter	18	50	0	7	10	22	29	13
	Annual	0	50	0	0	14	20	14	9
Min < 2°C	Spring	0		0		33	80	0	32
	Summer					0		0	0
	Autumn	0		0		0	0	0	0
	Winter	0	0	0	0	11	25	14	9
	Annual	0	0	0	0	11	25	0	7
Min < 0°C	Spring	0				33	0	33	25
	Summer							0	0
	Autumn					0	0	33	11
	Winter	0	0	0	0	8	20	33	10
	Annual	0	0	0	0	0	29	33	9

7.1.2.1. High maximum temperatures

All indices of extreme high maximum temperatures show a general increasing trend, although these trends are smaller than those for any of the other extreme events considered. Seventy-four percent of stations show an increase in the frequency of temperatures above the 90^{th} percentile, 72% an increase in the frequency of temperatures above the 95^{th} percentile, and 66%, 60% and 66% an increase in the frequency of temperatures over 30°C, 35°C and 40°C respectively.

For the percentile thresholds, the most coherent area of decreasing trends is in inland New South Wales, along with the coast of southern New South Wales and eastern Victoria. Other areas of decreasing trends are found in north-western Queensland and the southern coasts of Western Australia and western South Australia. Most other stations show increases, with scattered exceptions. The strongest increasing trends (generally more than 5 days/decade for the 90^{th} percentile) occur on the east coast of Queensland north of Bundaberg, in parts of central Australia, and in northern Tasmania.

Examining the seasonal breakdown, substantial areas of seasonal decreasing trends are found in the following areas:

- spring: south-eastern South Australia, southern New South Wales and most of Victoria (except the west coast), along with north-western Queensland.
- summer: south-western Western Australia, parts of inland northern NSW, all of Victoria and most of Tasmania, and much of the far north of Australia.
- autumn: parts of south-western Western Australia, south-eastern Queensland and most of New South Wales (except the north coast and far south), and parts of north-western Queensland and the Northern Territory.
- winter: north-western Queensland and the south coast of New South Wales.

The proportion of stations showing increasing trends is greatest in winter (83% for the 90th percentile), and least in summer and autumn (52% and 62% respectively).

The 90^{th} and 95^{th} percentiles show generally similar trends and spatial distribution of changes, although one interesting difference between the two occurs in summer in south-eastern Australia: the Sydney region shows an increase in the frequency of maxima above the 90^{th} percentile but a decrease in the frequency of maxima above the 95^{th} percentile, whereas the reverse is true in parts of northern Victoria.

The results for fixed thresholds follow some similar patterns to the percentile thresholds – such as a tendency to strong increases in coastal Queensland and decreases along the southern coasts. Differences between the two largely reflect differences in where the fixed thresholds fit in the climate of a particular region and season. Examples of substantial differences include:

- most stations in Victoria and southern New South Wales show a decrease in the frequency of maxima above the fixed thresholds. This matches the observed trends for summer, but not for the year as a whole, for the percentile thresholds, which is an unsurprising result as maxima above 30°C (and, even more so, 35° and 40°C) in this region are largely a summer phenomenon.
- most Queensland stations show an increase in the frequency of autumn maxima above 30°C, whereas there is little trend for the percentile thresholds. This reflects the fact that 30°C is not a particularly extreme event in most of Queensland during that season. This trend is not observable when a 35°C threshold is used.

7.1.2.2. High minimum temperatures

All indices of extreme high minima show increasing trends. Eighty-three percent of stations show an increase in the frequency of minima above the 90th percentile, and 86% show an increase in the frequency of minima above the 95th percentile. Seventy-six percent of stations for which the index was defined show an increase in the frequency of minima above 20°C.

The strongest increasing trends appear in Queensland, particularly the north-eastern half, and the Northern Territory, with many stations in this area showing trends for the

90th percentile in excess of 5 days/decade. The only coherent areas of stations with a decreasing annual trend for any of the thresholds are in south-eastern New South Wales and eastern Victoria, and in northern South Australia and western Queensland. A few scattered and widely separated stations in other regions also show decreasing trends.

The proportion of stations with increasing trends is greatest in winter (84% for the 90th percentile), and least in summer (72%). Notable regional areas of decreasing trends are:

- spring: parts of inland New South Wales, eastern Victoria, northern South Australia and south-western Queensland.
- summer: south-western Western Australia, and scattered stations in central Australia and Victoria.
- autumn: eastern Victoria.
- winter: parts of northern Western Australia.

Stations with a decreasing trend in the frequency of minima above the fixed threshold of 20°C are scattered in all seasons, with the most coherent region of such trends in any season being in the south-western half of Queensland in autumn. The strongest increasing trends, as for the percentile thresholds, are in the Northern Territory and on the coasts of Queensland and northern New South Wales.

7.1.2.3. Low maximum temperatures

All indices of extreme low maximum temperatures show a decreasing trend at the vast majority of stations. Seventy-eight percent of stations have recorded a decrease in the frequency of maxima below the 10th percentile, and 87% a decrease in the frequency of maxima below the 5th percentile. For the fixed thresholds, the figures are 83% for maxima below 15°C and 86% for maxima below 10°C, although it should be noted that the latter index is only defined at 18 of the 103 stations, and at only four stations is it defined in any season other than winter.

These overall results conceal considerable spatial variation, as extensive areas display increasing trends for the percentile thresholds in one or two seasons – in most cases an increasing trend in one season is offset by a larger decreasing trend in another, to a greater extent than is found for the other indices. The stations that do exhibit increasing trends for the year as a whole are mostly widely scattered, with the only coherent areas of such stations being in parts of southern Western Australia and inland New South Wales for the percentile thresholds, and in interior southern Queensland and northern New South Wales (where such temperatures are a rare – 5-15 days per year – and almost exclusively winter phenomenon) for maxima below 15°C.

The strongest decreasing trends (greater than 5 days/decade for the 10th percentile) are found in Tasmania and coastal South Australia, with particularly strong trends in that region in spring and autumn. Southern Victoria shows strong decreasing trends in winter, as do the northern Northern Territory and parts of northern South Australia.

Notable regional areas of increasing trends for the percentile thresholds in each season are:

- spring: much of Queensland, and inland New South Wales.
- summer: most of Victoria and southern New South Wales, south-western Western Australia and much of tropical Australia away from the eastern Queensland and northern NT coasts.
- autumn: parts of the Northern Territory and far eastern WA.
- winter: most of inland Queensland and adjacent regions of northern New South Wales.

Increasing trends are most common in summer (46% of stations for maxima below the 10th percentile) and least common in autumn (10%), a departure from the winter minimum observed for most of the other indices of extreme temperature.

It is interesting to note that Western Australia, which shows an increase in the frequency of extreme low summer maxima, has also shown a marked increase in summer rainfall between 1910 and 1995 (Hennessy et al., 1999), and particularly over the 1957-1996 period, with the trend accelerating in the later years of that period (see Fig. 7.3). In most of Australia away from the southern coasts extreme low maxima in summer mostly occur as a result of persistent cloud cover and/or rain (rather than through the presence of an air mass of southern origins), so this combination of results is not especially surprising.

The marked decrease in the frequency of extreme low maxima in the winter half of the year over those regions of south-eastern Australia that are particularly exposed to westerly and south-westerly flow may point to synoptic changes. An analysis of possible synoptic changes is beyond the scope of this thesis, but the possible implications of changes in the frequency distribution of maximum temperature are discussed in section 7.2.

7.1.2.4. Low minimum temperatures

The declining frequency of low minimum temperatures is the strongest trend for any of the four types of extremes considered in this study. This is particularly true of the fixed thresholds; more than 90% of stations show a decreasing trend in the frequency of minima below 5°C, 2°C and 0°C. The trend is not so striking for the percentile thresholds, but 84% of stations still show a decreasing trend in the frequency of minima below the 5th percentile, and 83% for the 10th percentile.

Those stations which do show increasing trends for any of the indices are mostly widely scattered. The one region with a number of stations showing increasing trends, particularly for the percentile thresholds, is eastern Victoria and south-eastern New South Wales. Particularly strong declines have occurred in much of Queensland and the Northern Territory, the south-west of Western Australia and southern South Australia, with many stations in those regions showing trends in excess of 5 days/decade for the 10^{th} percentile, and some exceeding 10.

All seasons and thresholds show a strong majority of stations with decreasing trends. As for the other indices, the proportion is smallest in summer (75% for minima below the 10th percentile) and greatest in winter (86%), but the seasonal differences are weaker than for the other indices.

Regions where a number of stations with increasing trends can be found for the percentile thresholds are:

- spring: much of northern Victoria and the tablelands of New South Wales.
- summer: the southern two-thirds of New South Wales, eastern Victoria and western Queensland.
- autumn: eastern Western Australia.
- winter: eastern Victoria and the far south-east of New South Wales.

As the previously noted results would suggest, stations showing an increasing trend for any of the fixed thresholds over the year as a whole are very rare. A notable seasonal exception, however, is that many Victorian and elevated New South Wales stations show an increase in the frequency of low minimum temperatures (particularly when 2°C is used as the threshold) in spring. As this is a region where late spring frosts are already an agricultural hazard (and either 2°C, or, historically, 36°F (2.2°C), has been routinely used as a threshold to determine the occurrence of frost in Australia (e.g. Foley, 1945)), this is a result of some potential significance.

7.1.3. Results over extended periods starting before 1957

The analysis of trends in the frequency of extreme temperature events prior to 1957 is made difficult, as discussed in Chapter 2, by the lack of digitised daily temperature data prior to that date. Of the 103 stations in the data set, only nine have 60 years or more of data, and three of these (Adelaide, Melbourne and Sydney) are city-centre sites where the existence of urban heat islands limit the use of the data for the analysis of climate change. There is a project currently in progress to digitise more historical daily data, which will enable such trends to be calculated over a longer period at many more stations, and over a much greater proportion of the Australian continent.

The remaining six stations, all in New South Wales, have data commencing in 1921 - the Moree data commences earlier, but the variety of instrument exposures in existence in New South Wales prior to 1908 (Torok, 1996; also discussed in the diaries of H.C.Russell, held in the National Meteorological Library) render that data difficult to use without reference to comparison data (which does not exist in a digitised form) from neighbouring stations. The 1921-56 data should still be treated with some caution because of a similar lack of comparison data for use in making adjustments for inhomogeneities.

Tables 7.5 and 7.6 show the observed trends for the percentile and fixed thresholds at the six stations for each season over the 1921-96 period. The spatial distribution of positive and negative trends is quite similar to those for the shorter 1957-96 period, with strong warming trends for most thresholds at the northern coastal sites (Yamba and Port Macquarie) and Tibooburra in the north-west, and more mixed results at Moruya, on the south coast, and Bathurst and Moree in central regions of the state. Also, similarly to the situation for the 1957-96 period, there is little statewide trend in the frequency of high maximum temperatures (and the decreasing trend in autumn which is so marked in 1957-96 is also visible for 1921-96), but a discernable trend for the other types of extreme events.

A comparison of the 1921-96 trends with those over the 1957-96 period is illuminating. Of the 48 percentile trends examined (8 indices at 6 stations), 35 show a 'warmer' trend over the 1957-96 period than over the full 1921-96 period, indicating an acceleration of a warming trend in temperature extremes over New South Wales over the last 40 years. This is consistent with the Australian annual mean temperature (http://www.bom.gov.au/climate/change/archive/media00.shtml), which showed little trend over the 1921-56 period before beginning a marked increase in the late 1950's.

7.2. Observed changes in parameters of frequency distributions of temperature

Changes in the parameters of the frequency distribution of daily maximum and minimum temperature were examined. This was carried out by breaking the time period of common record of most stations, 1957-1996, into two equal parts, 1957-1976 and 1977-1996.

For each station and month, and for maximum and minimum temperature separately, the parameters of the frequency distribution were calculated for each of these two periods, treating each as a separate distribution and using the compound Gaussian distribution model and decomposition procedure described in Chapter 6. For reasons of computational simplicity, only those stations/months where two component distributions had been found for the full period of record were used. This excluded 9% of station-months for maximum temperature and 12% for minima.

Two component distributions were used for each 20-year period. The two-distribution model was used, even though, in some cases, this model may have failed a goodness-of-fit test for an individual 20-year period.

Rabbit Flat and Learmonth were excluded from this part of the analysis, due to a lack of data in the 1957-1976 period.

The parameters of the component distributions for each 20-year period are given in Appendix D (Tables D.1a, D.1b).

7.2.1. The relationship between observed changes in threshold event frequency and changes predicted by the compound Gaussian distribution

In order to verify the effectiveness of the compound Gaussian distribution in modelling changes in the frequency of threshold events, the changes in the frequency of four threshold events (maxima and minima with a normalised value, z (as defined in Chapter 6) above +3.0 or below –3.0) in each of the four seasons were examined. The threshold of +/- 3.0 was chosen for consistency with the checks carried out on the overall effectiveness of the compound Gaussian distribution in modelling the frequency of extreme temperature events in Chapter 6.

The expected frequencies of these events from the modelled frequency distributions were calculated for the periods 1957-76 and 1977-96. The expected percentage change between the two periods was then calculated. This expected percentage change was compared with the actual percentage change from observed data between the two periods. Only stations which recorded at least one such threshold event in both of the periods were used in the analysis.

Station number	Station name	Threshold	Trend (days/decade)				
			Spring	Summer	Autumn	Winter	Annual
46037	Tibooburra	5% minimum	-0.24	-0.99	-0.72	0.13	-1.64
		10% minimum	-0.34	-1.47	-1.10	-0.19	-2.85
		90% minimum	0.47	1.33	0.94	0.94	3.21
		95% minimum	0.23	0.64	0.48	0.48	1.74
		5% maximum	0.04	0.01	-0.45	-0.12	-0.56
		10% maximum	-0.11	-0.07	-0.46	-0.30	-0.97
		90% maximum	-0.03	0.32	-0.12	0.00	0.29
		95% maximum	0.00	0.24	0.07	0.41	0.79
53048	Moree	5% minimum	-0.63	-0.76	-0.68	-0.78	-2.69
		10% minimum	-1.12	-1.36	-1.10	-1.22	-4.65
		90% minimum	0.12	0.41	1.36	0.57	2.35
		95% minimum	-0.10	0.14	1.01	0.52	1.52
		5% maximum	0.39	0.20	0.24	0.34	1.16
		10% maximum	0.78	0.44	0.32	0.63	2.16
		90% maximum	-1.18	-1.47	-0.57	-0.23	-3.41
		95% maximum	-0.57	-0.87	-0.45	-0.21	-2.09
58012	Yamba	5% minimum	-0.45	-0.61	-0.58	-0.81	-2.42
		10% minimum	-0.68	-0.95	-1.23	-1.23	-4.06
		90% minimum	0.96	0.75	0.62	0.24	2.58
		95% minimum	0.62	0.41	0.43	0.12	1.56
		5% maximum	-0.47	-0.54	-1.07	-0.86	-2.99
		10% maximum	-0.74	-1.02	-1.48	-1.58	-4.84
		90% maximum	0.64	-0.43	0.18	0.55	2.58
		95% maximum	0.18	-0.33	0.16	0.32	1.56
60026	Port Macquarie	5% minimum	-0.90	-1.14	-1.10	-1.22	-4.31
		10% minimum	-1.42	-2.04	-2.09	-2.26	-7.81
		90% minimum	-0.12	1.45	0.76	0.63	2.75
		95% minimum	-0.04	0.93	0.24	0.24	1.34
		5% maximum	-0.78	-0.42	-0.54	-0.44	-2.10
		10% maximum	-1.13	-1.01	-0.72	-1.06	-3.86
		90% maximum	-0.24	1.20	0.94	0.40	2.35
		95% maximum	0.22	0.69	0.34	0.30	1.57
63005	Bathurst ARS	5% minimum	0.24	0.15	0.18	-0.40	0.18
		10% minimum	0.14	0.17	0.39	-0.60	0.14
		90% minimum	0.21	-0.14	0.29	0.08	0.46
		95% minimum	0.07	-0.22	0.10	0.00	-0.04
		5% maximum	0.47	0.03	-0.42	0.08	0.16
		10% maximum	0.88	0.25	-0.53	-0.12	0.48
		90% maximum	-1.21	-0.58	-0.62	0.31	-2.10
		95% maximum	-0.67	-0.39	-0.59	0.28	-1.34
69018	Moruya Heads	5% minimum	0.29	0.59	0.24	0.87	1.95
		10% minimum	0.45	0.77	0.57	1.57	3.32
		90% minimum	-0.85	-0.98	-0.52	-0.30	-2.66
		95% minimum	-0.50	-0.46	-0.26	0.07	-1.18
		5% maximum	-0.09	-0.17	-0.66	-0.57	-1.51
		10% maximum	-0.48	-0.59	-1.17	-1.38	-3.61
		90% maximum	-0.09	-0.48	-0.05	0.22	-0.36
		95% maximum	-0.25	-0.08	-0.02	0.22	-0.11

Table 7.5. Trends in frequency of percentile threshold events, 1921-1996

Station number	Station name	Threshold	Trend (days/decade)				
			Spring	Summer	Autumn	Winter	Annual
46037	Tibooburra	Max > 30°C	0.21	0.20	-0.16		0.15
		Max > 35°C	-0.12	-0.48	-0.84		-1.51
		Max > 40°C		0.27			0.28
		Max < 15°C				-0.06	-0.23
		Max < 10°C					
		Min > 20°C	0.38	2.63	1.07		3.56
		Min < 5°C				-0.29	-0.78
		Min < 2°C				-0.20	-0.28
		Min < 0°C					
53048	Moree	Max > 30°C	-1.11	-0.55	-1.12		-2.56
		Max > 35°C	-0.99	-1.83			-3.04
		Max > 40°C					
		Max < 15°C				0.97	1.01
		Max < 10°C					
		Min > 20°C	0.23	1.69	0.10		1.96
		Min < 5°C	-0.54		-1.87	-0.92	-3.31
		Min < 2°C	-0.22			-1.67	-2.29
		Min < 0°C				-1.42	-1.74
58012	Yamba	Max > 30°C	-0.02	-0.06			0.03
		Max > 35°C					
		Max > 40°C					
		Max < 15°C					
		Max < 10°C					
		Min > 20°C	0.41	1.85	0.38		2.52
		Min < 5°C					
		Min < 2°C					
		Min < 0°C					
60026	Port Macquarie	Max > 30°C					0.20
		Max > 35°C					
		Max > 40°C					
		Max < 15°C				-0.63	-0.75
		Max < 10°C					
		Min > 20°C		2.47	-0.03		2.28
		Min < 5°C	-0.44			-3.50	-4.54
		Min < 2°C				-1.43	-1.52
		Min < 0°C					
63005	Bathurst ARS	Max > 30°C		-0.50			-1.45
		Max > 35°C					
		Max > 40°C					
		Max < 15°C	0.54		-0.71	-0.35	-0.59
		Max < 10°C				0.02	-0.08
		Min > 20°C					
		Min < 5°C	-0.30		-0.06	-0.09	-0.44
		Min < 2°C	-0.11		0.15	0.42	0.41
		Min < 0°C	0.20		-0.02	-0.09	0.05
69018	Moruya Heads	Max > 30°C		-0.06			-0.02
		Max > 35°C					
		Max > 40°C					
		Max < 15°C	-0.24			-2.17	-2.50
		Max < 10°C					
		Min > 20°C		-0.80			-0.88
		Min < 5°C	0.03			1.12	1.11
		Min < 2°C					
		Min < 0°C					

Table 7.6. Trends in frequency of fixed threshold events, 1921-1996

The results of this comparison are summarised in Table 7.7, with the full list of comparisons in Appendix D, tables D.2a-d. Whilst the simulation using the compound normal distribution clearly lacks precision in estimating the observed changes (the actual change is between 0.8 and 1.2 times the simulated change in between 26% and 37% of cases, depending on the element), a reasonable simulation (actual change between 0.5 and 1.5 times the simulated change) is achieved in between 61% and 74% of cases.

These results should be viewed with the perspective that a z value above +3.0 or below –3.0 is a rare event, and that in many cases the observed frequency in a 20-year period of 0.05 or 0.06% represents a single event in a 20-year period. As a result, one event in the observed record can have a major effect on the accuracy of the simulation for the most extreme events.

In those cases where $|z| > 3.0$ represents an event which occurs somewhat more frequently at the particular station (frequency > 0.5% over the 1957-96 period), the simulation is substantially better than it is for the set of stations as a whole, with a single exception (which involved a very small sample). The simulated change was between 0.5 and 1.5 times the actual change for at least 83% of such cases for every element. This suggests that the performance of the compound Gaussian distribution in simulating the occurrence of threshold events improves as the event becomes less extreme.

The results displayed in Table 7.7 also suggest that there is no inherent tendency for the simulation using the compound Gaussian distribution to either over-estimate or under-estimate the actual change in the frequency of threshold events.

7.2.2. Observed changes in the frequency distribution of maximum and minimum temperatures.

Changes in the parameters of the component distributions between the 1957-76 and 1977-96 periods were examined for each station/month in which two component distributions had been sufficient to model the distribution for the full period of record.

A proportion of the distributions underwent radical change between the two periods. A distribution was considered to have undergone radical change if at least one of the two component distributions fulfilled at least two of the following three (arbitrary) criteria:

(a) a change exceeding 0.2 in the weight, w_l

(b) a change exceeding 0.5 in the component mean, μ_n

(c) a change exceeding 0.5 in the component standard deviation, σ_n

((b) and (c) being expressed in terms of z-scores).

Station/months that fulfilled these criteria were not considered further in the analysis. This resulted in the exclusion of between 13% and 23% of station/months (depending on season and element).

A summary of the results from the remaining station/months is given in Tables 7.8a and 7.8b. In each case, distributions 1 and 2 are chosen such that $\mu_1 < \mu_2$.

A majority of Australian stations show an increase in the means of both the warmer and cooler component distributions in all seasons, and for both maximum and minimum temperature. For maximum temperature, this trend is almost equally observable in all seasons for the warmer and cooler components, and is strongest in spring and weakest in winter. For minimum temperature, whilst results for the year as a whole are similar for the two components, the warmer component shows a particularly strong increase in autumn, whilst the cooler component shows a strong increase in winter.

A majority of Australian stations show a decrease in the weighting of the cooler component in all seasons and for both maximum and minimum temperature. The decreases are more widespread for minimum temperatures than for maxima, and are particularly pronounced for minima in winter and spring.

Table 7.7. Similarity between changes in frequency of extreme events (|z| > 3) observed between 1957-76 and 1977-96, and changes modelled by compound normal distribution

Event		Element			
		High maxima	High minima	Low maxima	Low minima
Percentage of cases within 20%	All cases	37	26	37	32
	Cases with frequency > 0.5%	58	67	49	25
Percentage of cases within 50%	All cases	70	61	74	68
	Cases with frequency > 0.5%	90	100	88	83
Percentage of cases where actual change > modelled change		45	58	56	51
Total number of cases	All cases	187	142	177	104
	Cases with frequency > 0.5%	78	9	51	12

Table 7.8a. Summary of changes in parameters of frequency distributions between 1957-76 and 1977-96, maximum temperature

Season	Region	Percentage of cases with increase in				
		w_1	μ_1	σ_1	μ_2	σ_2
Spring (Sep-Nov)	Western Australia	56	75	50	56	50
	Northern Territory	36	91	64	64	55
	South Australia	60	86	41	93	66
	Queensland	38	59	54	62	46
	New South Wales	37	72	56	72	70
	Victoria	45	71	39	75	71
	Tasmania	50	94	25	81	75
	Australia (total)	45	74	48	70	60
Summer (Dec-Feb)	Western Australia	61	54	65	51	54
	Northern Territory	60	80	20	70	30
	South Australia	53	59	45	41	72
	Queensland	31	72	48	76	48
	New South Wales	44	60	58	70	45
	Victoria	32	28	36	48	68
	Tasmania	45	58	58	47	53
	Australia (total)	44	59	50	60	54
Autumn (Mar-May)	Western Australia	39	68	49	49	49
	Northern Territory	50	90	90	80	30
	South Australia	46	54	46	50	63
	Queensland	32	54	65	75	39
	New South Wales	43	59	57	52	48
	Victoria	46	54	57	57	50
	Tasmania	29	93	50	93	54
	Australia (total)	40	62	58	62	47
Winter (Jun-Aug)	Western Australia	64	56	52	58	47
	Northern Territory	54	100	64	73	64
	South Australia	38	56	36	44	56
	Queensland	51	57	64	55	50
	New South Wales	48	48	39	53	50
	Victoria	50	77	59	55	55
	Tasmania	17	67	39	61	67
	Australia (total)	48	59	50	55	53

Table 7.8b. Summary of changes in parameters of frequency distributions between 1957-76 and 1977-96, minimum temperature

Season	Region	Percentage of cases with increase in				
		w_1	μ_1	σ_1	μ_2	σ_2
Spring (Sep-Nov)	Western Australia	23	66	56	78	59
	Northern Territory	30	60	20	80	40
	South Australia	35	65	50	54	62
	Queensland	45	65	41	63	63
	New South Wales	33	53	29	40	57
	Victoria	42	53	53	42	74
	Tasmania	61	77	58	69	54
	Australia (total)	36	61	44	57	60
Summer (Dec-Feb)	Western Australia	44	67	37	52	52
	Northern Territory	25	75	50	50	50
	South Australia	40	65	35	65	25
	Queensland	37	59	61	75	57
	New South Wales	36	52	48	65	46
	Victoria	50	60	58	44	48
	Tasmania	50	21	43	43	36
	Australia (total)	41	56	49	61	47
Autumn (Mar-May)	Western Australia	35	63	45	84	55
	Northern Territory	43	86	43	86	57
	South Australia	43	65	35	65	57
	Queensland	53	64	59	82	47
	New South Wales	36	57	46	84	22
	Victoria	48	48	44	48	36
	Tasmania	55	63	26	74	47
	Australia (total)	44	61	45	77	41
Winter (Jun-Aug)	Western Australia	44	52	44	68	60
	Northern Territory	14	43	43	14	86
	South Australia	31	67	50	44	63
	Queensland	34	60	36	47	50
	New South Wales	28	60	44	54	51
	Victoria	77	73	55	59	50
	Tasmania	50	75	42	42	58
	Australia (total)	38	61	44	51	55

The results for standard deviations of the components are much more mixed than for means or weightings, although there is a very slight tendency towards increased variability of maximum temperatures and decreased variability of minima. One consistent result is that a majority of stations show a decrease in the standard deviation of the cooler component in all four seasons.

The results observed for the distribution means suggest that the observed warming in Australia over the 1957-96 period is distributed across all air masses, and cannot be explained by synoptic changes alone. The changes in distribution weighting are not so easy to interpret without knowledge of the exact air mass characteristics associated with each component distribution (and, as has been discussed in section 6.5, it is likely that, with only two component distributions in use, each one is an amalgamation of several air mass types). For example, the marked decrease in the weighting of the cooler component for winter and spring minimum temperature could suggest an increase in cloud cover. Plummer and Power (pers.comm.) found evidence of such an increase over the 1957-95 period over most of Australia in these seasons (except for south-western Australia in winter), whilst Jones (1991) and Jones and Henderson-Sellers (1992) also found an increase in cloud cover over Australia since 1910, whilst not separating results into seasonal or regional trends. One might, however, also expect that this increase in cloud cover would be associated with an increase in the weighting of the cooler component for maxima in these seasons. There is no evidence of that on a national basis, although there is on a regional scale (e.g. South Australia and Western Australia in spring, and Queensland and the Northern Territory in winter).

The results shown are also consistent with the observation that trends in threshold event frequency are stronger for low minima than for other types of events, as all three parameters of the cooler component are changing in a way that has the effect of decreasing the frequency of low minima (decreasing weight, increasing mean and decreasing standard deviation), whereas the role of changes in component variability is more ambiguous for the other three threshold event types. The results are, however, less useful in explaining the relatively weak trends observed in the frequency of high maxima.

Whilst it has been demonstrated in section 6.5.3 that the sensitivity of threshold event frequency to changes in the standard deviation of the components increases (relative to sensitivity to changes in component means or weights) as the event becomes more extreme, the lack of evidence of consistent changes in component standard deviations limits the applicability of that theoretical result to the observed conditions.

The relationship of changes in the distribution parameters to regional and seasonal anomalies in threshold event trends was also examined. It was shown in section 7.1 that most threshold event indices showed their strongest warming in winter and weakest in summer. The changes in summer distribution parameters on a national scale, for both maxima and minima, support the notion of it being a season of relatively weak change (the increases in component means and of the weighting of the warmer component do not rank first amongst the seasons for any of the six parameters). However, the changes in distribution parameters also suggest that winter maxima should show changes as weak as those for summer, which does not match the observed trend in threshold event frequency. This is not so pronounced for minima, but the distribution parameters still suggest that spring and autumn, not winter, should be the seasons with the strongest trends.

The distribution model is more accurate in handling some of the regional anomalies observed. A particularly interesting result is that the marked reduction in the frequency of low maxima observed in Tasmania, Victoria and parts of South Australia in the cooler months appears to be associated more strongly with an increase in the mean of the cooler component than with a decrease in its weighting. This would suggest that the observed trend is driven by an increase in the temperature of air masses of southerly or south-westerly origin, rather than a decrease in the frequency of such events. It is plausible that this might be associated with an increase in winter sea surface temperatures in the Southern Ocean, although there are insufficient pre-1980 data available from higher latitudes in the Southern Ocean to allow the objective testing of such a theory (Slutz et al., 1985).

The anomalously strong warming of minimum temperatures (and consequent marked decrease in the frequency of low minima) observed in Queensland also appears to be more strongly associated with changes in component means than with their weights, with the proportion of stations showing an increase of the mean of each of the two components exceeding the national average in all seasons except winter. Changes in component means are also associated with the observed cooling trends in threshold event frequencies for summer maxima in Victoria, whilst a cooling trend in the mean of the warmer component for spring minima in New South Wales matches an observed decreasing trend in the frequency of high maxima.

On the other hand, Western Australia and the Northern Territory show an increase in the weight of the cooler component of summer maximum temperatures. Whilst the component means are still warming (weakly in Western Australia, more strongly – albeit from a small sample – in the Northern Territory), this result is consistent with the observed increase in the frequency of low summer maxima in much of this region, and further reinforces the possibility, first noted in section 7.1, that that change may be driven by the increased summer rainfall in the region.

Some of the regional anomalies in observed threshold event trends are not replicated well by the distribution model, or only match the model partially. Examples of the latter are the observed trends in spring towards an increased frequency of low maxima in Queensland and low minima in Victoria. In each case, whilst the changes in the component means suggest weaker warming than in other states (particularly in Queensland, where the figure of 59% of stations with a warming in the mean of the cooler component for maxima is 12% below that for any other state), they do not support cooling. Similarly, the results from the distribution model suggest little change in the frequency of high autumn maxima and low summer minima in New South Wales, whereas the observed trends point to cooling in both cases.

7.3. Summary

The results obtained for individual stations show that, at most stations and in most seasons, the frequency of warm extremes (maxima and minima) has increased over the period 1957-1996, and the frequency of cool extremes has decreased. The trends have, in general, been stronger for cool extremes than for warm extremes, and stronger for minima than for maxima, suggesting that a decrease in the diurnal temperature range and a decrease in interdiurnal temperature variability may be superimposed upon a general warming trend. The compilation of the station results into national and regional averages will be undertaken in Chapter 8.

The general picture that emerges from an analysis of changes in the frequency distribution is one of changes in threshold event frequencies being driven primarily by changes in the mean temperature of air masses. Changes in component weightings, which could suggest synoptic changes, appear to play a more limited role, with the exception of much of tropical Australia in summer where changes in component weights may be associated with rainfall and cloud cover changes.

Chapter 8

Regional Trends in Spatially Analysed Temperature Data

8.1. Introduction to the spatial analysis of temperature data

In chapters 6 and 7 the frequency of extreme temperature events at individual stations was discussed. In order to gain a broader perspective, it is useful to analyse the frequency of extreme events on a national and regional basis. This allows us to obtain a broader picture of trends over large areas, and summarise the results of a study such as this in a single result or a small number of results. It also minimises the impact of trends that may arise from the use of individual stations whose frequency of extreme events differs from that of their broader regions. For example, at exposed coastal stations, a reduction in the frequency of strong offshore winds, and hence a decline in the weight of the warmer component of the frequency distribution (as discussed in Chapters 6 and 7) is likely to lead to a reduction in the frequency of extreme high temperatures, even if the inland climate becomes hotter. The use of spatial averages furthermore lessens the influence of stations (especially the more isolated ones) where inhomogeneities in the record may have been undetected or inadequately corrected for because of a lack of suitable comparison data. When presenting the results to a non-technical audience (such as policy-makers) it is also far easier for them to understand a statement along the lines of 'The number of days over 35°C in Australia has increased by x%' than 'Positive trends in the frequency of maximum temperatures above the 95 percentile significant at the 5% level were observed at y out of z stations in Australia', even if the latter is more meaningful in a scientific sense.

The first question we must confront in the spatial analysis of extreme event frequency is whether the station network being used covers Australia sufficiently well for us to be able to say that there is at least one station that adequately represents any given part of the country. This issue will be discussed in section 8.2. We must also consider the methods used in the spatial interpolation of extreme event frequency between stations, and which is the most appropriate for use in the context we are examining.

8.2. The spatial coherence of Australian temperature data

8.2.1. Methods for consideration of spatial coherence

As a prelude to considering spatial averages of the frequency of extreme temperature events in Australia, it is important to consider the spatial coherence of temperature over the country. This is examined on both the monthly and daily timescale.

The method used involves the use of the correlation between temperatures at pairs of sites. These correlations are examined in two separate ways:

- Examine the pattern of correlations between a particular station and all other stations in the data set.
- Examine the characteristic distance from a station at which the correlation falls to a certain level, and any tendency to strong or weak correlations in a particular direction from a station.

The correlations are developed using the set of 103 stations defined in Chapter 2. The basic data used are the set of standardised departures from normal (z-scores) developed in Chapter 6. For each pair of stations from amongst the 103, the correlation of the z-scores between the two is determined, for maximum and minimum temperature separately for each of the 12 months of the year. As a separate exercise, the correlation of the monthly means of the z-scores is also found.

For the daily correlations, all days in the record for which data are available for both stations were used in the calculation. For the monthly correlations, all months for which a mean is defined at both stations were used. (The requirement for a mean to be defined was that at least 20 days (not necessarily the same 20) of observations were available.

The smallest number of years of record for any station pair is 18 (Learmonth and Butlers Gorge) and the largest is 138 (Melbourne and Sydney).

For each month, for maximum and minimum temperature, this results in a set of cross-correlation coefficients for each pair of the 103 stations.

8.2.2. Patterns of correlations of daily temperature between stations

An exhaustive examination of the correlation patterns for each of the 103 stations in all seasons would clearly be unmanageable. Section 8.2.3 presents a national analysis of important characteristics of the correlation patterns for all stations. In this section, we will present examples of the patterns at specific stations in specific seasons.

Figs. 8.1a-m. shows examples of the correlation fields with maximum and minimum temperature at a number of stations which illustrate characteristics of the correlation fields.

Notable features exhibited in these figures include the following:

(a) The general NW-SE orientation of the correlation fields of summer daily maximum temperature in extratropical eastern Australia, and winter daily maximum temperatures in tropical Australia

Many stations in extratropical eastern Australia (for these purposes, bounded approximately by the Western Australian border and the Tropic of Capricorn) show a marked NW-SE orientation of the correlation field, indicating that summer maximum temperatures at stations in this region tend to be more strongly correlated with stations to their north-west and south-east than similarly distant stations to the south-west and north-east. Of the plots shown, this feature is exhibited most strongly by Wagga Wagga (Fig. 8.1a), Melbourne (Fig. 8.1c) and Adelaide (Fig. 8.1d) in January, but is also visible at Sydney (Fig. 8.1f) and Alice Springs (Fig. 8.1g).

The effect is even more obvious in tropical Australia in winter, as the plot for Charters Towers in July (Fig. 8.1j) shows; a belt with correlations exceeding 0.5 extends across the continent to northern Western Australia.

This pattern is less visible in the 'opposite' season (January in the tropics, July in the extratropics), as shown by the plots for Adelaide (Fig. 8.1e) and Charters Towers (Fig. 8.1i). It is non-existent for winter minimum temperatures in much of the south-east, as Wagga Wagga – with a near-circular correlation field in July (Fig. 8.1b) – illustrates. It is also nearly invisible in Western Australia (shown by Cunderdin (Fig. 8.1k)).

It is interesting to note that Seaman (1982), in an analysis of the spatial correlation of upper-air temperature and geopotential heights, also found a tendency towards a NW-SE (or, to be more precise, a WNW-ESE) oriented correlation field of those variables in the Australian extratropics.

(b) The marked influence of the east coast on suppressing the spatial coherence of daily maximum temperature

The east coast, particularly in New South Wales, has a marked effect on suppressing the spatial coherence of daily maximum temperature, especially in summer; coastal temperatures are relatively poorly correlated with those further inland, due to the influence of sea breezes in moderating coastal temperatures in otherwise hot conditions.

This has two influences on the correlation fields shown in the plots. The January plot for Wagga Wagga (Fig. 8.1a) demonstrates how sharply the correlations of daily maximum temperature fall away to the south and east as one approaches the coast. In addition, stations on the east coast themselves display weak correlations of daily maximum temperature with inland stations, as shown by the plot for Sydney (Fig. 8.1f). Interestingly, this effect does not appear to influence the Victorian coast, as a comparison of Melbourne (Fig. 8.1c) and Sydney illustrates – this may reflect the role of the

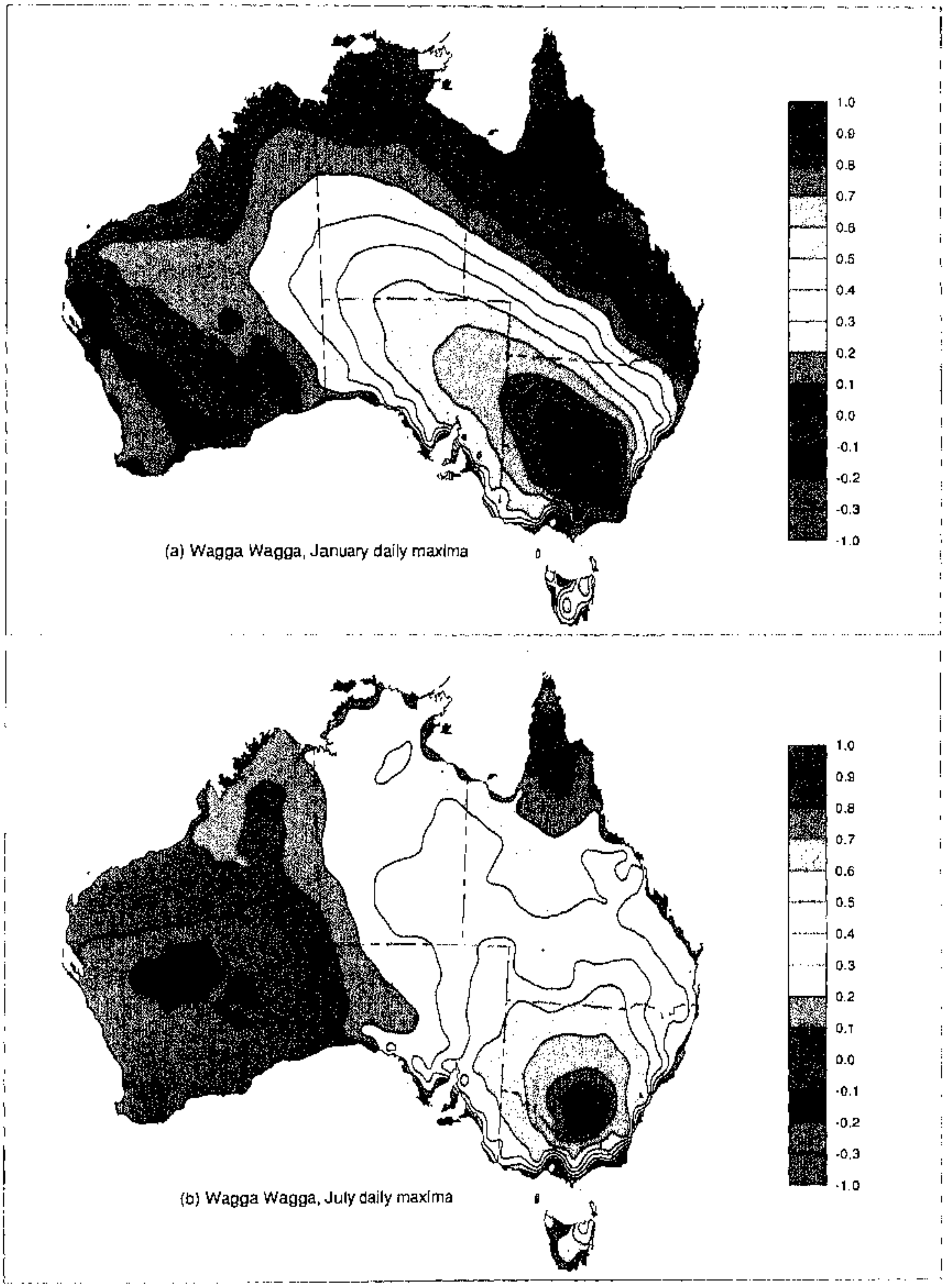


Fig. 8.1a-b. Examples of correlation fields for temperature

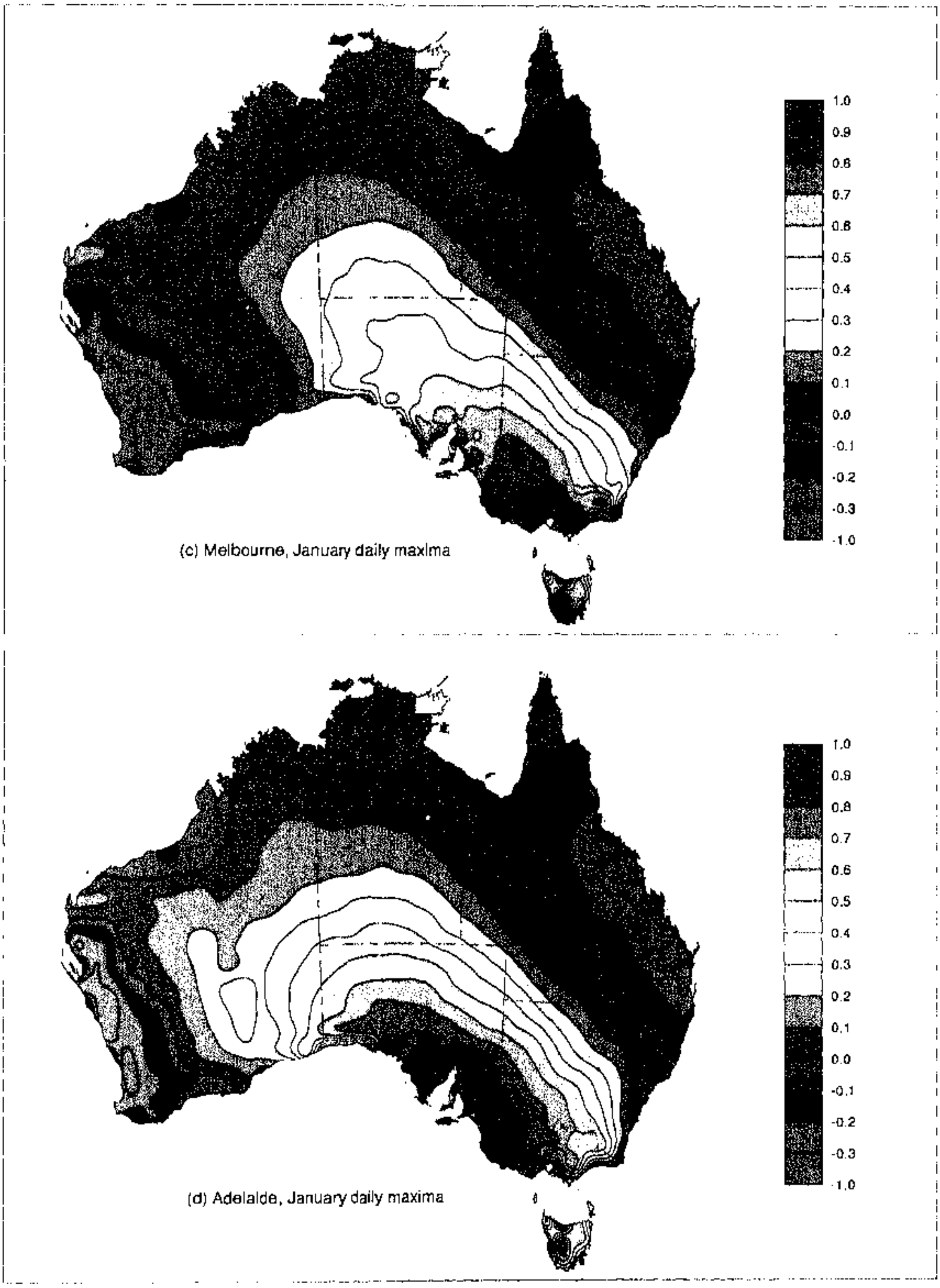


Fig. 8.1c-d. Examples of correlation fields for temperature

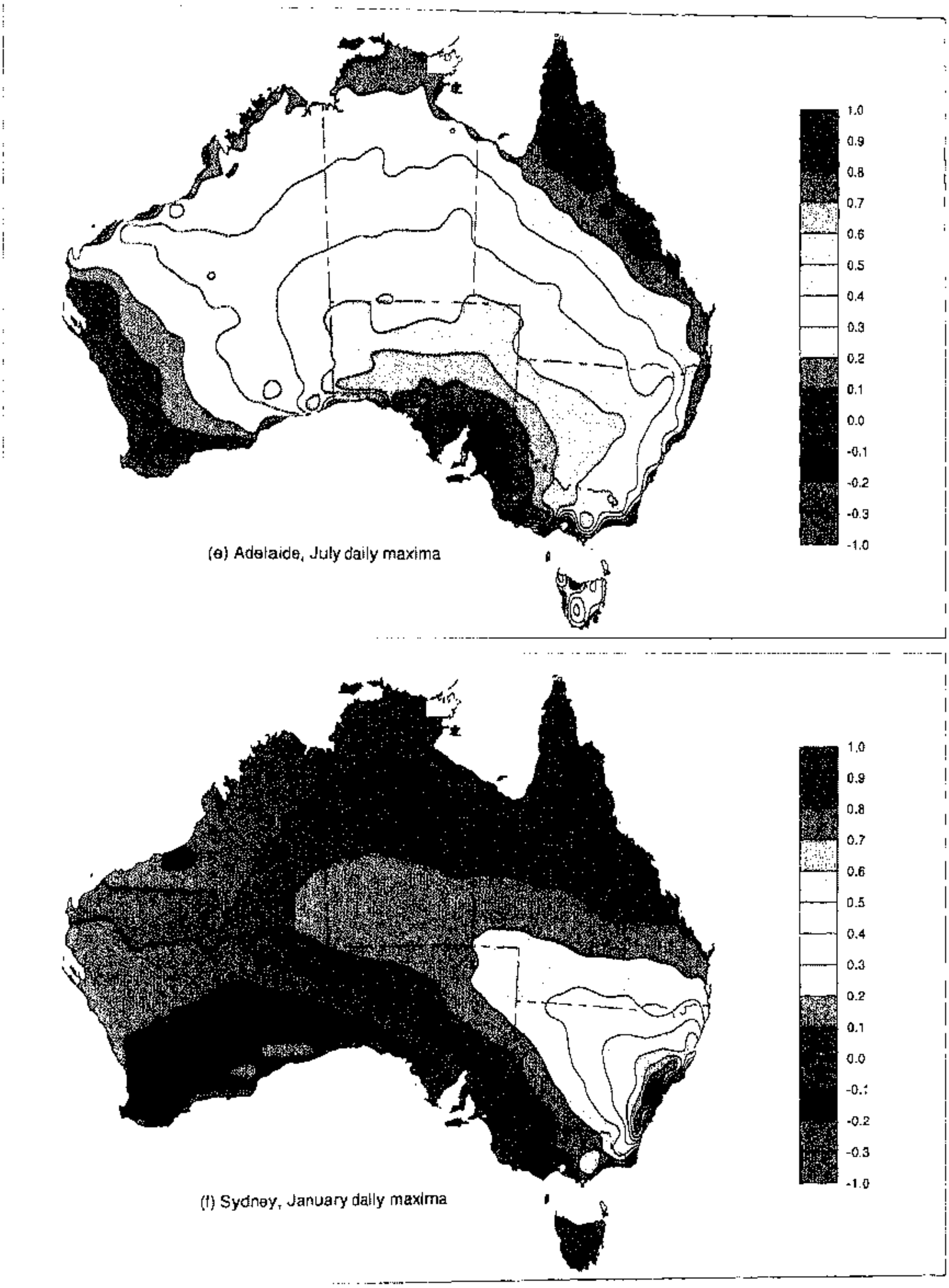


Fig. 8.1e-f. Examples of correlation fields for temperature

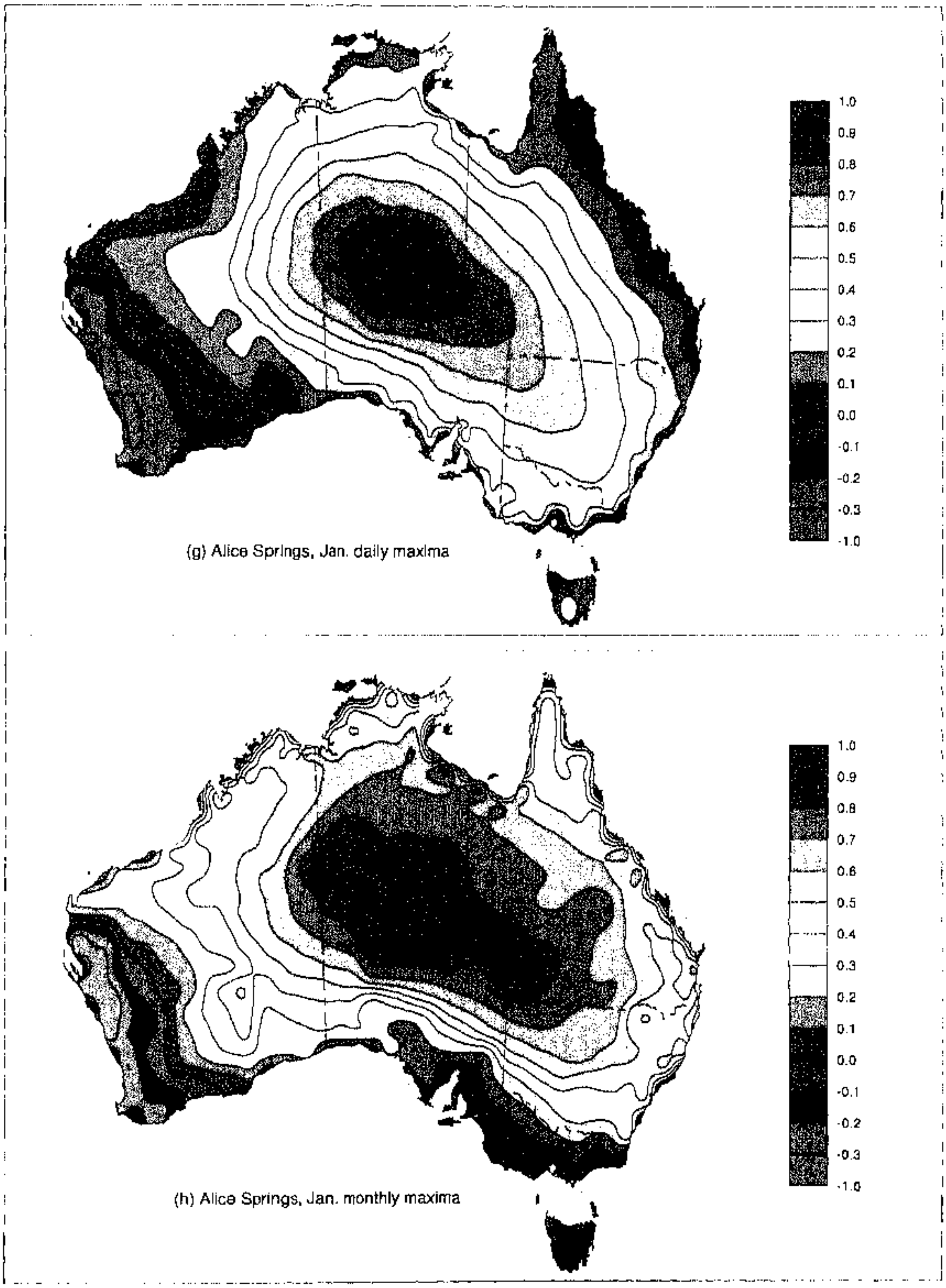


Fig. 8.1g-h. Examples of correlation fields for temperature

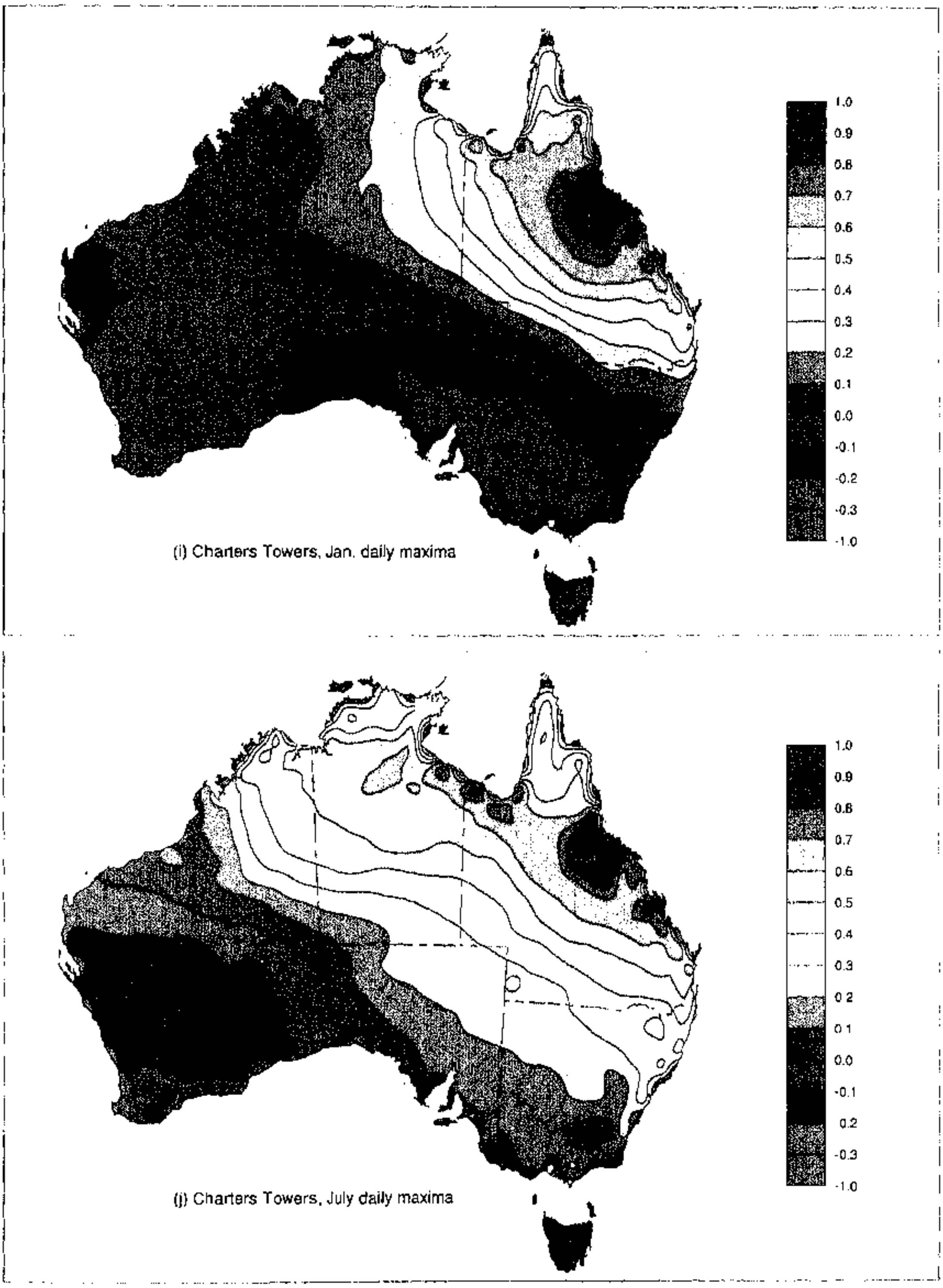


Fig. 8.1i-j. Examples of correlation fields for temperature

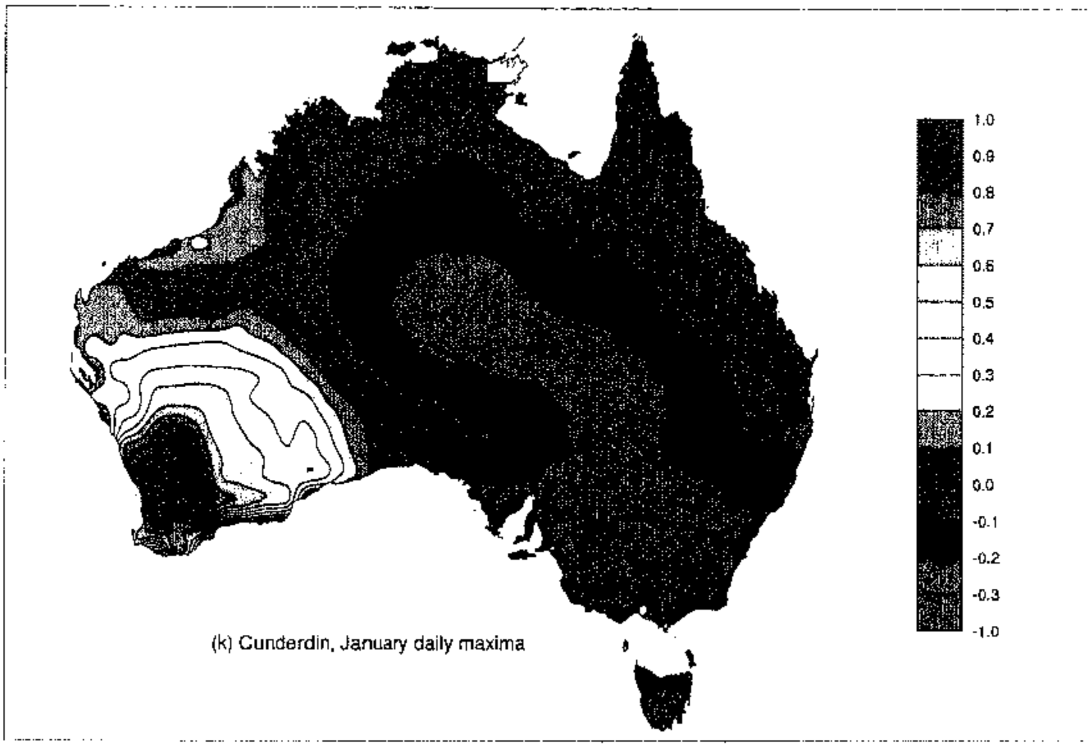
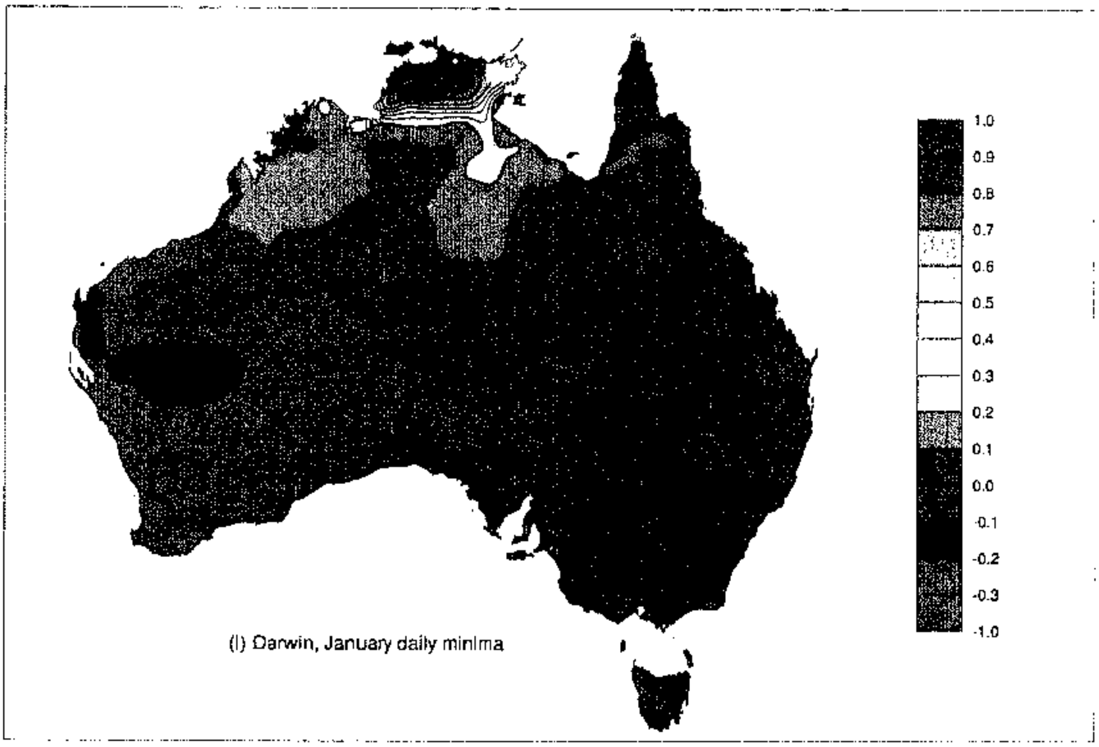


Fig. 8.1k. Examples of correlation fields for temperature



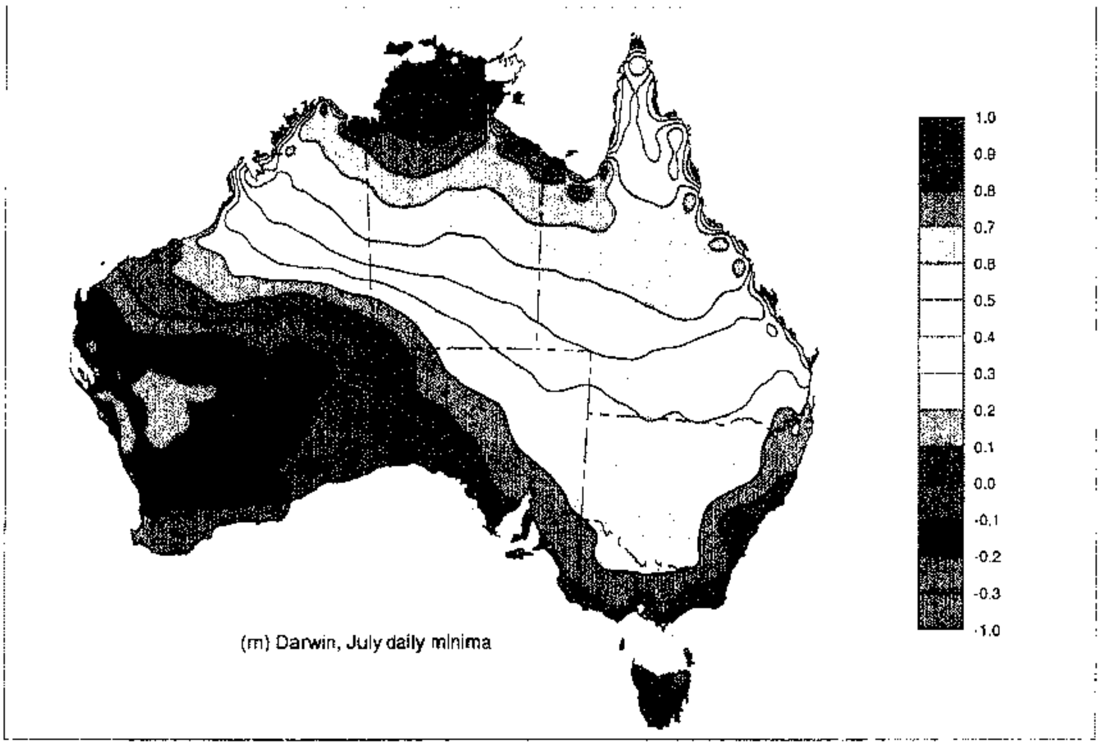


Fig. 8.1l-m. Examples of correlation fields for temperature

mountain barrier inland from the New South Wales coast, which has only a limited Victorian equivalent, in limiting the influence of hot air of inland origin on the coast. The Cunderdin plot (Fig. 8.1k) suggests a similar effect on the south coast of Western Australia, but the station network is not sufficiently dense to resolve this with the same degree of confidence as is possible in New South Wales.

(c) *The seasonal variation in the spatial coherence of daily minimum temperatures in tropical Australia*

There is a very marked seasonal variation in the spatial coherence of daily minimum temperature in tropical Australia. This is shown particularly strongly by the plots for Darwin for January (Fig. 8.1l) and July (Fig. 8.1m). In January, when low minimum temperatures occur principally as a result of downdrafts in thunderstorms – and are consequently localised – Darwin shows very weak correlations with all stations outside its immediate region. Conversely, in July, when low minimum temperatures occur principally in south-easterly surges – a broad-scale synoptic phenomenon – Darwin displays strong (> 0.4) correlations with most of the region north of the Tropic of Capricorn. A particularly striking contrast is that January minimum temperatures in Katherine display the same level of correlation with Darwin as do July minimum temperatures in northern Victoria!

8.2.3. Variation between the correlation fields on the daily and monthly timescales

An example of the difference between the correlation fields on the daily and monthly timescales is shown by the plots for January maximum temperature at Alice Springs (Fig. 8.1g, 8.1h). The monthly mean temperatures show greater spatial coherence than the daily temperatures, as one might expect, but differences and similarities in the nature of the fields are of interest. The most substantial differences between the two fields are that monthly mean temperatures on the Queensland coast are quite strongly correlated (0.4-0.6) with those at Alice Springs, whereas there is little or no correlation for daily temperatures between the two regions; and that monthly mean temperatures in Victoria and southern South Australia are much more weakly correlated with those at Alice Springs. than daily temperatures are, reaching the extent that in western Victoria and the far south-east of South Australia the daily temperatures are positively correlated with those at Alice Springs, but for monthly mean temperatures the correlations are negative.. This may reflect the role of the El Niño-Southern Oscillation in influencing temperatures on the monthly timescale; it is interesting to note that the pattern of correlations of monthly mean maximum temperatures with those at Alice Springs closely parallels the pattern of their correlations with the Southern Oscillation Index (Jones, 1999).

A similarity between the monthly and daily timescales is that both display quite strong negative correlations between Alice Springs and the west coast of Western Australia.

8.2.4. Calculation of the characteristic distance from a station at which correlations fall to a certain level

An indicator of the spatial coherence of temperature in a region is the characteristic distance at which the correlation of the temperature between pairs of stations falls to a certain level.

This is determined by carrying out the following procedure for each station and month, and for maximum and minimum temperature separately:

1. Analyse the correlations of all other stations with that station onto a 1° by 1° grid, using the Barnes analysis scheme initially described in section 4.2.3.
2. For each of the correlation thresholds 0.8, 0.6 and 0.4, find the number of grid points where the analysed correlation exceeds the threshold.

3. Determine the proportion of land within the radius from the station at which the correlation exceeds the threshold level. This is determined by finding, for each of the 10 distances 1, 2,..., 10 degrees (calculated as the Pythagorean distance, treating the latitude/longitude grid as a regular grid, as previously defined in Chapter 4) the proportion of land, and hence the land area (expressed as a number of grid points), within that radius of the station. This gives a set of land areas within a radius of 1, 2, ..., 10 degrees of the station.
4. Find the estimated radius which corresponds to the number of grid points in step 2, by finding the pair of calculated land areas from step 3 which that number of grid points lies between. (For example, if step 3 gives 140 land grid points within 7 degrees of the station and 170 land grid points within 8 degrees of the station, and step 2 gives 155 grid points with a correlation exceeding 0.4, this gives an estimated radius between 7 and 8 degrees).
5. Find the proportion of land within the estimated radius of the station by linearly interpolating between the proportions found for fixed radii either side of the estimated radius in step 3.
6. Find the 'equivalent land area' with correlations exceeding the threshold by dividing the number of grid points found in step 2 by the proportion of land within the estimated radius found in step 5. This step has the effect of nominally extending the region of correlations over a threshold over the ocean.
7. Find the characteristic radius of a certain correlation by finding the radius of the circle which has the area of the 'equivalent land area' in step 6.

Maps of the characteristic radius of the 0.4 correlation for each of four mid-season months (January, April, July and October), adopted as a broad indicator of the spatial coherence of the variables under examination, are displayed for daily temperature data in Figs. 8.2a (maximum temperatures) and 8.2b (minima), and for monthly data in Figs. 8.3a and 8.3b. The full list of characteristic radii of the threshold correlations for each station are listed in Appendix E (Tables E.1a-d).

These maps show clearly the regional and seasonal variations in the spatial coherence of temperature, and the differences between the spatial coherence of temperature on the daily and monthly timescale.

Daily maximum temperature

The characteristic radius of the 0.4 correlation for daily maximum temperature is greater over most of Australia than that for daily minimum temperature, and shows less seasonal variation, although values are generally lower in summer than winter. In winter the radius exceeds 1000 km over most of Australia, reaching 1400 km in parts of Queensland and the Northern Territory, whereas in summer 1000 km is only reached over parts of the inland south-east. The lowest values occur in summer on those coasts where sea-breezes have the greatest influence on maximum temperatures – New South Wales and the southern half of Western Australia – with 358 km being reached at Carnarvon in January.

Daily minimum temperature

The most striking result is the complete seasonal reversal in the geographical pattern of the spatial coherence of daily minimum temperature. Minimum temperature shows weak spatial coherence over most of northern Australia in summer, with the characteristic radius of the 0.4 correlation below 500 km over most of the tropics and closer to 300 km in the far north, but in winter the radius exceeds 1000 km over almost all of this region (except for the Cape York Peninsula), and reaches 1521 km at Darwin. (This is consistent with the correlation fields for Darwin displayed in Figs. 8.1l and 8.1m). Even more strikingly, using Darwin as an example, much of the shift takes place in a single month – the radius increases from 678 km in April to 1630 km in May, then decreases from 1146 km in September to 428 km in October. This behaviour appears to reflect the role of mesoscale phenomena, such as thunderstorms, in influencing low minimum temperatures in the tropical wet season – radiational cooling at night is not the influence on minimum temperatures here that it is elsewhere in Australia. Southern coasts display the opposite pattern, with the characteristic radius having a summer maximum and winter minimum.

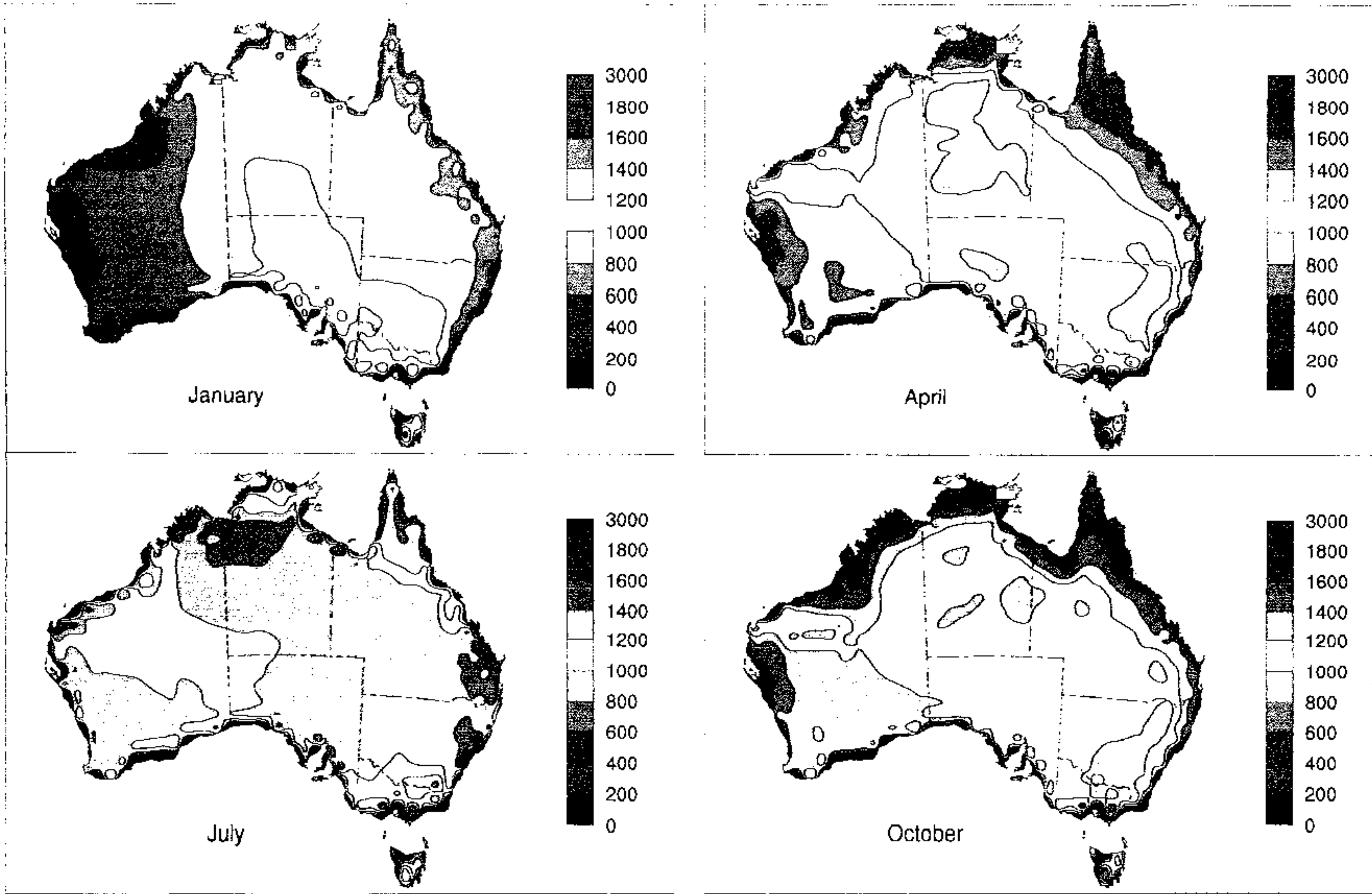


Fig. 8.2a. Characteristic radius of correlations - daily maximum temperature

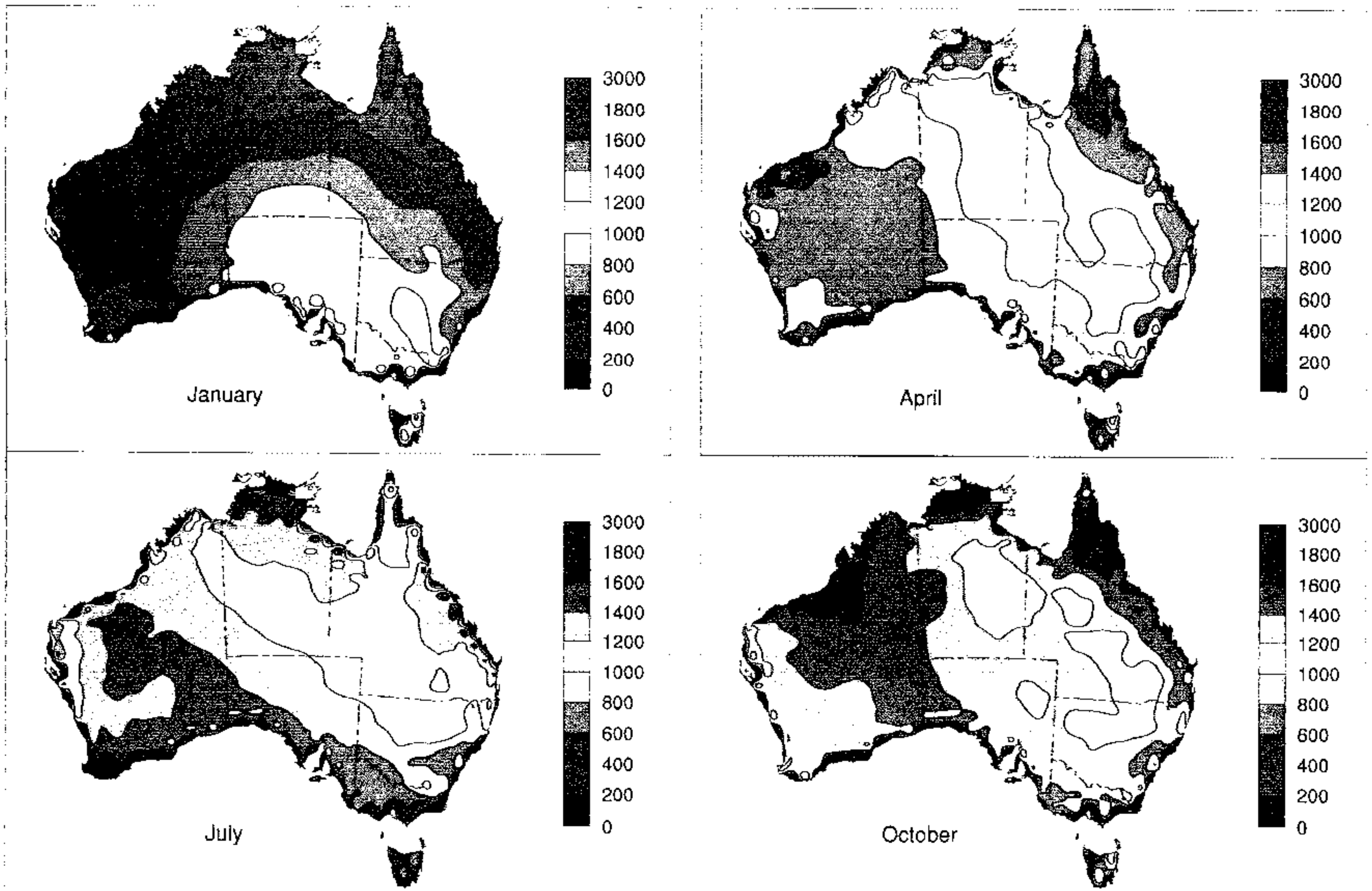


Fig. 8.2b. Characteristic radius of correlations - daily minimum temperature

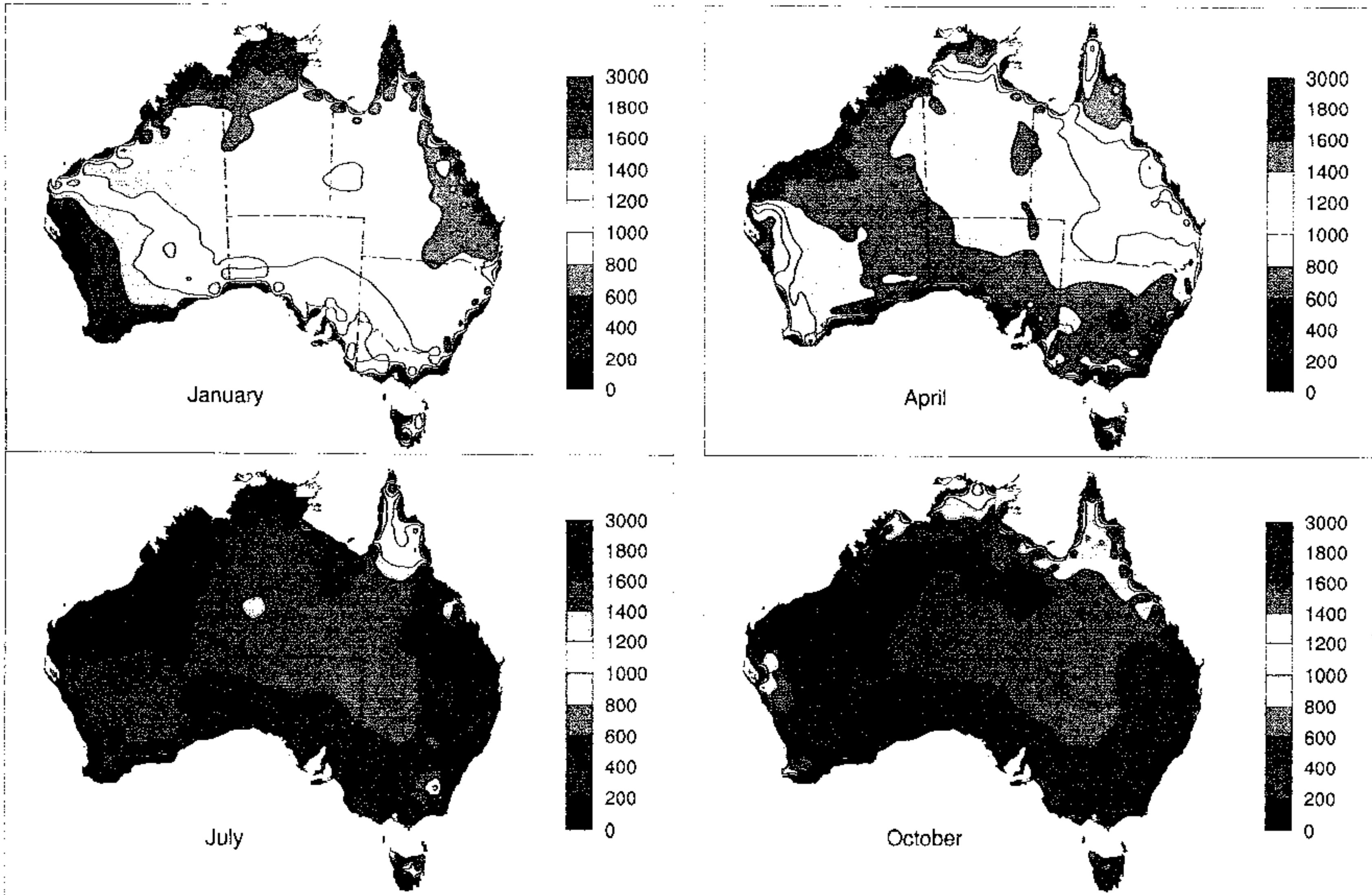


Fig. 8.3a. Characteristic radius of correlations - monthly maximum temperature

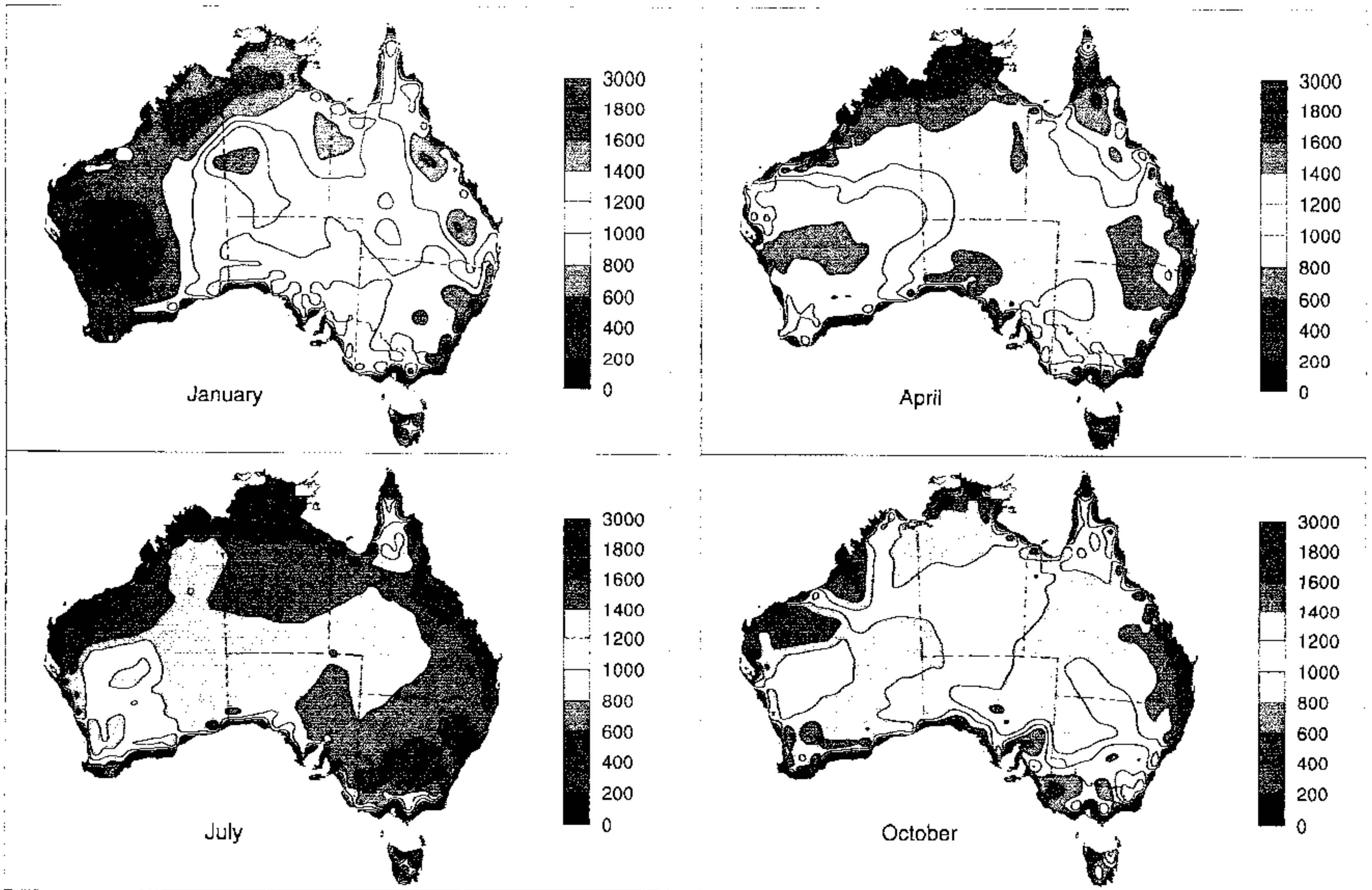


Fig. 8.3b. Characteristic radius of correlations - monthly minimum temperature

although the contrasts are weaker (at Melbourne, the radius is 935 km in January and 576 km in July).

Monthly mean maximum temperature

Generally speaking, the monthly mean temperatures are more spatially coherent than their daily counterparts. This is an expected result, as the statistical noise inherent in daily temperatures would be expected to be reduced when averaged over a monthly mean. The regional patterns of spatial coherence, however, differ considerably from those at the daily timescale.

Monthly mean maximum temperature is the most spatially coherent of the variables under consideration, with the characteristic radius of the 0.4 correlation exceeding 1000 km over the vast majority of Australia in all seasons, the only real exceptions being the coasts of northern and western Australia at times in summer and autumn. The lowest values occur on the coasts of Western Australia, with January values of 501 km at Albany and 450 km at Carnarvon.

During winter, the characteristic radius exceeds 1400 km over almost all of Australia, and reaches 2000 km in northern New South Wales and southern Queensland. Even in summer, it reaches 1600 km in parts of the Northern Territory and Queensland, and exceeds 1200 km away from the southern coasts. Inland southern New South Wales is a region of strong spatial coherence of maximum temperature in all seasons.

Monthly mean minimum temperature

The largest values of the characteristic radius of the 0.4 correlation occur during the winter half-year, approaching 2000 km in parts of northern Australia during April and July. 1100 km is exceeded over almost all of Australia in winter, except for the south coast of Western Australia. The sharp drop in the spatial coherence of daily minimum temperatures along the southern coasts from summer to winter has no counterpart at the monthly timescale, although there is some evidence of a spring minimum there. On the other hand, northern Australia shows a marked winter peak, as it does at the daily timescale. Darwin shows very marked changes between months in spring and autumn, as it does for the daily timescale, but the timing is slightly different (jumping from 875 km in March to 2037 km in April, then dropping from 1454 km in October to 406 km in November). This may reflect the strength of the main monsoon as an influence on mean monthly temperatures in this region, while daily temperatures are influenced by individual storm events, which take place over a slightly longer season.

As at the daily timescale, the characteristic radius is generally shorter in western than it is in eastern Australia.

A comparison with rainfall

By way of comparison, the spatial coherence of daily and monthly rainfall, using data from the same stations as temperature, is displayed in Figs. 8.4 and 8.5. These show that temperature shows substantially greater spatial coherence than rainfall. Monthly rainfall displays a characteristic radius of the 0.4 correlation which is generally of comparable magnitude to daily temperature, while daily rainfall is even less spatially coherent, with the characteristic radius rarely exceeding 600 km in any season.

8.3. The development of spatial averages of Australian extreme temperature data

The following sections of this chapter are based on a set of 99 stations. This is the set of high-quality temperature stations described in Chapter 3, without island and Antarctic stations or the city locations in Sydney, Melbourne, Brisbane and Adelaide. Perth Airport is retained in the set, despite some evidence of an artificial warming trend since 1970 (presumably resulting from urbanisation), because of the lack of a suitable substitute non-urban station to represent the coastal region of Western Australia between Geraldton and Cape Leeuwin. As much of the available daily data commences in 1957, spatial averages are calculated for each year from 1957 to 1996 inclusive. There is insufficient spatial

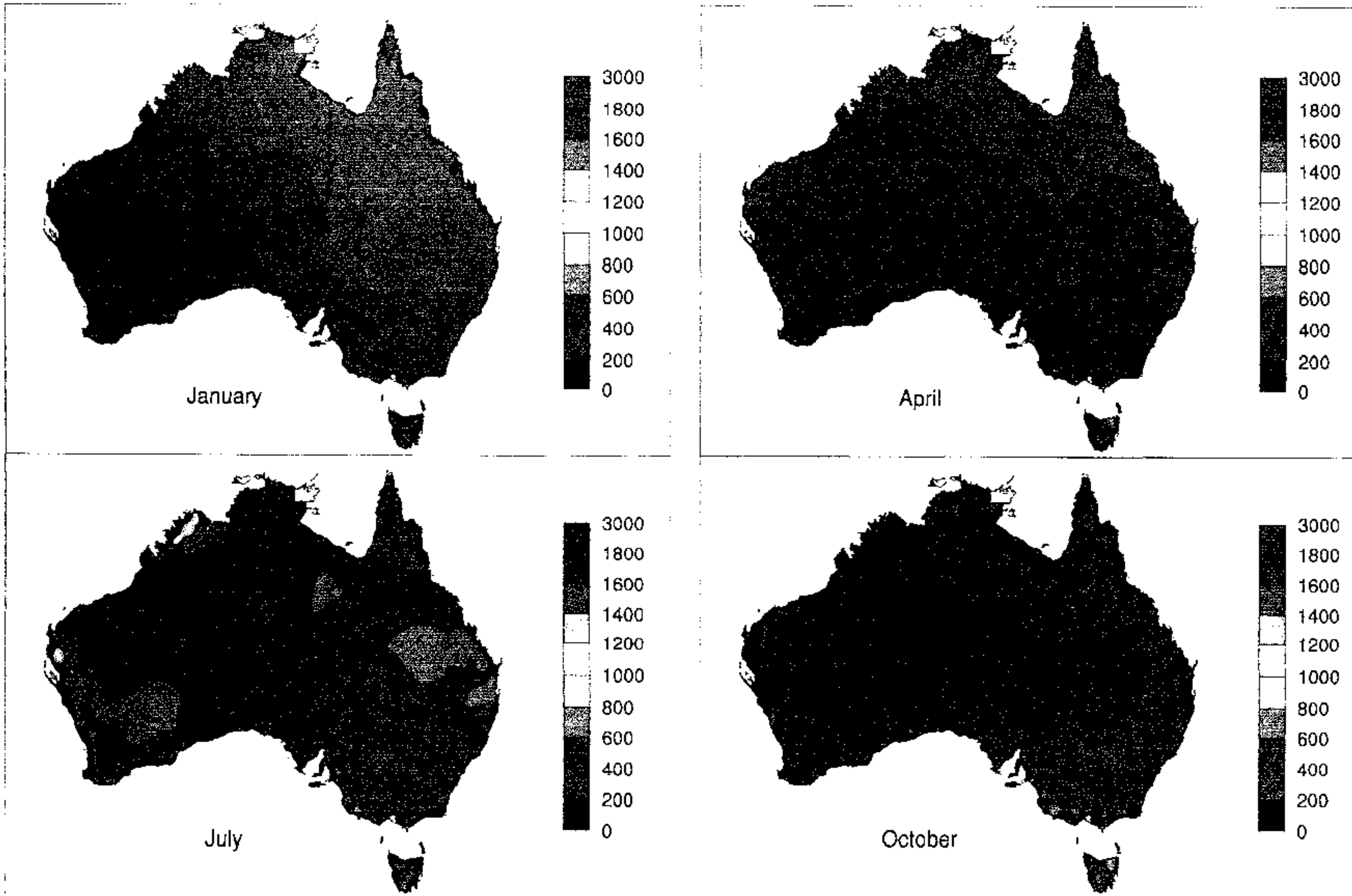


Fig. 8.4. Characteristic radius of correlations - daily rainfall

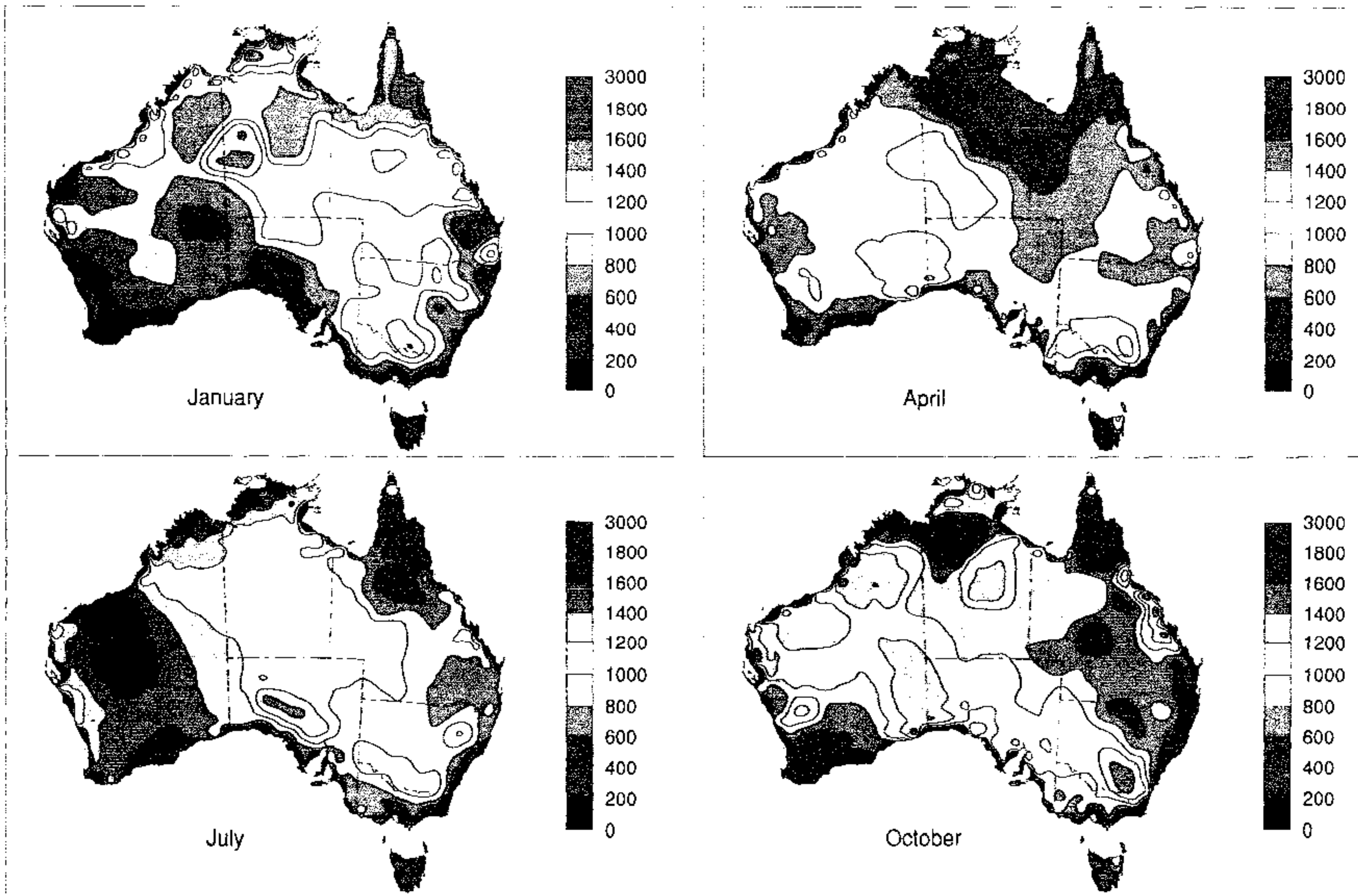


Fig. 8.5. Characteristic radius of correlations - monthly rainfall

coverage prior to 1957 to allow the analysis to be extended back beyond that year (at least until additional digitisation of manuscript data takes place).

8.3.1. Methods used in the development of spatial averages

The simplest possible method for calculating a spatial average is to take the arithmetic mean of data from a representative sample of stations for the period of interest. Whilst it is simple – and is the method used for the calculation of district average rainfalls for Australia (Jones and Beard, 1998) – the inadequacies of this method are obvious. It takes no account of changes in the density of stations (other than in the original choice of stations, if the station network is sufficiently dense to allow a choice of stations within it), meaning that areas with sparse station networks are under-represented in the results. Jones and Beard (1998) found substantial differences between district average rainfalls generated by this method and those generated by a more sophisticated gridding technique (for example, the mean annual rainfall for district 97, in western Tasmania, is 2320 mm in the conventional district series, but 1588 mm – 31% lower – using a grid-derived series, because of the clustering of long-term stations in the wetter parts of the district), while both they and Chappel (1995) found that changes in the station network in district 96 (central Tasmania) had led to an artificial increase in the district average rainfall in this region, if a simple arithmetic mean is used. Nicholls (2000) also found an artificial negative trend in mean annual rainfall in district 71 (Snowy Mountains), due to the closure of two stations in the wettest part of the district.

This deficiency was first recognised by Thiessen (1911), who developed a method of dividing a region into polygons by drawing lines equidistant from each member of a pair of neighbouring stations (the polygons thus produced contain all points that are closer to the station within that polygon than to any other). The spatial mean – of precipitation, in the case of Thiessen's paper – was then calculated by weighting the value at each station by the area of its associated polygon. This is now known as the method of Thiessen polygons.

Since Thiessen, there has been an extensive and increasingly complex literature in the development of spatial averages of climatological variables. These have been particularly well-developed for precipitation, because of the importance of a measure of total precipitation over a catchment in hydrology; the reader is referred to (insert review ref here) for a discussion of methods used in that field. Far less attention has been given to spatial averages of other climatological variables, including temperature. Nevertheless, there is a growing literature in the field. Jones et al. (1982) provides an extensive review of those methods which had been used to that time.

Analysis methods can be classified into the following broad categories:

(a) Grid-point values based on a function of distance between a station and the grid-point (e.g. Jones et al., 1986a, 1986b), sometimes with a lapse rate function and digital elevation models incorporated (e.g. Dodson and Marks, 1997) or successive correction (e.g. Barnes, 1964, 1973).

(b) Grid-point values based on a regression relationship with neighbouring stations (e.g. Bolstad et al., 1998).

(c) Statistical interpolation (sometimes referred to as optimal interpolation) (e.g. Lorenc 1981, 1986).

(d) Spline functions (e.g. Wahba and Wendelberger, 1980; Zheng and Basher, 1995), sometimes incorporating elevation as an explicit variable along with latitude and longitude (e.g. Hutchinson, 1991).

(e) Kriging (e.g. Hevesi et al., 1992; Hudson and Wackernagel, 1994).

(f) Optimal weighting of stations (e.g. Hardin and Upson, 1993).

The bulk of these studies have involved either the routine operational analysis of observational data for assimilation into operational forecast models (e.g. Lorenc, 1981, 1986), or the generation of fields of long-term mean values of climatological variables - for example, Hutchinson (1991) and Hudson and Wackernagel (1994) use their techniques to generate fields of monthly climatological means of maximum and minimum temperature.

Those studies which have compared methods in specific situations have, in general, found relatively small differences between techniques. Jones and Trewin (2000b), in an examination of the effectiveness of the Barnes successive correction technique, statistical interpolation and thin-plate splines, found that, whilst statistical interpolation (SI) was the most effective (in the sense of producing the lowest root-mean-square (RMS) average error) of these methods for the interpolation of mean monthly maximum and minimum temperatures over Australia, the differences between the techniques were small (the RMS errors for the SI technique were 0.52°C for maxima and 0.55°C for minima, compared with 0.61°C and 0.62°C respectively for the Barnes scheme). Small differences were also found between kriging and a technique based on simple inverse-distance weighting and a lapse rate function by Dodson and Marks (1997), whilst Bolstad et al. (1998) found a regression-based technique performed better than kriging for their data set, noting that kriging did not perform well where data were sparse.

Given the small differences found between techniques, and the small differences in computational efficiency between the Barnes scheme, SI and splines (D. A. Jones, pers. comm.), it was decided to test the Barnes scheme (as the system that is in operational use within the Australian National Climate Centre), along with three schemes which were much more computationally simple and had been used previously for the compilation of large sets of spatial averages:

- Thiessen polygons (Thiessen, 1911)
- The method of Shepard et al. (1968)
- The method of Jones et al. (1986a, b)

8.3.2. Specific methods used in this study

8.3.2.1. The Jones method

This method was used by Jones et al. (1986a, b) in the development of a global data set of monthly mean temperatures on a grid of 5° latitude by 10° longitude.

Each station is associated with its nearest grid point (i.e. each station only influences the value at one grid point). For each grid point, the monthly mean temperature anomaly of all stations associated with that grid point is averaged, with the value from each station weighted using the weighting function:

$w_i = 1/d_i$ where d_i = the distance between the station and the gridpoint or 50 nautical miles, whichever is the greater

(the 50 nautical miles condition being added to prevent problems arising when a station is very near the gridpoint).

The global mean temperature anomaly is then calculated as the arithmetic mean of the value at all grid points. This method uses distance as the sole criterion for the weight that a station carries in the calculation of the station mean.

8.3.2.2. The Shepard method

This method, like the Jones method, associates each data point with a single grid point. However, in addition to using distance as a criterion for the weight a station carries, Shepard's method uses a measure of the angular density of stations. The principle used is that the data in each direction from a grid point should carry equal weight in the calculation of a value at that grid point. Accordingly, the method gives lesser weight to the data from stations which are clustered in the same direction from a grid point than it does to data from a isolated station which is the same distance away in a different direction.

The algorithm used is that the weighting function, b_i, at station i is given by:

$b_i = (1 + a_i)(w_i^2)$, where a_i and w_i are calculated as follows:

$w_i \quad = 1/d, \quad d < 133.3$ km

$\quad = [(6.75/d)((d/400 - 1)^2)], \; d > 133.3$ km, where d = distance (km) between station i and grid point

$$a_i = \frac{\sum_{j=1}^{n} w_j(\cos(\theta_j - \theta_i))}{\sum_{j=1}^{n} w_j}$$

where θ_i represents the direction of station i from the grid-point concerned.

8.3.2.3. Barnes analysis

This is a successive-correction scheme, which was introduced in section 4.2.3. The grid-point values are based on data from nearby observation points; however, unlike the Jones and Shepard methods, an observation can influence the value at more than one grid point. The analysis is performed in four iterations, with the weighting function adjusted such that the nearest observational data are given greater weight in the later iterations, thus reducing the difference between the grid and observed data. The use of a given observation at more than one grid point makes it feasible to carry out this analysis scheme on a much finer grid resolution than the Jones and Shepard methods. In this study it was carried out at grid points separated by 1 degree in both latitude and longitude (compared with 5 degrees for Jones and Shepard).

This is the scheme currently used for the production of operational analyses of climate data in the Australian Bureau of Meteorology.

As introduced in section 4.2.3, the algorithm for the n-th iteration at a grid-point (i,j), $t_n(i,j)$, is given by:

$$t_n(i,j) = t_{(n-1)}(i,j) + \frac{\sum_{s=1}^{N} w(d)(T(s) - T(x(s), y(s)))}{\sum_{s=1}^{N} w(d)}$$

$$w(d) = \exp(\log_e(0.5)\frac{d^2}{g_n D^2})$$

where: $T(s)$ is the observed value of the analysed variable at station s
$T(x(s),y(s))$ is the value, interpolated from the analysis, of the analysed variable at the position of station s, with co-ordinates $(x(s),y(s))$
d is the distance of station s from the grid point (i,j)
D and g_n are constants which determine the effective length scales (the distance at which the weighting function becomes 0.5) for each iteration of the analysis

The constants are given the values:

D	500 km
g_1	1.00
g_2	0.36
g_3	0.04
g_4	0.04

which correspond to those used by the National Climate Centre in the routine analysis of temperature. These values correspond to effective length scales of 500, 300, 100 and 100 kilometres respectively.

If the value of w(d) was less than 0.0001 then it was set to zero. At some grid points in remote areas no station had a value of w(d) greater than 0.0001 on the third and fourth pass. In this case $t_4(i,j) = t_3(i,j) = t_2(i,j)$ (i.e., in effect the third and fourth passes were not run at these points and the value at the grid point was taken as that from the broader-scale first and second passes).

8.3.3. Advantages and disadvantages of the analysis and spatial averaging schemes

No spatial averaging or interpolation scheme is perfect; to achieve a perfect spatial average would require the use of a set of stations which perfectly represented all of the variations in the field being measured over a given region. A further consideration, albeit one which is becoming less important as computing power becomes cheaper and more accessible, is that two of the schemes outlined above, the Barnes and Thiessen schemes, are quite computationally intensive when used with a varying station network, as will be detailed further below.

Specific areas of interest include:

1. Representativeness of the interpolation/averaging

In three of the four schemes above, distance is, in effect, used as the sole measure of how representative an observation at a station is of the actual conditions at some point. The sole exception is the Shepard scheme, where the relative density of stations in a given direction from the point is also given weight.

We have seen, in section 8.2, that there are marked variations over Australia in the spatial coherence of temperature, and, in particular, that summer maximum temperatures display far less spatial coherence near some coasts than they do further inland. We have also seen in that section that, in many cases, temperatures at a given site are much more strongly correlated with those at a site in one direction than with one the same distance away in another direction; examples include the tendency, already described, of maximum temperatures in much of southern Australia to be more strongly correlated along a NW-SE axis than a NE-SW one, and that coastal sites on the New South Wales coast tend to be more strongly correlated with each other than with inland sites, even if the inland sites are closer.

The effect of these factors is that most distance-based interpolation or averaging schemes tend to 'project' the influence of coastal sites further inland than is climatologically justified. As an example, Bathurst is almost equidistant from Sydney and Dubbo, and hence a distance-based interpolation scheme would give Sydney and Dubbo equal weight in the estimation of conditions at Bathurst; however, the correlation of January maximum temperatures at Bathurst with those at Dubbo is 0.91, while that of Bathurst and Sydney is 0.50.

The use of statistical interpolation would alleviate some of this lack of representativeness, in as much as its use of a two-dimensional covariance function allows observations in some directions to be given more weight than those in others. This type of function would allow adjustments to be made for the observed NW-SE axis of strong correlations. In its usual form, however, the covariance function over a field remains independent of the location of the origin and its value depends only on the vector displacement of a point from the origin. This does not allow the taking into account of the influence of the coast at near-coastal sites, nor the marked latitudinal and seasonal variations in the spatial coherence of temperature described in section 8.2. Attempting to extend and adapt the concept of statistical interpolation to cover such situations is beyond the scope of this thesis.

As all of the schemes discussed above are distance-based, none has a particular advantage over the others in this respect. The directional weighting in the Shepard scheme only takes into account the density of stations in a given direction, and is designed to give practical effect to the intent to weight data from all directions equally, without the distortions caused by varying numbers of stations.

2. *Computational simplicity*

The simplest schemes computationally, by some margin, are the Jones and Shepard schemes, as both allow observations to influence the value at one grid point only, and use a relatively coarse grid. The Jones method is particularly simple as it uses a single distance-based calculation to determine the weight that any observation plays at a grid point.

In a complete data set, the Thiessen method is also computationally simple, as the most computationally complex part of the calculation, determining the area of the polygons associated with each data point, only has to be carried out once. In a real data set, the area of the polygons has to be recalculated every time the station network changes – that is, on every occasion that there is missing data at one of the stations. This adds considerably to the computational demands.

The Barnes scheme is the most computationally complex, because of its finer grid spacing – 1° instead of 5°, as in the Jones and Shepard schemes – and because it uses four iterations at every grid point. The finer resolution is not inherent to the schemes *per se*, but is a consequence of the fact that the Jones and Shepard schemes only allow an observation to be associated with its nearest grid point, which in turn would result in no value being defined at many grid points if a resolution of finer than 5° were to be used. The size of the data set used in this part of the study (99 stations) was small enough for Barnes analysis to be able to be run without undue difficulty, so computational simplicity was not a significant factor. It would become more important in a global data set in which several thousand stations were involved, the type of data set for which the Jones algorithm was specifically designed.

3. Detail of analysis

As a result of the constraint that no data point may influence the value at more than one grid point, the Jones and Shepard methods are effectively limited to a relatively coarse grid. The global analysis of Jones et al. (1986a, b) is run on a grid of 5° latitude by 10° longitude. In this study a 5° by 5° grid is used. This is the smallest spacing feasible in order for most grid points to have at least one station associated with them; even so, there are three grid points in Western Australia with which no station is associated (i.e. there is no station within 2.5° in any direction). National averages can be calculated on this scale, but any finer-scale breakdown is difficult. In particular, on this scale no grid point lies within Victoria or Tasmania.

The Barnes scheme is run at a 1° by 1° resolution. This is feasible because of the use of the data from each station at multiple grid points. It could be argued that this grid scale gives a level of detail in remote areas that is not justified by the sparseness of the data. The strong spatial coherence of temperature in these regions, though, should minimise any distortions caused. The fine scale of the analysis makes it feasible to calculate state-by-state averages, although these are subject to their own distortions (see section 8.4).

8.3.4. An objective assessment of the spatial averaging techniques

To present a case study of the consistency and bias of the spatial averaging techniques, the Australia-wide average of the number of days with minima below 0°C was calculated for each year between 1957 and 1996.

Table 8.1 shows the mean number of such days calculated using each of these techniques for the 40-year period, while Table 8.2 shows how well-correlated the results from each technique are with each other. These results show that, on the annual timescale, the results from the four methods are extremely well-correlated ($r > 0.977$), and hence any of the four are essentially consistent in their representation of interannual variation of the frequency of days with minima below 0°C.

The mean annual number of days, averaged over Australia, with minima below 0°C is calculated as being 10% greater using the Jones method than the Thiessen method, to take the two extremes. These reflect opposite biases in the two methods. The Jones and Shepard methods effectively exclude three Western Australian grid points, as noted in section 8.3.3, because of a lack of nearby data, and therefore give additional weight to the other Australian grid points – in particular, those in south-eastern Australia where minima below 0°C are most frequent. (This bias would be more substantial for high maximum temperatures, as these are likely to be frequent at all of the three grid points in question). Conversely, the Thiessen method effectively gives each point the value of its nearest station, extending the influence of coastal stations to the point inland that is equidistant between the coastal station and the nearest inland station. As most coastal stations rarely or never record minima below 0°C, this reduces the calculated mean frequency of such events. (The other methods also project coastal observations inland, but the inland observations still have some influence, even at near-coastal grid points).

The results shown in Tables 8.1 and 8.2 suggest that, for this particular case, it does not greatly matter, in the representation of the frequency of extreme temperature events, which of the four methods is chosen. The Barnes method is therefore used for the remainder of the analysis, because of its greater level of spatial detail.

8.4. Spatial averages of the frequency of extreme temperature events

8.4.1. Which extreme events should be analysed?

The question of whether to use fixed or percentile-based thresholds for the analysis of extreme events has been previously been discussed in Chapter 7, and the advantages and disadvantages of both were discussed there. In the context of spatial averages, fixed thresholds suffer from two particular disadvantages:

1. Impact of changes in station network

The station network is not static; many stations miss days on an irregular basis, and some were not open for the entire 1957-1996 period. This biases the spatial averages in situations where the station whose data are missing is significantly warmer or colder than its neighbouring stations. If a station's data are missing the values at neighbouring stations will effectively be interpolated to that station, thus producing a bias in the record.

The Tasmanian data shown in Fig. 8.6 illustrate this point. The Butlers Gorge station closed in 1993, and its data are therefore not included in the averages for 1994-1996. As Butlers Gorge has a much greater frequency of minima below 0°C than any other Tasmanian station (Table 8.3, station numbers 91000-99999), its removal will cause a sharp downward bias in the calculated mean number of days below 0°C. The absence of Cabramurra (opened 1962) from 1957-61 data has a similar impact on the frequency of low maximum temperatures (not shown).

2. Lack of areal representativeness of station network

Many fixed-threshold extreme events are only observed in parts of Australia, or are observed with a much greater frequency at some stations than others. Table 8.3 shows an example of this, the frequency of minima below 0°C at all stations within Australia. It may be seen that there are only nine stations in the data set which record a mean of more than 20 nights per year with minima below 0°C, and five with 50 or more such nights. The interannual variability of the all-Australian average is therefore likely to be dominated by changes at these sites. As a result, a figure purporting to be an all-Australian average is dominated by a few sites in a particular region of the country, which is clearly not an especially representative outcome.

Furthermore, spatial averages of breaches of fixed thresholds will be dominated by events in one season; summer for high thresholds, winter for low thresholds. To gain an

Table 8.1. Mean number of days with minima below 0°C over Australia, using differing spatial averaging techniques

Technique	Mean number of days per year below 0°C
Thiessen	3.99
Jones	4.55
Shepard	4.28
Barnes	4.38

Table 8.2. Correlations of annual frequency of minima below 0°C using different spatial averaging techniques

Technique	Technique			
	Thiessen	Jones	Shepard	Barnes
Thiessen	1.000	0.977	0.978	0.988
Jones	0.977	1.000	0.993	0.987
Shepard	0.978	0.993	1.000	0.991
Barnes	0.988	0.987	0.991	1.000

Fig. 8.6. Frequency of minima below 0 degrees C, Tasmania

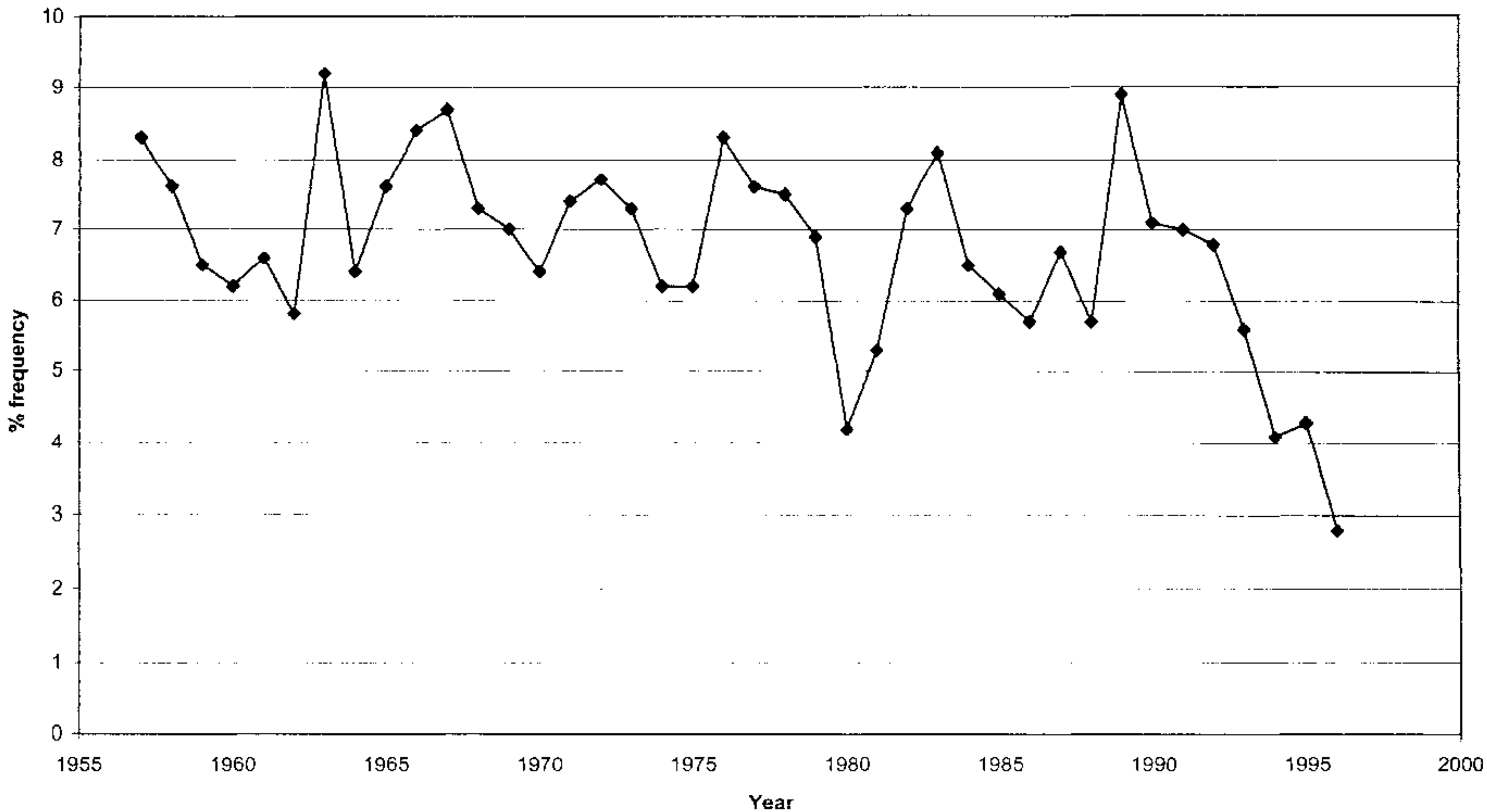


Table 8.3. Mean frequency of minima below 0°C at stations used in study

Station number	Station name	Frequency (days/year)	Station number	Station name	Frequency (days/year)
01021	Kalumburu	0.0	39128	Bundaberg	0.0
02012	Halls Creek	0.0	40004	Amberley	5.9
03003	Broome	0.0	40223	Brisbane AP	0.0
04032	Port Hedland	0.0	40908	Tewantin	0.0
05007	Learmonth	0.0	42023	Miles	18.2
05026	Wittenoom	0.0	43034	St. George	1.6
06011	Carnarvon	0.0	44021	Charleville	12.1
07045	Meekatharra	0.0	45017	Thargomindah	1.4
08039	Dalwallinu	0.2	46037	Tibooburra	1.7
08051	Geraldton	0.0	46043	Wilcannia	4.6
09021	Perth AP	0.1	48027	Cobar	1.7
09518	Cape Leeuwin	0.0	48239	Bourke	2.0
09741	Albany	0.0	52088	Walgett	5.2
09789	Esperance	0.0	53048	Moree	11.5
10035	Cunderdin	0.5	55024	Gunnedah SC	3.5
10648	Wandering	19.2	56017	Inverell PO	59.9
11052	Forrest	4.2	58012	Yamba	0.0
12038	Kalgoorlie	4.6	59040	Coffs Harbour	0.7
13017	Giles	0.4	60026	Port Macquarie	0.0
14015	Darwin	0.0	61078	Williamtown	0.8
14825	Victoria River Downs	0.3	61089	Scone SC	4.7
15135	Tennant Creek	0.0	63005	Bathurst ARS	58.6
15548	Rabbit Flat	3.1	65012	Dubbo	15.1
15590	Alice Springs	11.8	66062	Sydney RO	0.0
16001	Woomera	0.1	67105	Richmond	11.3
16044	Tarcoola	5.6	68034	Jervis Bay	0.1
17031	Oodnadatta	1.3	68076	Nowra	0.1
17043	Marree	2.5	69018	Moruya Heads	0.1
18012	Ceduna	3.8	70014	Canberra Airport	61.4
18070	Port Lincoln	0.0	72161	Cabramurra	104.8
21046	Snowtown	5.5	72150	Wagga Wagga	22.0
22801	Cape Borda	0.0	73054	Wyalong	16.3
23090	Adelaide RO	0.1	74128	Deniliquin	8.2
23321	Nuriootpa	11.0	76031	Mildura	3.9
26021	Mount Gambier	5.7	78031	Nhill	13.4
26026	Robe	0.1	80023	Kerang	4.8
27022	Thursday Island	0.0	82039	Rutherglen	43.2
27045	Weipa	0.0	84016	Gabo Island	0.0
28004	Palmerville	0.0	84030	Orbost	3.7
29004	Burketown	0.0	85072	Sale	12.3
30045	Richmond	0.3	85096	Wilsons Promontory	0.0
31011	Cairns	0.0	86071	Melbourne RO	1.5
32040	Townsville	0.0	87031	Laverton	5.0
33119	Mackay MO	0.0	90015	Cape Otway	0.0
34084	Charters Towers	0.0	91057	Low Head	0.3
36007	Barcaldine	0.6	91104	Launceston AP	28.7
36031	Longreach	1.4	92045	Eddystone Point	0.0
37010	Camooweal	0.2	94010	Cape Bruny	0.3
38002	Birdsville	0.2	94029	Hobart RO	1.6
38003	Boulia	0.0	94069	Grove	40.8
39039	Gayndah	2.6	96003	Butlers Gorge	91.2
39083	Rockhampton	0.1			

indication of changes in frequency of extreme events through the year as a whole, a broader measure is needed.

The principal method used in this study to analyse spatial averages of threshold event frequency involves the use of percentile thresholds, that is, temperatures (maximum and minimum) above the 90th and 95th percentile level for a calendar month, or below the 10th and 5th percentile level. The major advantage of this method is that the expected frequency of such events is exactly the same – 5% or 10% (depending on the threshold chosen) – for every station and season, so the removal of a station from the network or the choice of a season will not result in an intrinsic bias in the outcome. This is the approach being followed by the WMO Commission for Climatology Climate Change Detection Methodologies and Indices task group (Plummer, pers. comm.).

8.4.2. Method of calculation of the percentile thresholds

Percentile thresholds in each month for each station are calculated as per the method outlined in the analysis of individual stations in section 7.1.1. Once the thresholds are calculated for each of the 12 months, the number of times that threshold is breached in each month of the 40 years was calculated. This gives, for each station and threshold, a 40-year time series of monthly data for each of the four thresholds for minimum and maximum temperature. The spatial averages of the threshold event frequencies were then calculated for each month of the 40-year period using the Barnes analysis technique, as described in section 8.3.2.4.

8.4.3. Trends in spatial averages of the frequency of extreme temperature events

The results of an analysis of spatial averages of the frequency of extreme temperature events are presented in Tables 8.4 to 8.7 and Figs. 8.7 to 8.10. Each of the types of event analysed are discussed separately in this section.

8.4.3.1. High maximum temperatures

Over the period from 1957 to 1996, an increase of 21% (1.7 days/decade), as derived from the trend in a linear regression of the data, has occurred in the frequency of maximum temperatures above the 90th percentile in Australia. This increase is observed in all seasons, but is most marked in winter (29%) and least marked in autumn (12%). The upward trend is not constant, but, as may be seen from Fig. 8.7a, reflects the existence of two distinct periods of relative stability in the record, with a sharp jump between the two in the late 1970's. The question of whether this can be explained, in part, by the influence of an increased frequency of El Niño events will be addressed in Chapter 9.

An upward trend has occurred in all states, although it is minimal in New South Wales and Victoria. The most marked trends are found in Tasmania, especially in autumn and winter, in which the frequency of maxima above the 90th percentile has increased by 58% over the 40 years. Fig. 8.7g shows that this largely reflects the occurrence of a number of very warm years during the 1980's.

8.4.3.2. High minimum temperatures

Over the period from 1957 to 1996, an increase of 32% (2.5 days/decade) has occurred in the frequency of minimum temperatures above the 90th percentile in Australia (Fig.8.8a). The most marked increases (40-41%) are observed in spring and autumn, with lesser increases in summer and winter. Even more so than the frequency of high maximum temperatures, the frequency of high minimum temperatures shows a marked jump in the late 1970's, between two periods of relative stability.

The trends are strongest in north-eastern Australia, with New South Wales and Queensland displaying increases in excess of 30%. Queensland has shown an increase in frequency of these events of 50%, with strong trends in all seasons, but especially in autumn. Increases in spring and autumn are observed everywhere, but Queensland and

Region	Spring (Sep-Nov)		Summer (Dec-Feb)		Autumn (Mar-May)		Winter (Jun-Aug)		Annual	
	Days/ decade	% change 1957-1996	Days/ decade	% change 1957-1996	Days/ decade	% change 1957-1996	Days/ decade	% change 1957-1996	Days/ decade	% change 1957-1996
Australia	0.4	19	0.4	19	0.3	12	0.6	29	1.7	21
NSW	-0.1	6	0.2	10	-0.2	-7	0.3	16	0.2	2
Victoria	-0.1	5	-0.3	-12	0.5	25	0.4	18	0.5	5
Queensland	0.3	17	1.0	57	0.3	17	0.6	26	2.2	28
S. Australia	0.5	25	0.9	50	0.5	25	0.5	25	2.5	32
W.Australia	0.3	17	0.1	4	0.4	19	0.7	36	1.5	19
Tasmania	0.3	16	0.0	-1	1.2	75	1.3	83	3.0	39

Table 8.4. Trends in frequency of maxima above 90th percentile

Region	Spring (Sep-Nov)		Summer (Dec-Feb)		Autumn (Mar-May)		Winter (Jun-Aug)		Annual	
	Days/ decade	% change 1957-1996	Days/ decade	% change 1957-1996	Days/ decade	% change 1957-1996	Days/ decade	% change 1957-1996	Days/ decade	% change 1957-1996
Australia	0.8	41	0.4	19	0.7	40	0.4	21	2.5	32
NSW	0.3	16	0.7	36	0.9	50	0.7	40	2.7	35
Victoria	0.6	26	-0.1	-2	0.5	23	0.6	26	1.7	20
Queensland	0.9	51	0.8	43	1.2	68	0.6	32	3.6	50
S. Australia	0.4	21	0.1	7	0.6	31	0.2	10	1.5	18
W.Australia	0.8	48	0.2	10	0.4	19	0.3	16	1.8	22
Tasmania	0.6	25	-0.2	-8	0.6	25	0.1	6	1.1	12

Table 8.5. Trends in frequency of minima above 90th percentile

Region	Spring (Sep-Nov)		Summer (Dec-Feb)		Autumn (Mar-May)		Winter (Jun-Aug)		Annual	
	Days/ decade	% change 1957-1996	Days/ decade	% change 1957-1996	Days/ decade	% change 1957-1996	Days/ decade	% change 1957-1996	Days/ decade	% change 1957-1996
Australia	-0.3	-13	-0.1	-2	-0.7	-25	-0.5	-19	-1.5	-15
NSW	-0.2	-9	0.0	1	-0.5	-19	-0.3	-14	-1.0	-10
Victoria	-0.5	-20	0.2	10	-1.0	-35	-0.8	-29	-2.1	-21
Queensland	0.0	-1	-0.5	-19	-1.3	-41	0.0	1	-1.8	-18
S Australia	0.9	-33	-0.1	-2	-0.8	-30	-1.4	-46	-3.2	-30
W Australia	-0.3	-12	0.2	12	-0.4	-14	-0.3	-14	-0.7	-7
Tasmania	-1.3	-42	-0.3	-14	-1.5	-49	-0.7	-26	-4.0	-36

Table 8.6. Trends in frequency of maxima below 10th percentile

Region	Spring (Sep-Nov)		Summer (Dec-Feb)		Autumn (Mar-May)		Winter (Jun-Aug)		Annual	
	Days/ decade	% change 1957-1996	Days/ decade	% change 1957-1996	Days/ decade	% change 1957-1996	Days/ decade	% change 1957-1996	Days/ decade	% change 1957-1996
Australia	-1.0	-37	-0.7	-26	-0.5	-20	-1.0	-35	-3.3	-30
NSW	0.8	30	0.1	5	-0.7	-26	-1.2	-39	-2.7	-26
Victoria	0.2	-7	0.1	2	-0.8	-31	-0.5	-18	-1.7	-17
Queensland	1.4	-47	-1.2	-39	-1.4	-45	-1.5	-50	-5.6	-47
S Australia	1.3	-42	-0.7	-25	-0.6	-24	-1.2	-40	-3.9	-35
W Australia	0.9	-33	-0.5	-19	0.1	2	-0.6	-21	-2.0	-20
Tasmania	0.8	-30	-0.5	-17	-0.8	-30	-0.5	-20	-2.9	-27

Table 8.7. Trends in frequency of minima below 10th percentile

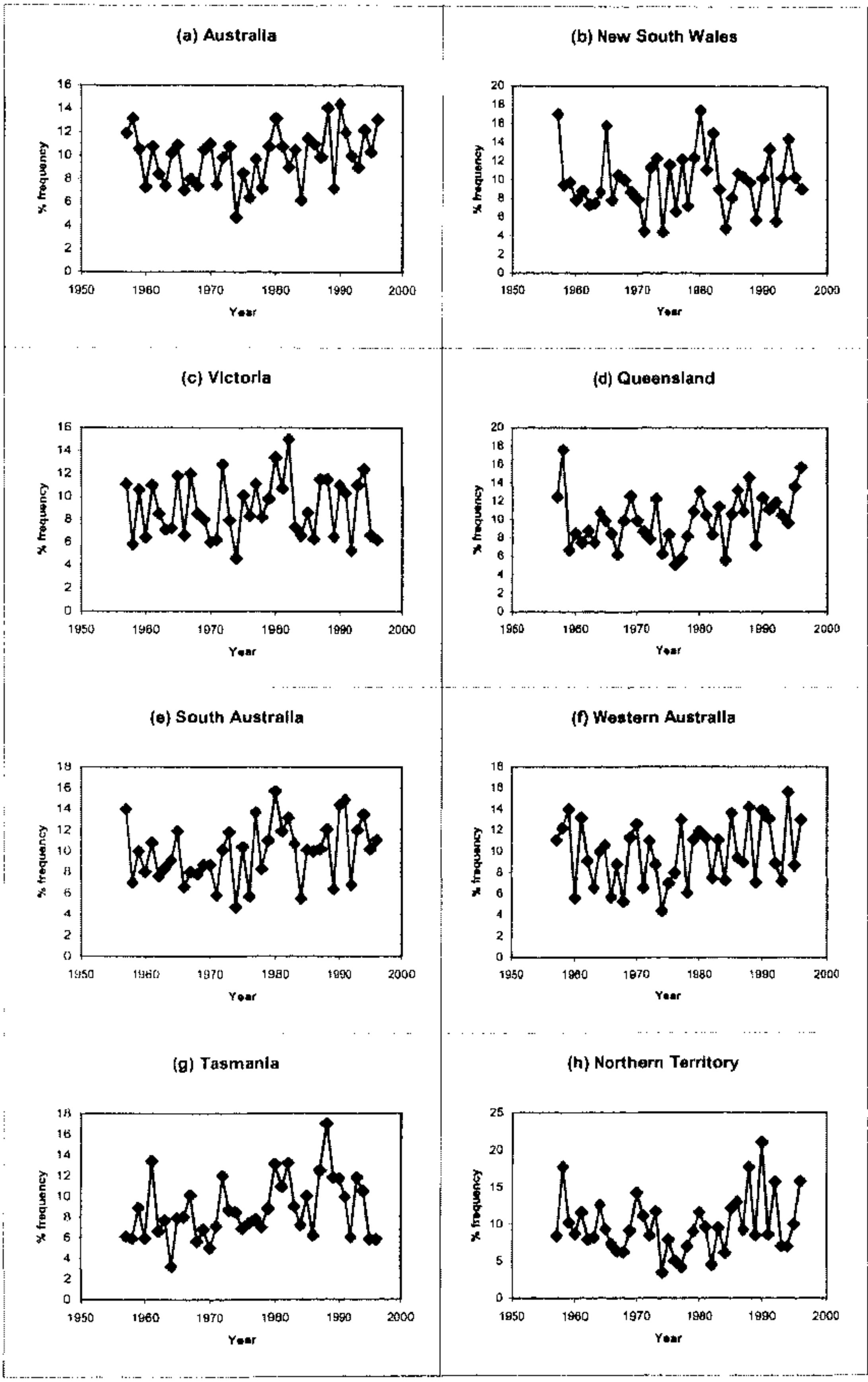


Fig. 8.7. Frequency of maxima above 90 percentile level

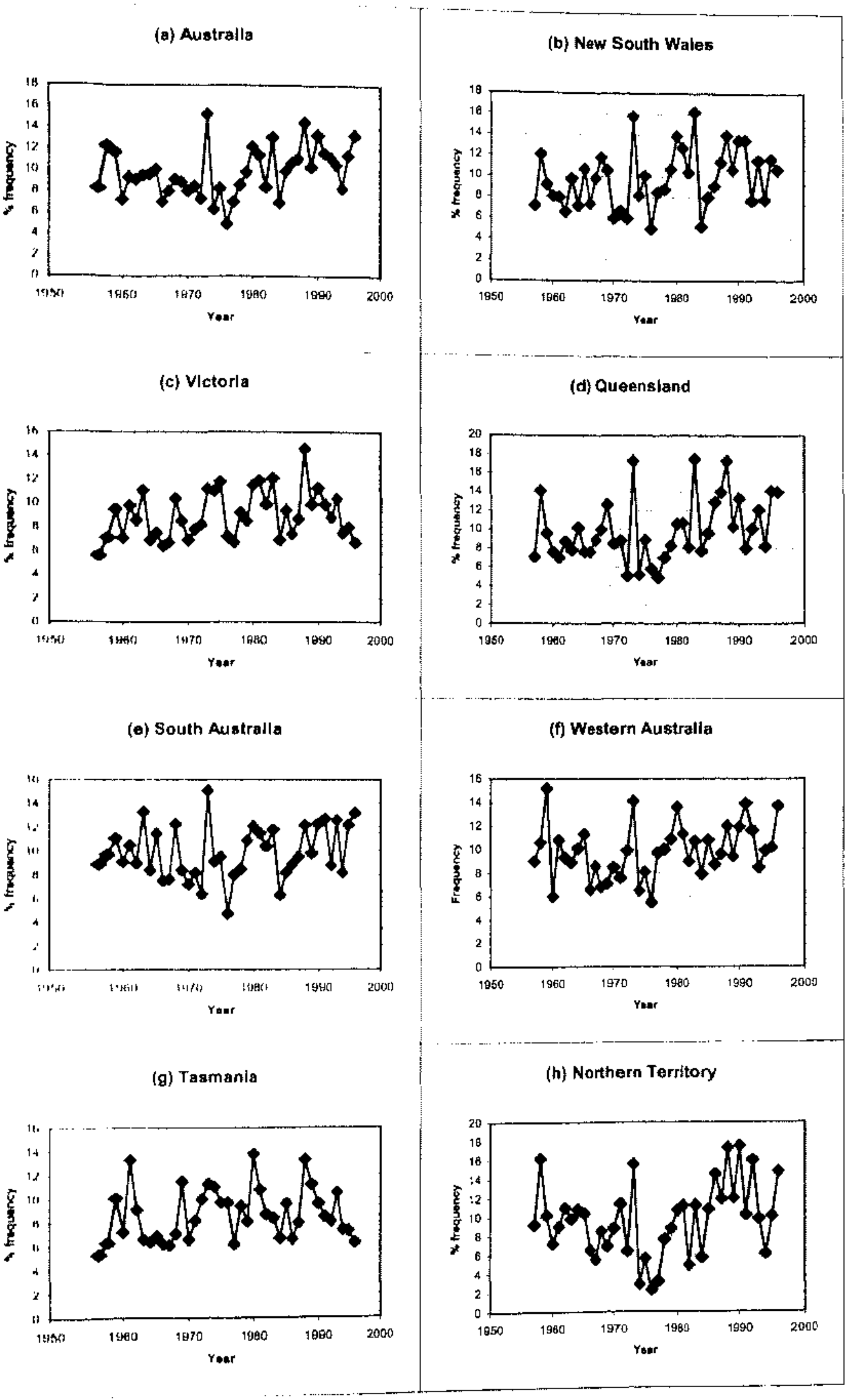


Fig. 8.8. Frequency of minima above 90 percentile level

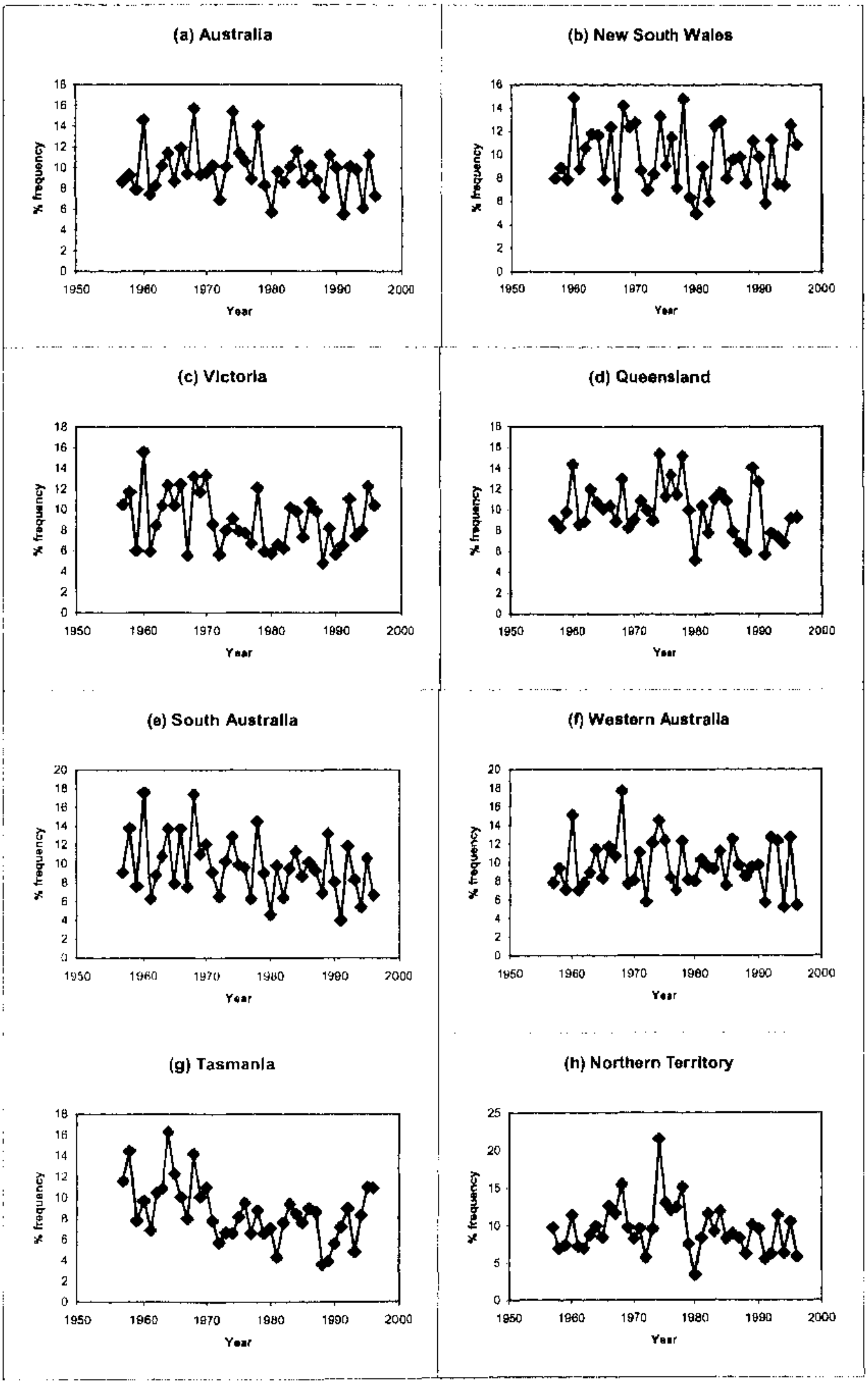


Fig. 8.9. Frequency of maxima below 10 percentile level

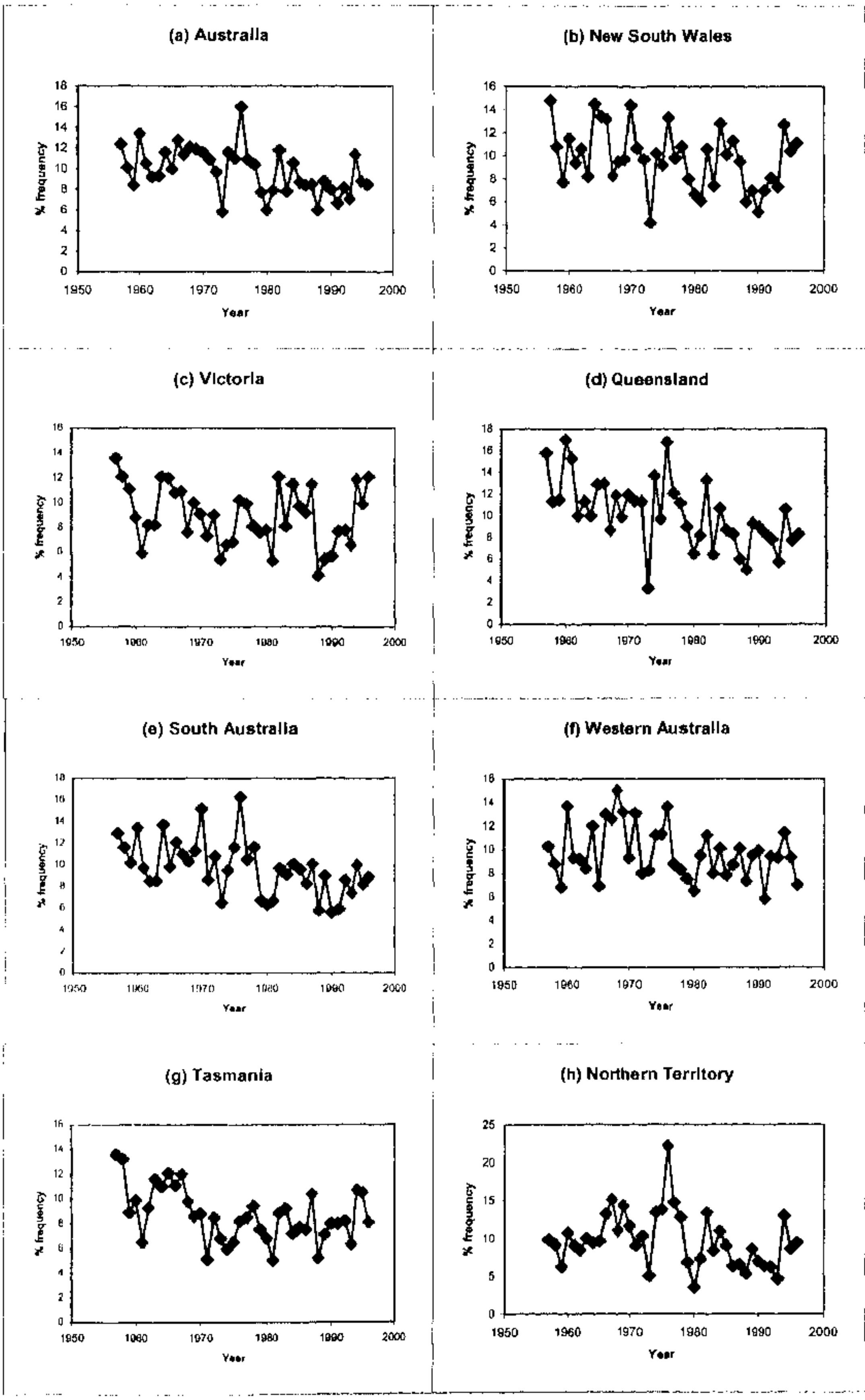


Fig. 8.10. Frequency of minima below 10 percentile level

New South Wales are the only states to record more than minimal increases in summer. The weakest trends through the year as a whole have occurred in Tasmania.

8.4.3.3. Low maximum temperatures

Over the period from 1957 to 1996, a decrease of 15% (1.5 days/decade) has occurred in the frequency of maximum temperatures below the 10th percentile in Australia (Fig.8.9a). This is the weakest trend of the thresholds examined. It is most pronounced in autumn and winter, with a decrease of 25% in autumn. There is virtually no trend in summer. The trend for the annual data reflects the presence of four years in the record (1960, 1968, 1974 and 1978) with very high frequencies of days with maxima below the 10th percentile. Apart from these four years, the frequency of such days has remained virtually unchanged through the record.

The decline is most pronounced in southern Australia, particularly in autumn and winter. South Australia and Tasmania have both observed large declines in the frequency of these events. A possible cause for this change could be a change in the frequency of 'cold outbreak' conditions over south-eastern Australia. The weakest trends are observed in Western Australia, with an increase in the frequency of low maximum temperatures being observed in summer.

8.4.3.4. Low minimum temperatures

Over the period from 1957 to 1996, a decrease of 30% (3.3 days/decade) was observed in the frequency of minimum temperatures below the 10th percentile level (Fig.8.10). This is, by some margin, the most substantial trend observed of the threshold events examined. The trends are strongest in winter and spring. The trend is a relatively consistent one throughout the period of record (Fig. 8.10a), with the exception of a period of frequent low minimum temperatures in the mid-1970's.

A decrease in the frequency of these events occurred in all states. The decline in Queensland, which has occurred evenly throughout the year, is a particularly notable 47% over the 40 years. Strong declines in winter and spring are observed in all states, except for Victoria in spring. There was little trend observed in summer in New South Wales and Victoria.

8.5. The preparation of a gridded data set of daily maximum and minimum temperature

The preparation of meteorological data sets on a regular grid has been an active area of interest, on both the global (e.g. Jones et al., 1986a, b) and national (e.g. Mills et al., 1997) scales. It is an approach which, as discussed earlier, offers considerable advantages in allowing data to be analysed on a consistent basis despite changes in station networks, and in studying data spatially over specified areas, or over the globe. In particular, a set of gridded daily temperature data for an extended period would allow an analysis of variables such as the area over which a threshold is exceeded on any given day (for example, the area over which 35°C is exceeded on each day of a period).

As has been the case with spatial averages (as described in 8.3.1), limited attention has been given to gridded analyses of daily temperature. The National Climate Centre of the Australian Bureau of Meteorology has been producing gridded analyses of daily maximum and minimum temperatures for Australia since 1996, using the Barnes analysis scheme. More recently, Janowiak and Bell (1999) have produced a set of gridded daily maximum and minimum temperature data for the contiguous United States since 1948, using (unadjusted) data from approximately 6000 co-operative stations and using the analysis technique described in Cressman (1959).

The main purpose to which a gridded daily data set is put in this thesis is as an additional tool in the quality control of the data, as described in Chapter 4. Its use for the analysis of additional indices of extreme temperature values, beyond those previously discussed, is beyond the scope of this thesis, but is certainly a potential area of study at a later date.

An important consideration in the generation of a gridded analysis of daily temperature data is the station network to be used, and consequently the level of topographic detail that is incorporated. One possible approach is to use all possible station data, no matter what its period of record or quality. This approach would allow the maximum possible level of detail to be obtained from station data, but would also induce numerous problems with the lack of homogeneity through time of the analyses generated, as well as with the effects of occasional erroneous or spurious data. This is not an intractable barrier for the production of, for example, routine daily analyses for public information, but is a greater problem if it is intended to use such a data set for the study of climate change. A more subtle point is that some of the more extreme environments – for example, mountain tops – are represented for only part of the period of record (a problem also discussed in section 8.4.1. in the context of thresholds), and the use of station data alone would result in these environments being lost from the record during periods when there are no data from those stations. (To use a Tasmanian example, there have been data from high mountain sites above 1200 metres – Mount Wellington or Mount Barrow – only between 1961 and 1974 and since 1990, and hence Tasmanian station data would not allow the representation of regions above 1200 metres between 1974 and 1990).

The problem of data homogeneity can be addressed by using only data from known high-quality stations – in this context, the set of high-quality daily temperature data developed earlier in this study. This, though, leaves a rather sparse network, with additional data required in order to represent the full range of climates in Australia.

Willmott and Robeson (1995) found that the most satisfactory results for the analysis of temperature data were obtained by splicing anomalies from mean conditions, generated from a particular set of data, onto a higher-resolution climatology developed using additional data. Whilst their approach involved annual mean temperatures, there is no reason why it could not be applied to shorter timescales. This is a particularly feasible approach for Australian temperature data. High-resolution climatologies of monthly mean temperature in Australia have been developed by D. A. Jones (pers.comm..), using techniques developed by Hutchinson (1991) to incorporate a wide range of station temperature data, as well as high-resolution topographic models.

In this thesis, the data sets which were developed were daily anomalies from the mean daily maximum and minimum temperature. These were interpolated onto a 1 x 1-degree grid using Barnes analysis, with the same parameters as described in section 8.3.2.3. This was done separately for maximum and minimum temperature for each day from 1 January 1957 to 31 December 1996.

Examples of the data sets produced by this scheme are shown in Fig. 8.11. These show the general spatial coherence of daily maximum and minimum temperature, except near the coasts. The greatest problem in the development of such a data set is the sharp temperature gradient near some of the coasts. While the use of anomalies in the gridding process ameliorates this problem to some extent, the Barnes technique is still reliant on the available station data. This means, using the case of 11 January 1957 for example, that the data are approximately linearly interpolated between Kalgoorlie and Esperance (in southern Western Australia), whereas it is likely, given the region's meteorology, that there would be a rapid increase over the area immediately inland from Esperance, followed by a levelling-out. This problem of capturing sharp gradients is inevitable anywhere where the characteristics of the temperature field are on a finer resolution than the station network used to analyse it.

If these were to be developed into gridded sets of daily maximum and minimum temperature covering the same dates, a possible method would be to splice the daily anomalies onto the high-resolution monthly climatology of Jones. To achieve this, it would first be necessary to interpolate the Jones climatology to the daily timescale, as the anomaly grids are based on station anomalies from smoothed daily normals. This could be done, for example, by using a sinusoidal curve to interpolate a daily mean temperature curve at each grid point from the monthly data.

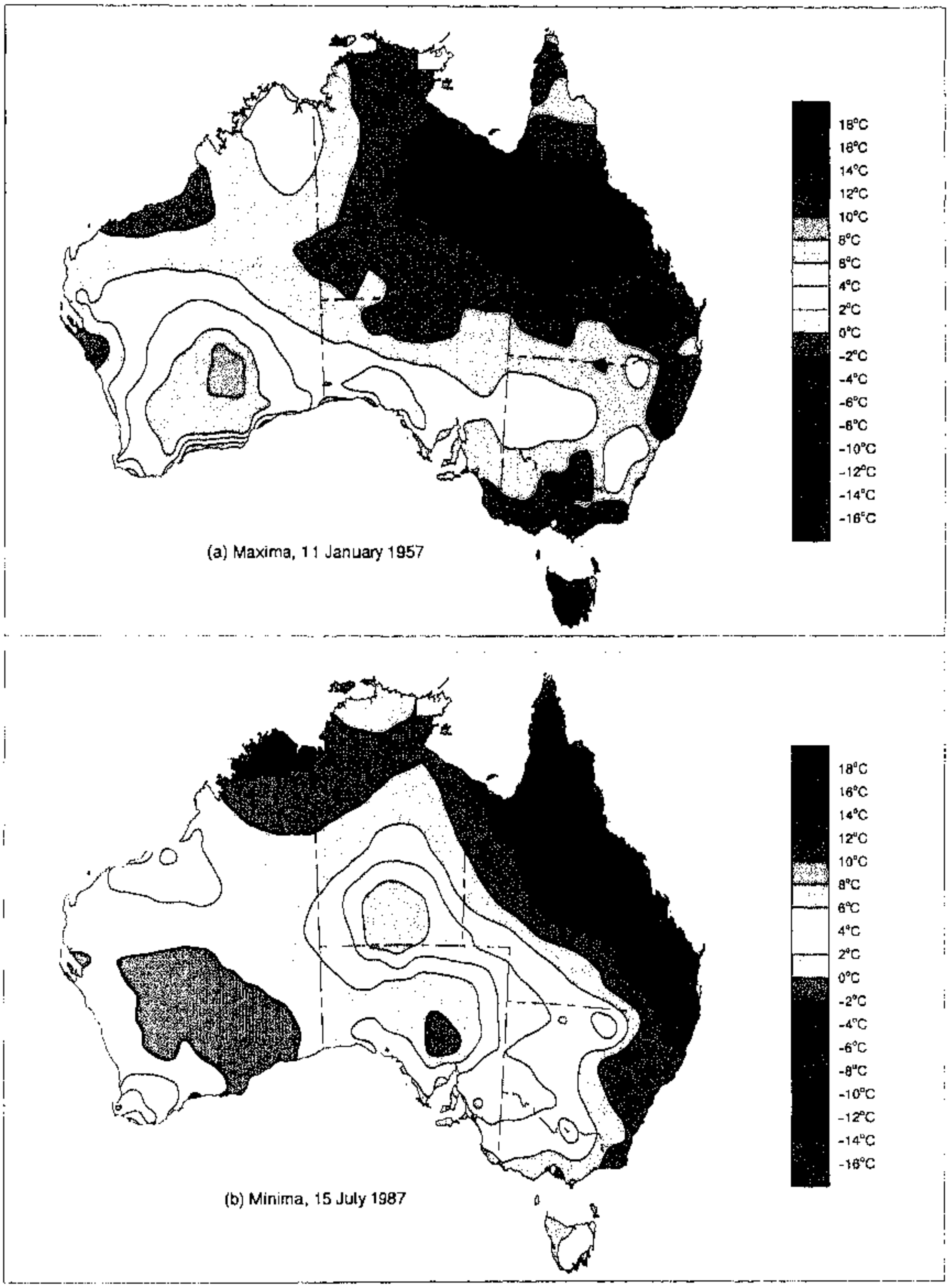


Fig. 8.11. Examples of spatial analyses of daily temperature anomalies

8.6. Summary

The spatial averages calculated in this section reinforce the results obtained from individual stations in Chapter 7. They show a tendency towards an increase in the frequency of warm extremes and a decrease in the frequency of cool extremes, with particularly marked trends noticeable for low minimum temperatures in Queensland. The relationship of Queensland minimum temperatures to the El Niño-Southern Oscillation, which has itself shown a trend towards more frequent El Niño conditions, will be investigated further in Chapter 9.

Chapter 9

Relationships between the Southern Oscillation Index (SOI) and the frequency of extreme temperatures in Australia

9.1. Introduction

The relationship between the El Niño-Southern Oscillation (ENSO) and Australian rainfall has received considerable attention (e.g. Quayle, 1929; Pittock, 1975; McBride and Nicholls, 1983). There has been more limited attention given to the relationship between ENSO and Australian temperatures, especially at the seasonal (as opposed to annual) timescale.

The simultaneous relationship between ENSO and the mean seasonal maximum and minimum temperature over Australia has been most thoroughly examined by Jones (1999) and Jones and Trewin (2000a). Their major findings, in general, were that significant simultaneous correlations existed:

Summer mean maximum temperature

Strong negative correlations (up to –0.6) were found in much of northern and eastern Australia, whilst strong positive correlations were found locally in southern Victoria, Tasmania and the central west coast of Western Australia.

Winter mean maximum temperature

Strong negative correlations (typically –0.3 to –0.5) were found over most of Australia south of the tropics, whilst positive correlations were found in the north, strongest over Cape York Peninsula and in the Top End of the Northern Territory.

Summer mean minimum temperature

The pattern of positive and negative correlations was similar to that for maximum temperatures, but the negative correlations were weaker, except in north-western Australia.

Winter mean minimum temperature

Positive correlations were found over much of the eastern two-thirds of Australia, but were significant only over New South Wales and the far north. Negative correlations were found through much of southern Western Australia in winter and spring, reaching up to –0.5 in the south-west in spring.

Lough (1995, 1997) examined the relationship between an areally-averaged temperature series for Queensland and the SOI over the summer (October-March) and winter (April-September) half-years. Her conclusions agreed broadly with those above. She also found substantial interdecadal variability in the SOI-temperature relationship, with the relationship between summer temperature (maximum and minimum) and the SOI almost disappearing in the 1931-50 period, but that for winter minimum temperature reaching its greatest strength during that period. This will be discussed further later in this chapter.

The only Australian study to make extensive consideration of extreme temperatures (as opposed to means) was that of Stone et al. (1996). Using thresholds ranging between -3°C and 3°C to define 'frost' at a number of stations in interior eastern Queensland and northern New South Wales, they examined the relationship between the May SOI and the total number of frosts for the following season. For most thresholds, they found negative correlations (generally in the –0.25 to –0.4 range) which were significant at the 5% level for most of the Queensland sites, but only weak (and non-significant) correlations, generally negative, for the northern New South Wales sites. Outside Australia, Gershunov and Barnett (1998) examined the relative frequencies of temperatures above the 95th percentile and below the 5th percentile in the United States winter during El Niño and La Niña conditions, finding substantial differences between the two, particularly in the case of the frequencies of extreme high temperatures.

9.2. Methods of analysis

Two forms of analysis were carried out. These involved:

(a) The correlation between the SOI and the frequency of temperatures above given temperature thresholds.
(b) The examination of the relative frequencies of days with temperatures above or below certain thresholds in each of three categories of seasons, stratified by terciles of the SOI.

Correlations were carried out between the following data sets:

(a) The three-month mean SOI and the frequency of temperatures above the 5, 10, 15, ..., 90, 95 percentile levels for the simultaneous three-month period ('simultaneous correlations')
(b) The three-month mean SOI and the frequency of temperatures above the 5, 10, 15, ..., 90, 95 percentile levels for the following three-month period ('lag correlations')

In each case:

1. The correlations were calculated separately for maximum and minimum temperature, using the full period of available record, and for each of the twelve possible three-month periods (January-March through to December-February).
2. The daily maximum and minimum temperatures used were standardised anomalies, as defined in Chapter 6.
3. The percentile thresholds used for each station were calculated using the procedure in Chapter 8, with all available data used.
4. For each individual three-month period, the frequency of temperatures above each percentile threshold was calculated as a percentage of all possible observations during the period. The frequency was regarded as missing for a given three-month period if there were fewer than 60 observations during that period.

5. The SOI used was based on the mean and standard deviation of Darwin-Tahiti pressure anomaly differences between 1933 and 1992 (source: Bureau of Meteorology web site, http://www.bom.gov.au/climate/current/soihtm1.shtml)

In the case of the lag correlations, the results are attributed to the season whose temperatures are under review (for example, the June-August (winter) results are for the correlation between June-August threshold exceedances and March-May SOI).

Negative correlations indicate a tendency for more warm (fewer cold) days in El Niño years, whilst positive correlations indicate a tendency for fewer warm (more cold) days in La Niña years.

The bulk of the discussion of the results will concentrate on correlations for the 10th and 90th percentiles. Correlations for the 50th percentile are also shown, in order to indicate how ENSO affects the median (as opposed to the extremes).

In the comparison of relative frequencies of days with temperatures above or below thresholds in the three SOI terciles:

1. Four types of events were examined: the frequency of days with temperatures below the 10th percentile, and above the 90th percentile, separately for maximum and minimum temperatures.
2. The SOI used was a three-month mean value. The tercile boundaries were calculated using the full 1876-1999 SOI data set. The boundaries were calculated separately for each of the twelve possible three-month periods, although only the four calendar seasons, spring (September-November), summer (December-February), autumn (March-May) and winter (June-August), were examined in any detail.
3. As for the correlations, the analysis was carried out for values of the SOI for the season simultaneous with that for which the temperatures were being reviewed, and for SOI values one season before the temperature measurements (lag sensitivities).

4. Each day was sorted into one of three categories, depending on which tercile the relevant three-month mean SOI fell into. The frequency of temperatures beyond the overall thresholds above was then calculated for each tercile. (The terciles will henceforth be referred to as terciles 1, 2 and 3, with 1 denoting the lowest one-third of SOI values and 3 the highest one-third).
5. As a measure of the sensitivity of the frequency of extreme temperatures to the SOI, the following ratio was calculated for all thresholds, and both simultaneously and at lag:

$$\frac{\text{(Frequency of temperature beyond threshold in SOI tercile 1)}}{\text{(Frequency of temperature beyond threshold in SOI tercile 3)}}$$

   Ratios substantially above 1 indicate a tendency to more extreme events in El Niño years, whilst ratios substantially below 1 indicate a tendency to more extreme events in La Niña years.

6. The standardised temperature anomalies, percentile thresholds and SOI definitions were as for the analysis of correlations above.

9.3. Relationships between extreme temperature frequency and the SOI

Figs. 9.1a-l show the correlations r between the frequencies of maximum and minimum temperatures above the 90, 50 and 10 percentile levels and the SOI, both simultaneously and at one season's lag. The maps are drawn by using a four-pass Barnes analysis (see Chapters 4 and 8) on data from each of the 103 stations. The time series from the stations vary in length from 22 to 142 years.

Figs. 9.2a-h show the ratio between the frequency of extreme events in SOI tercile 1 and the frequency in tercile 3, as defined in section 9.2 above. A full listing of the correlations and ratios for each station is given in Tables F.1 and F.2.

9.3.1. High maximum temperatures

Figs. 9.1a and 9.1b show the simultaneous and lag correlations between the SOI and the frequency of maxima above the 90th percentile.

In spring, strong negative correlations exist, both simultaneously and at lag, in two distinct areas; the south-west of Western Australia and south-eastern Australia, comprising most of Victoria, Tasmania, and New South Wales west of the Great Dividing Range. They are below -0.4 in much of Victoria and inland southern New South Wales, and reach -0.5 locally in Western Australia. Positive correlations exist over most of tropical Australia simultaneously (with the boundary moving further north at lag). Values exceed 0.3 in parts of the far north simultaneously, but only locally at lag.

Negative correlations dominate mainland Australia in summer, with the strongest correlations being in Queensland and New South Wales. The simultaneous and lag patterns are very similar, with values below -0.3 over almost all of Queensland, except for parts of the coast, and much of New South Wales. Much of this area has values below -0.4, and -0.6 is reached locally in inland northern Queensland. Positive correlations are confined to Tasmania and the coastal fringes of Victoria, South Australia, and Western Australia south of Learmonth, and only at Carnarvon and Robe (both sites highly exposed to the ocean that are somewhat unrepresentative of their wider regions, as reflected by very strong gradients of mean summer maximum temperature (Bureau of Meteorology, 1998b)) do they reach 0.3.

As in summer, negative correlations dominate mainland Australia in autumn. The simultaneous correlations are mostly weak, with only a few stations below -0.3. However, at lag there are strong correlations through much of tropical Australia, with values below -0.3 over most of that area, reaching -0.5 in central Queensland.

The simultaneous winter correlations show a striking north-south divide. Strong positive correlations (exceeding 0.4) are evident over tropical Queensland and the Northern Territory, with values as high as 0.6 over Cape York Peninsula. In contrast, negative correlations below -0.3 occur over most of Australia south of 28°S, except

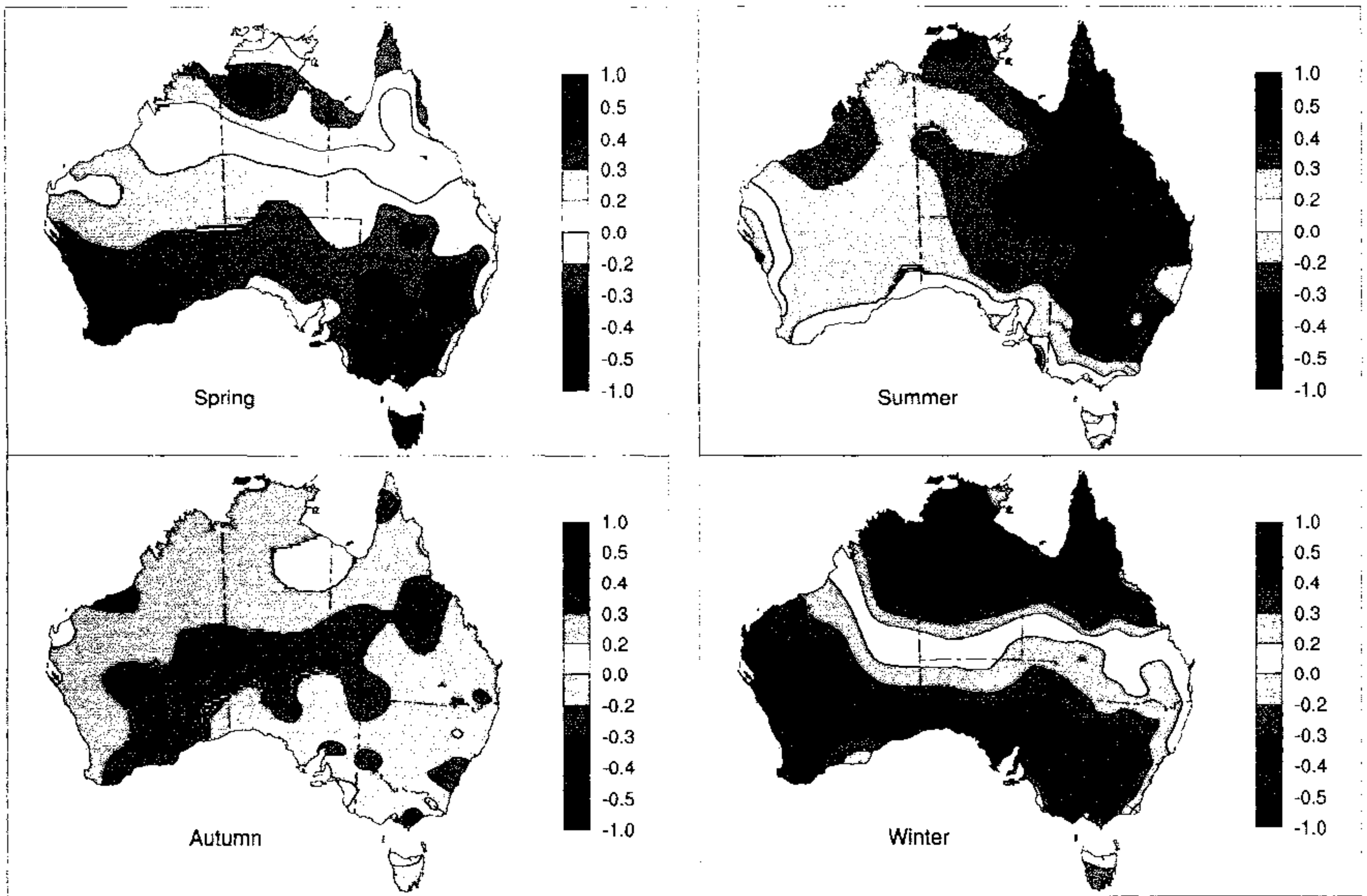


Fig. 9.1a. Correlation between frequency of maxima above the 90th percentile and SOI, simultaneous

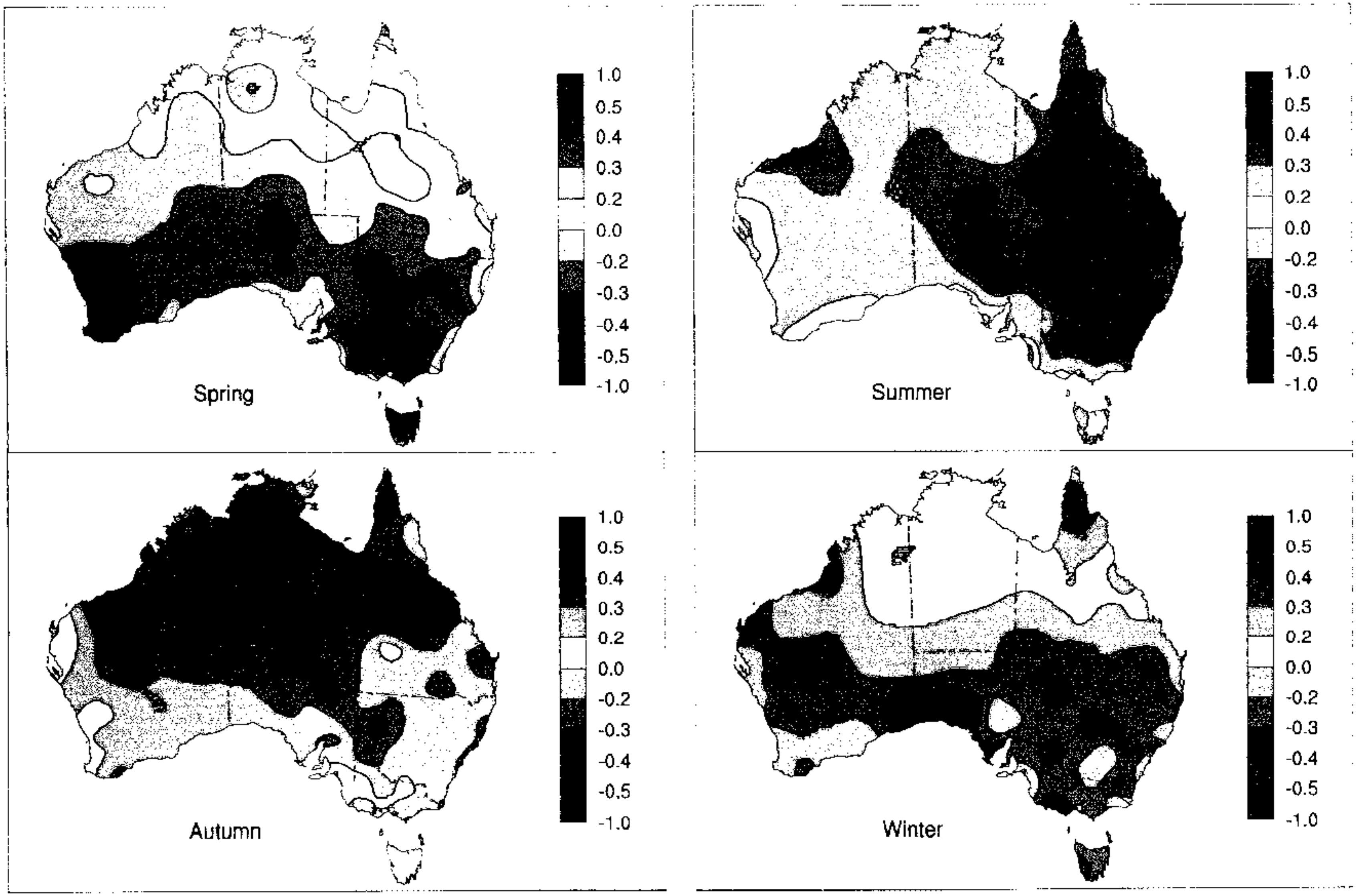


Fig. 9.1b. Correlation between frequency of maxima above the 90th percentile and SOI, lag

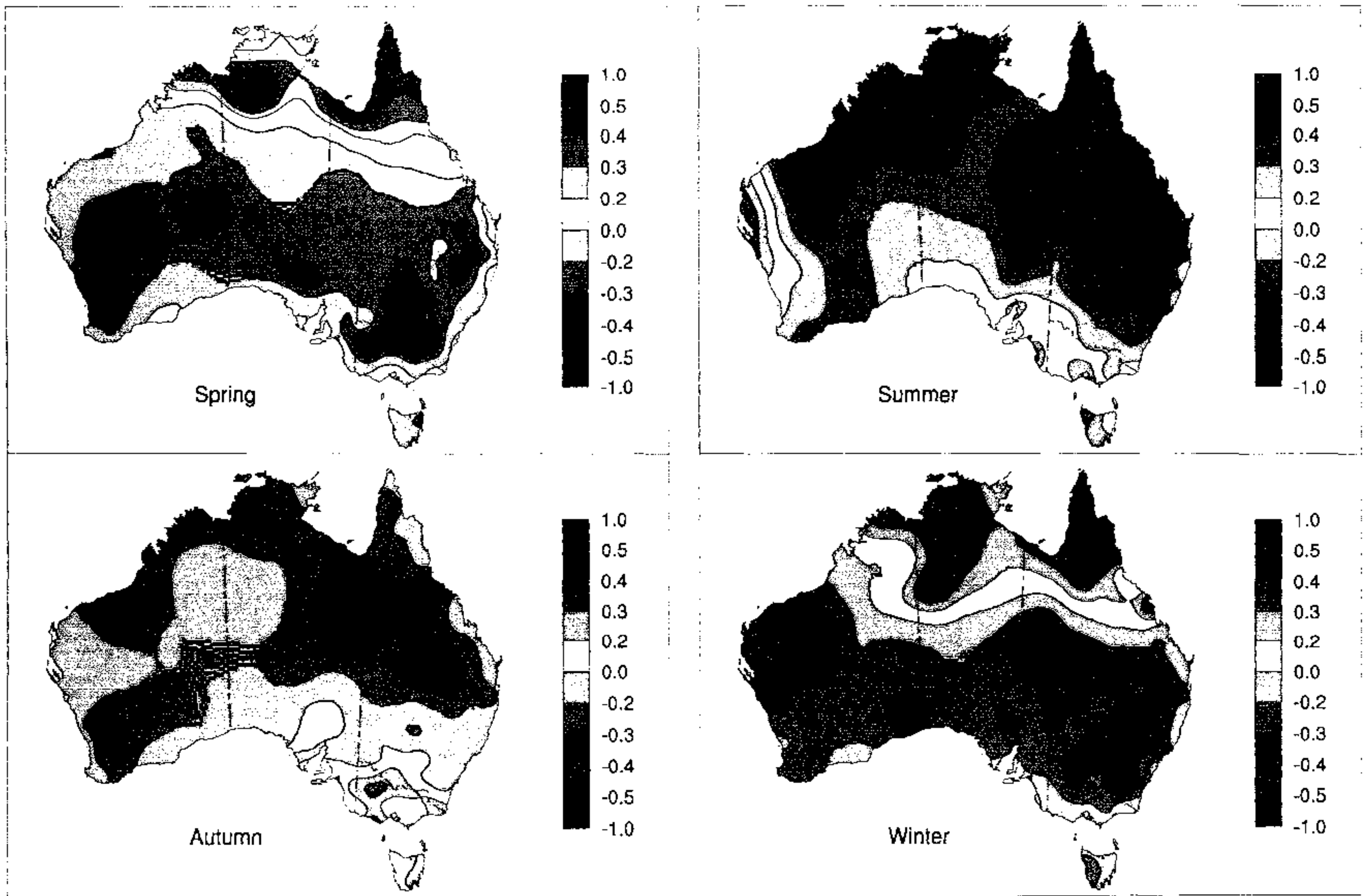


Fig. 9.1c. Correlation between frequency of maxima above the 50th percentile and SOI, simultaneous

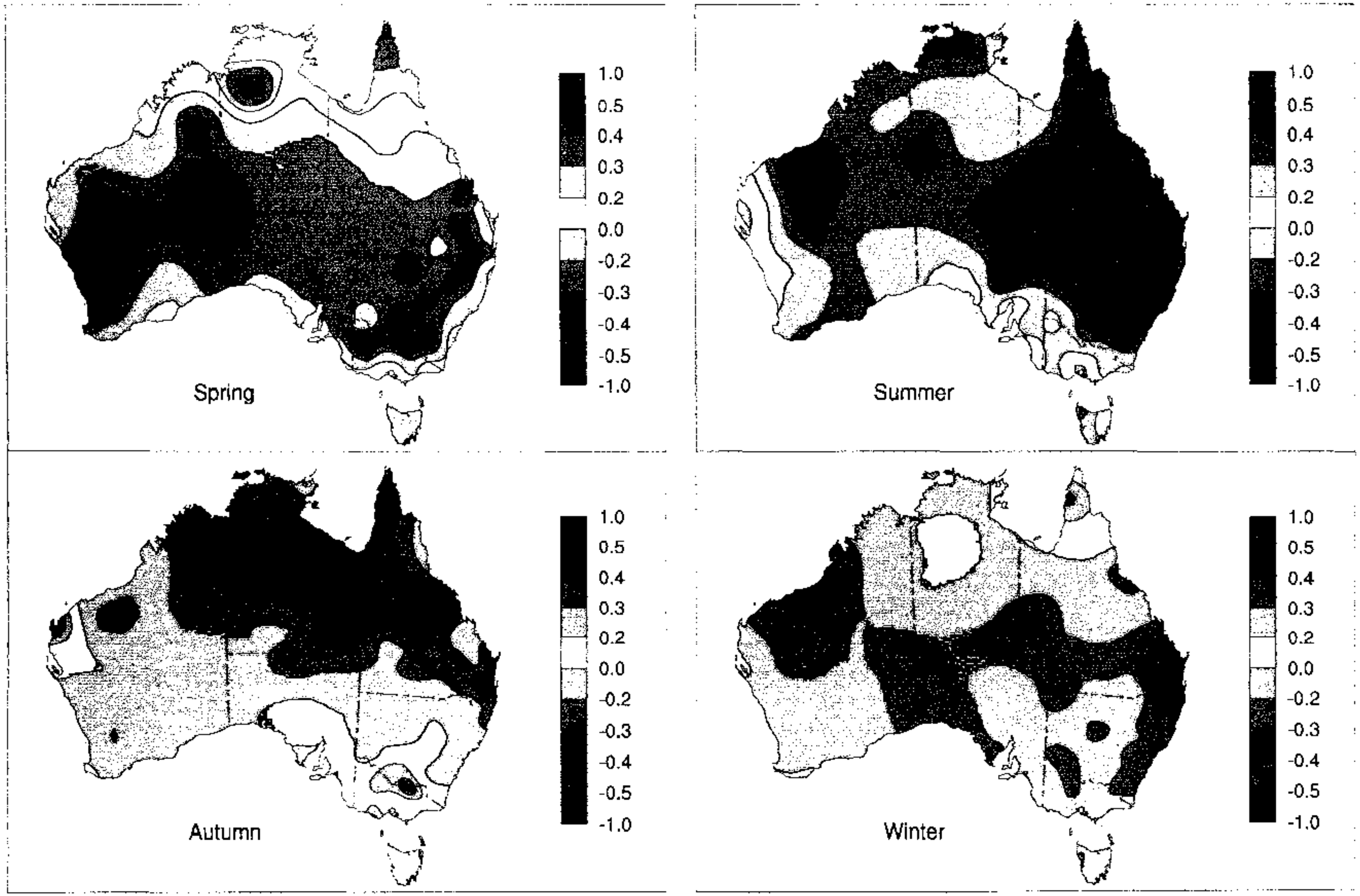


Fig. 9.1d. Correlation between frequency of maxima above the 50th percentile and SOI, lag

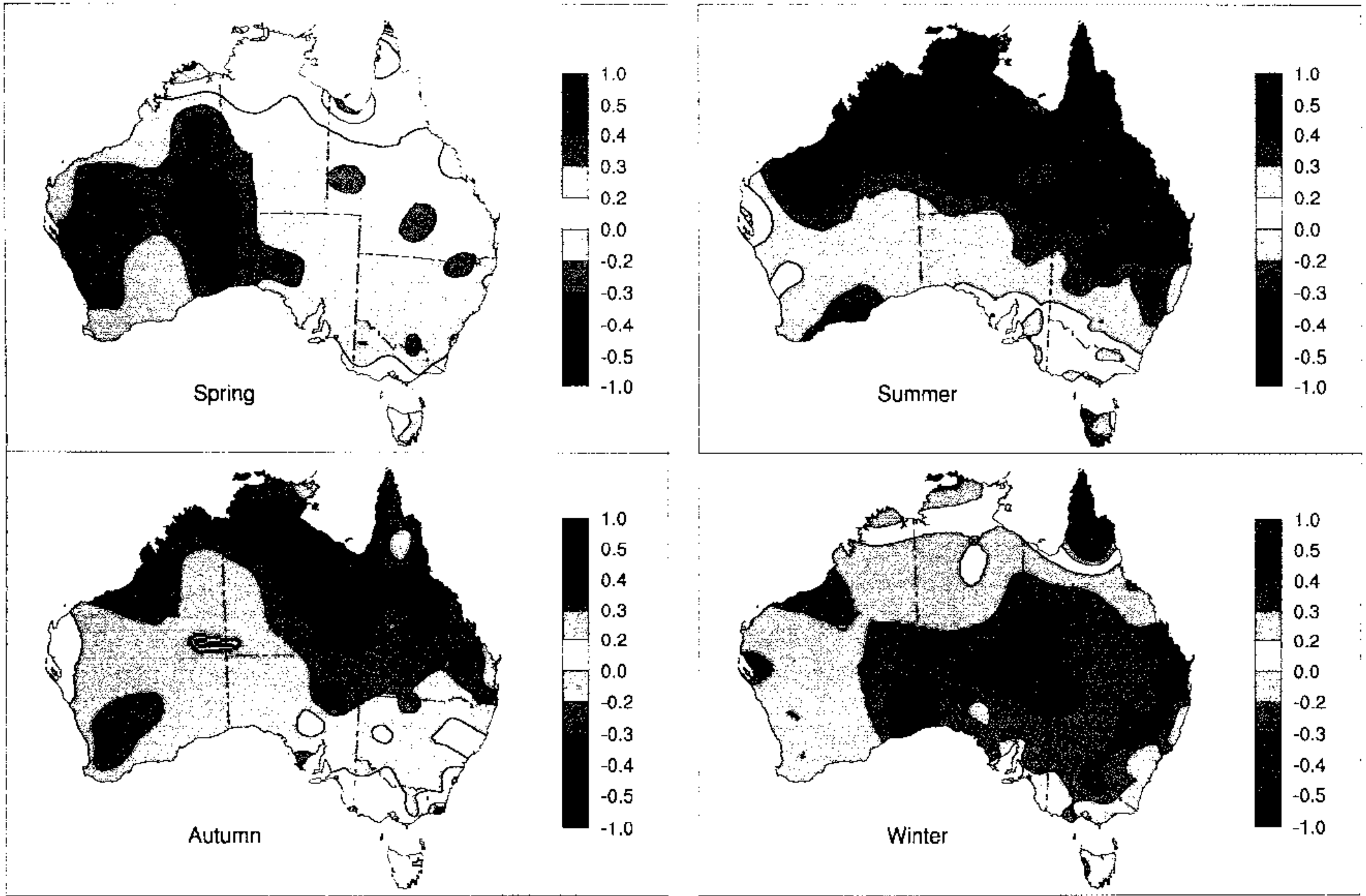


Fig. 9.1e. Correlation between frequency of maxima above the 10th percentile and SOI, simultaneous

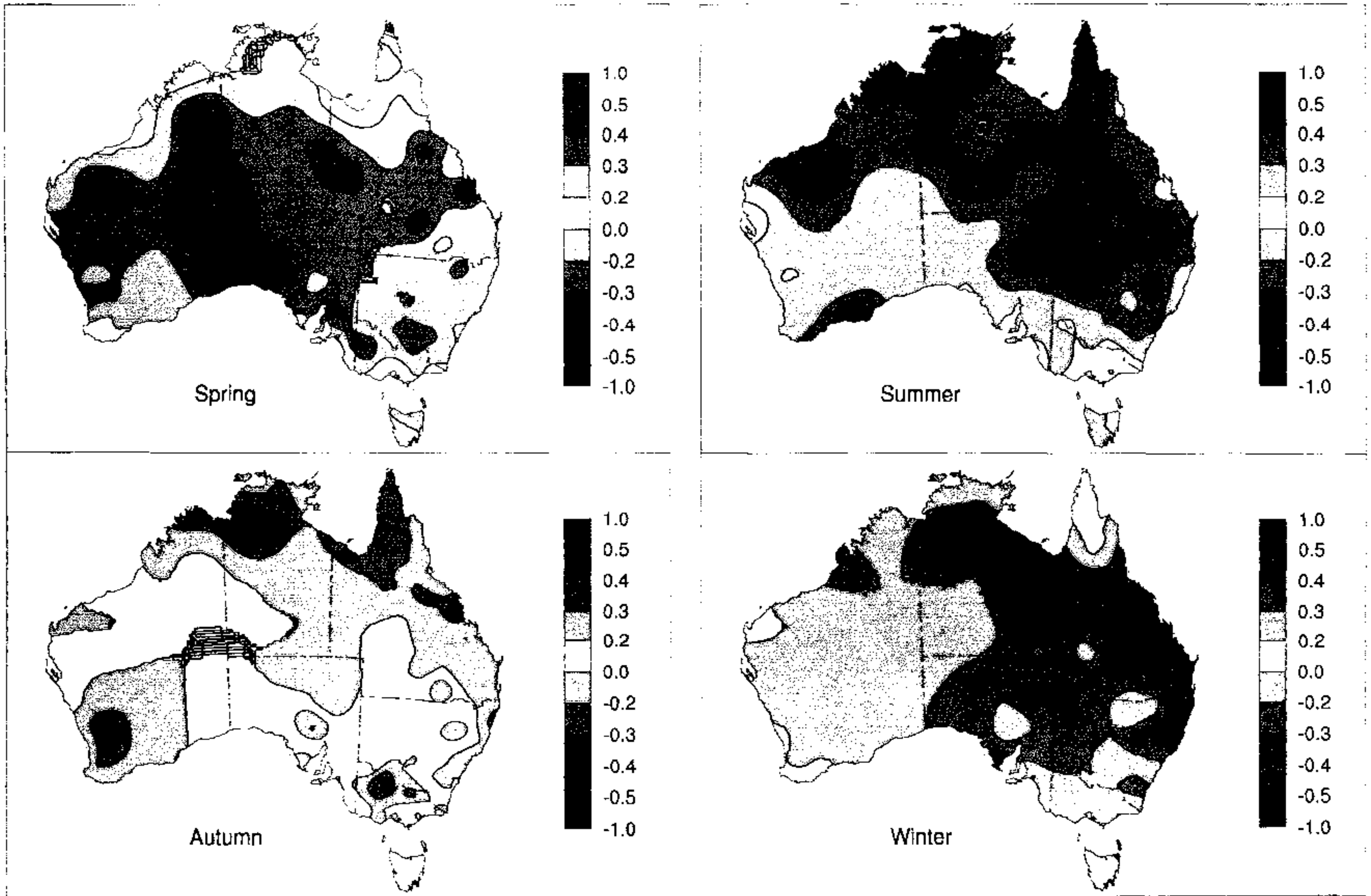


Fig. 9.1f. Correlation between frequency of maxima above the 10th percentile and SOI, lag

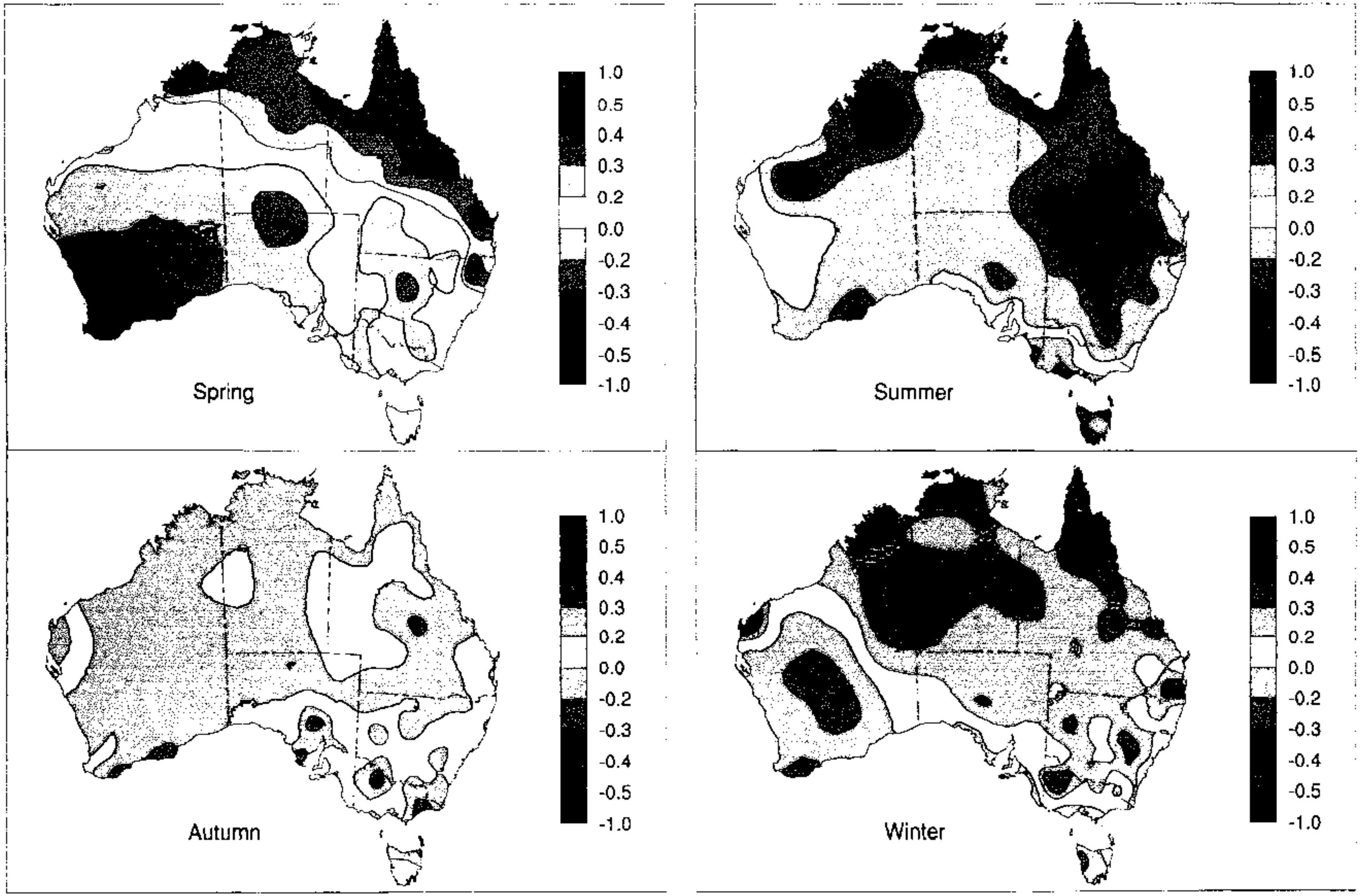


Fig. 9.1g. Correlation between frequency of minima above the 90th percentile and SOI, simultaneous

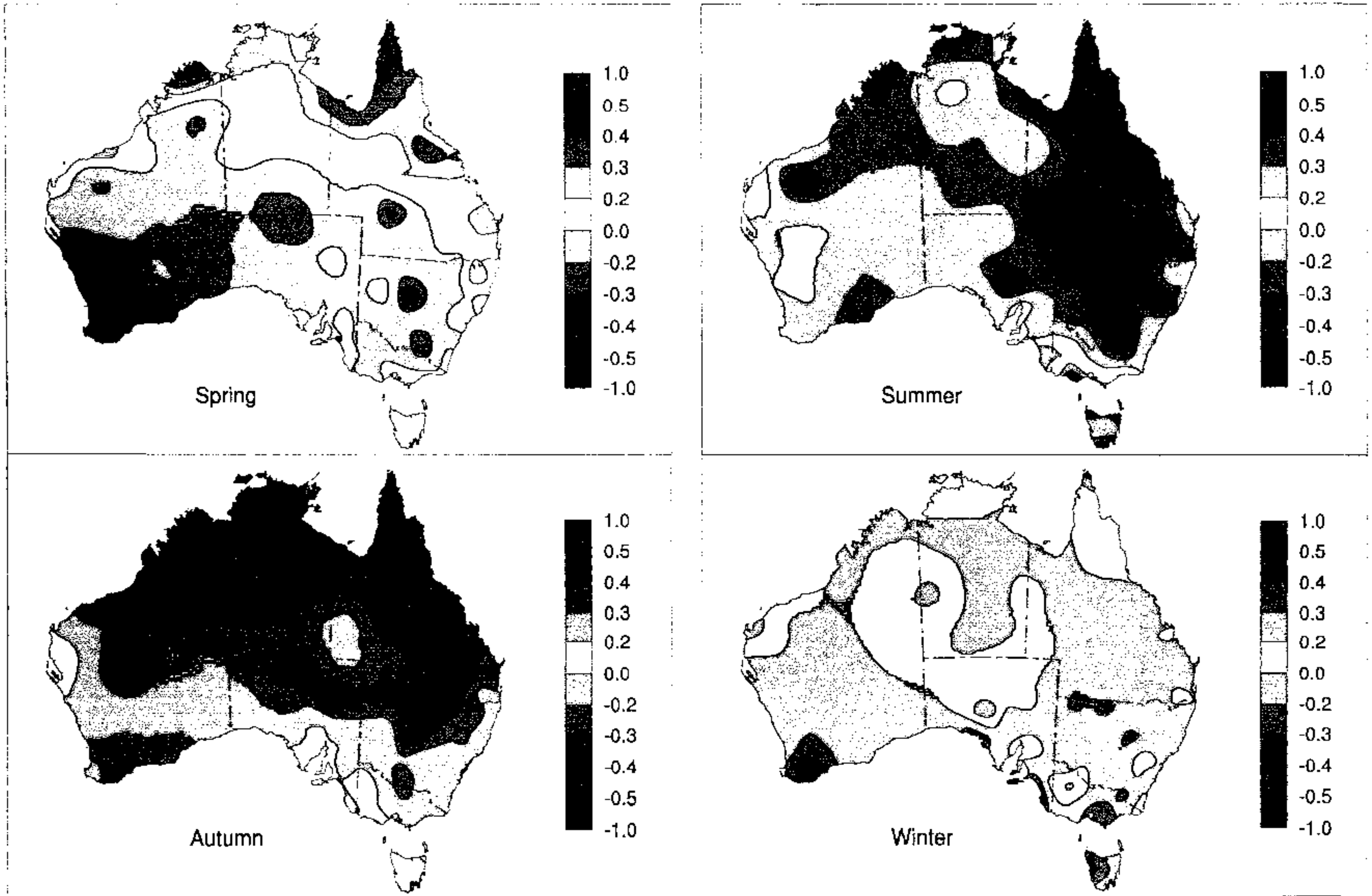


Fig. 9.1h. Correlation between frequency of minima above the 90th percentile and SOI, simultaneous

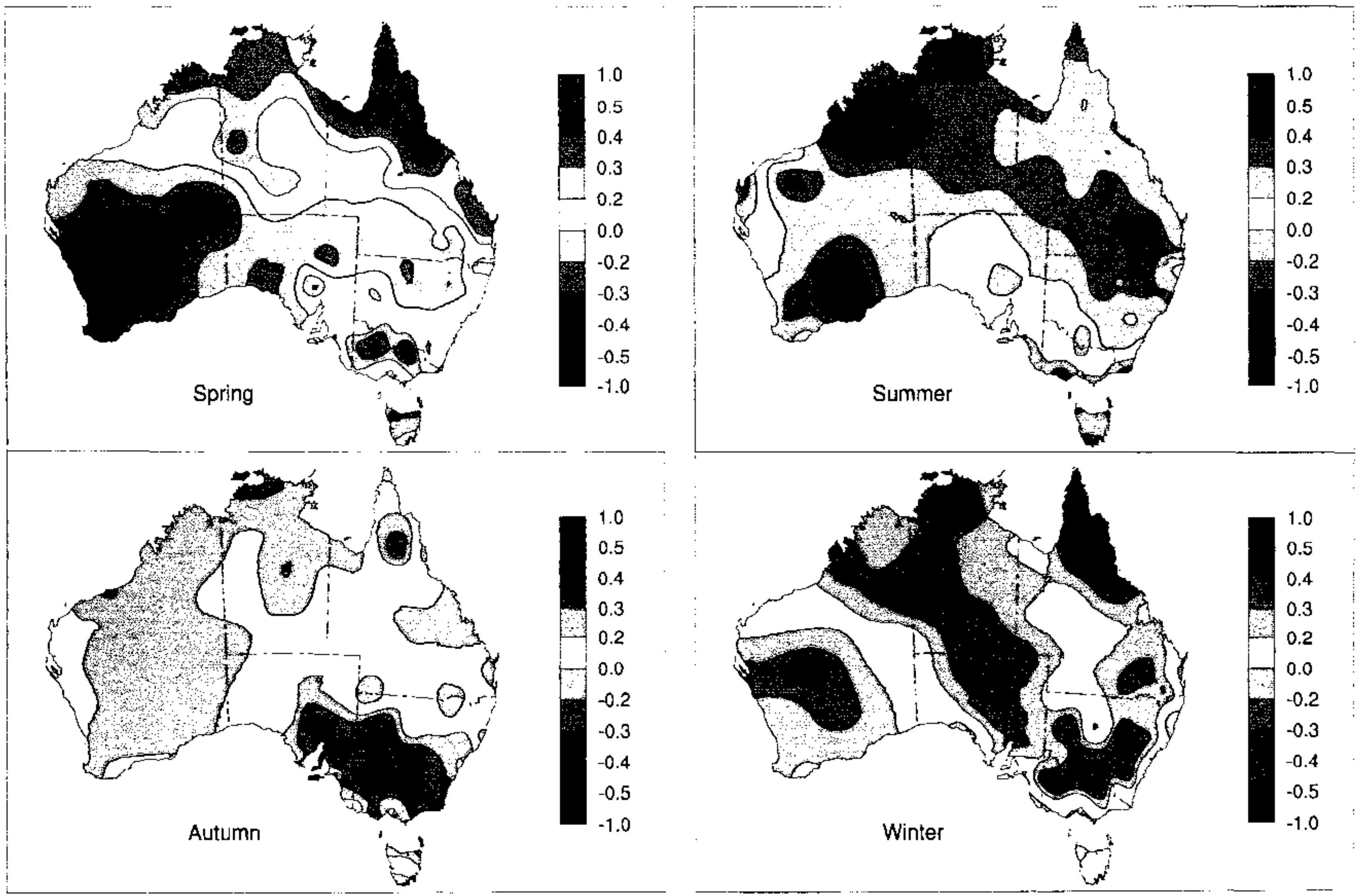


Fig. 9.1i. Correlation between frequency of minima above the 50th percentile and SOI, simultaneous

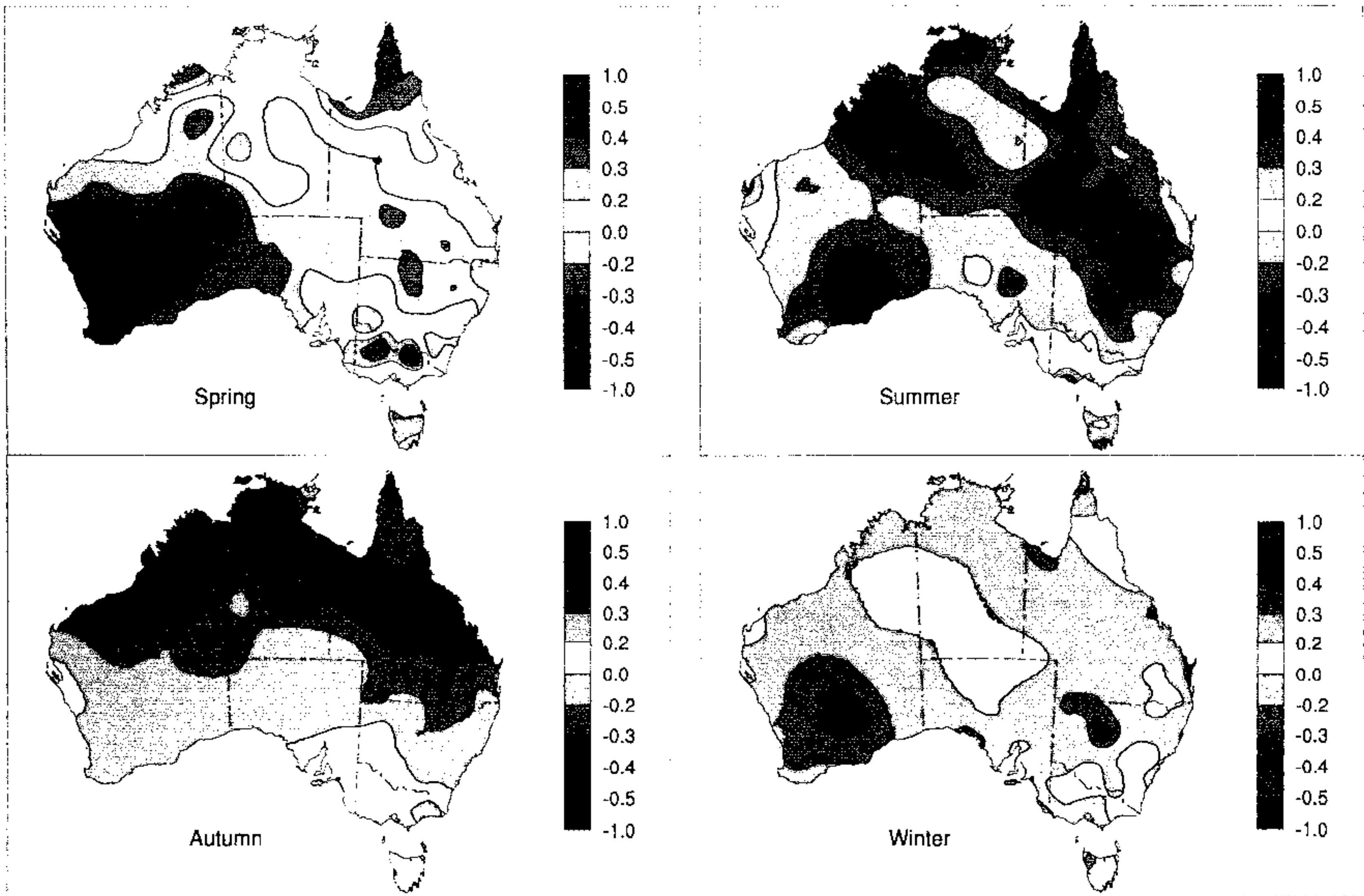


Fig. 9.1j. Correlation between frequency of minima above the 50th percentile and SOI, lag

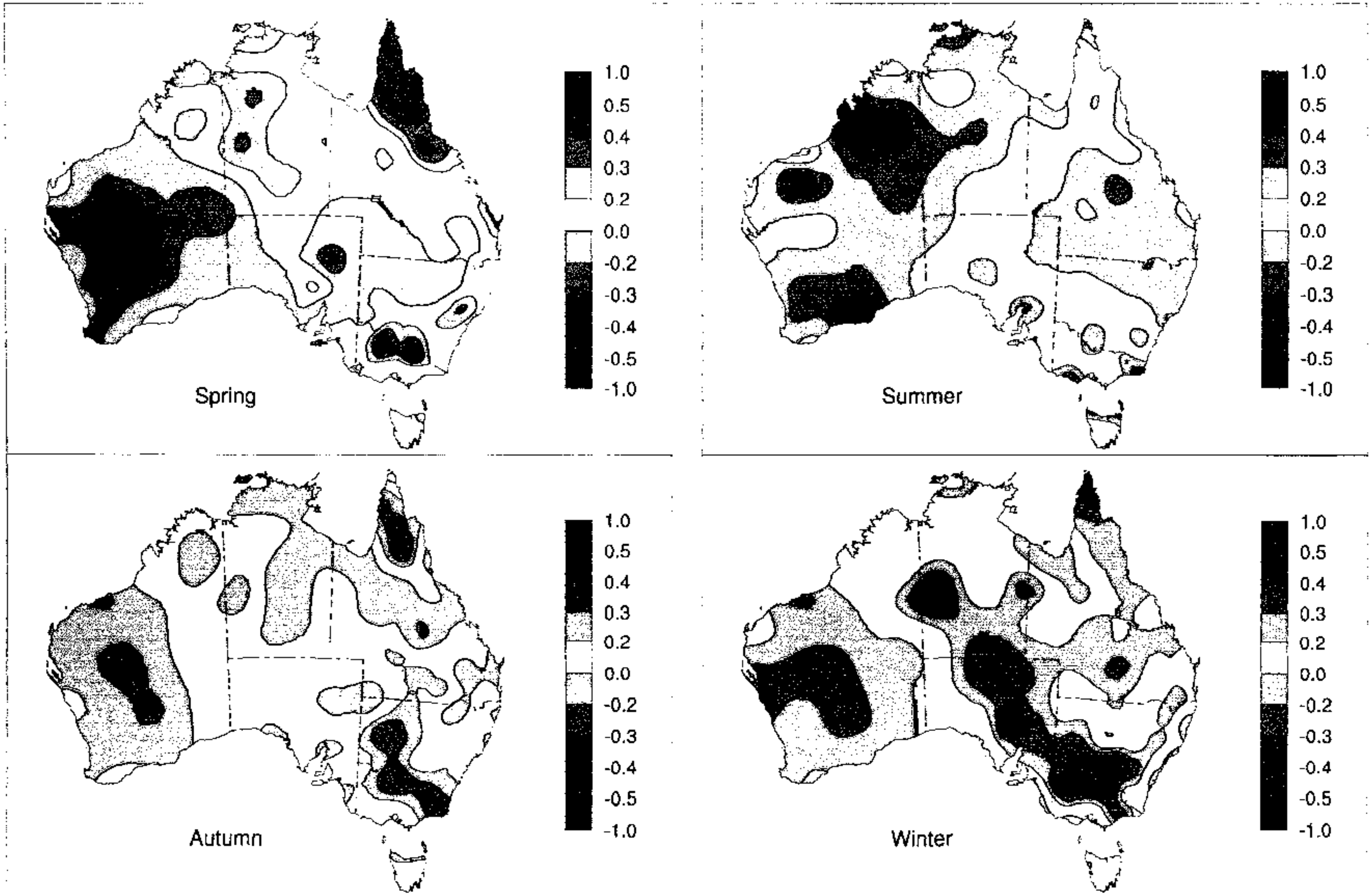


Fig. 9.1k. Correlation between frequency of minima above the 10th percentile and SOI, simultaneous

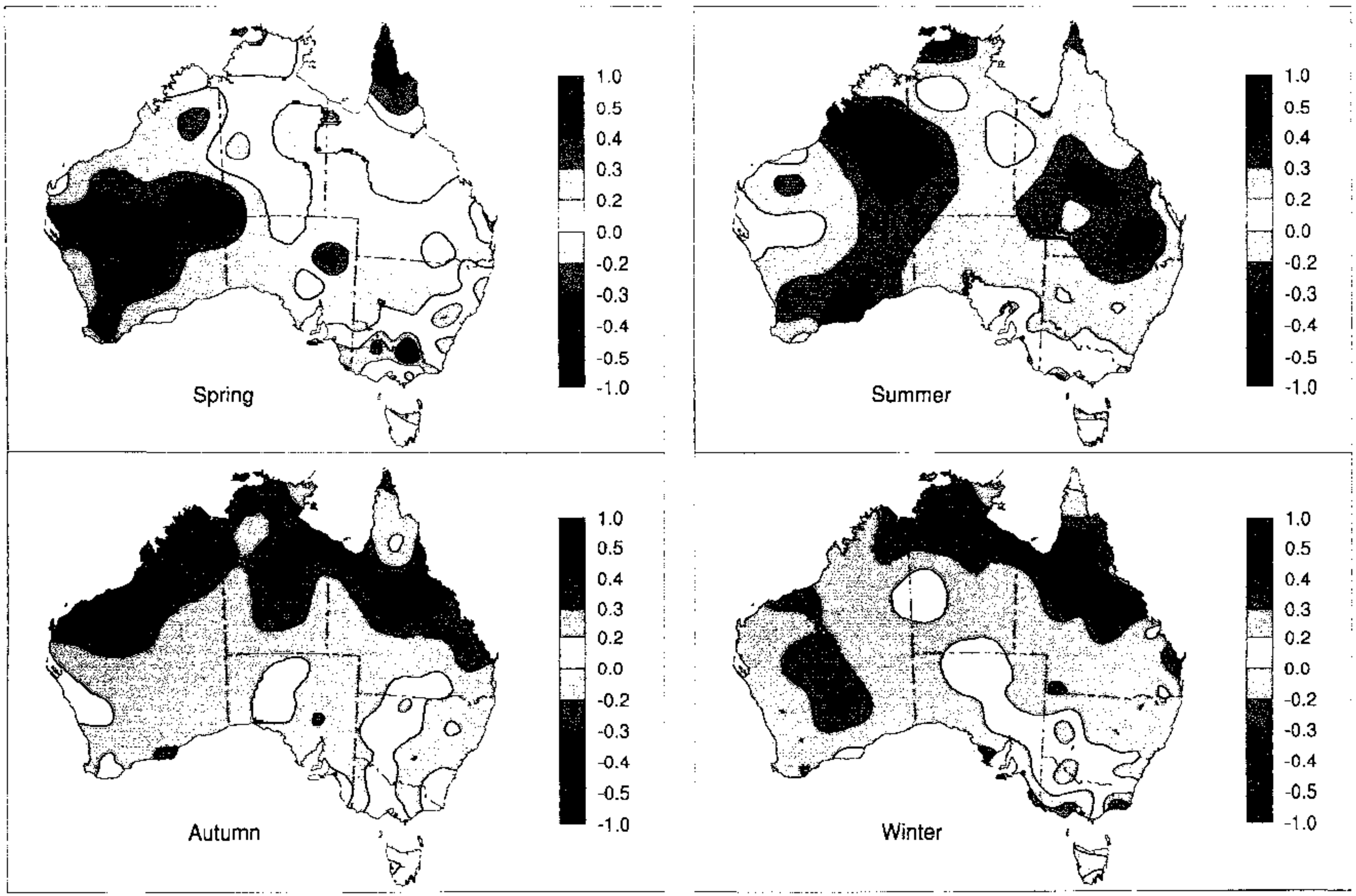


Fig. 9.11. Correlation between frequency of minima above the 10th percentile and SOI, lag

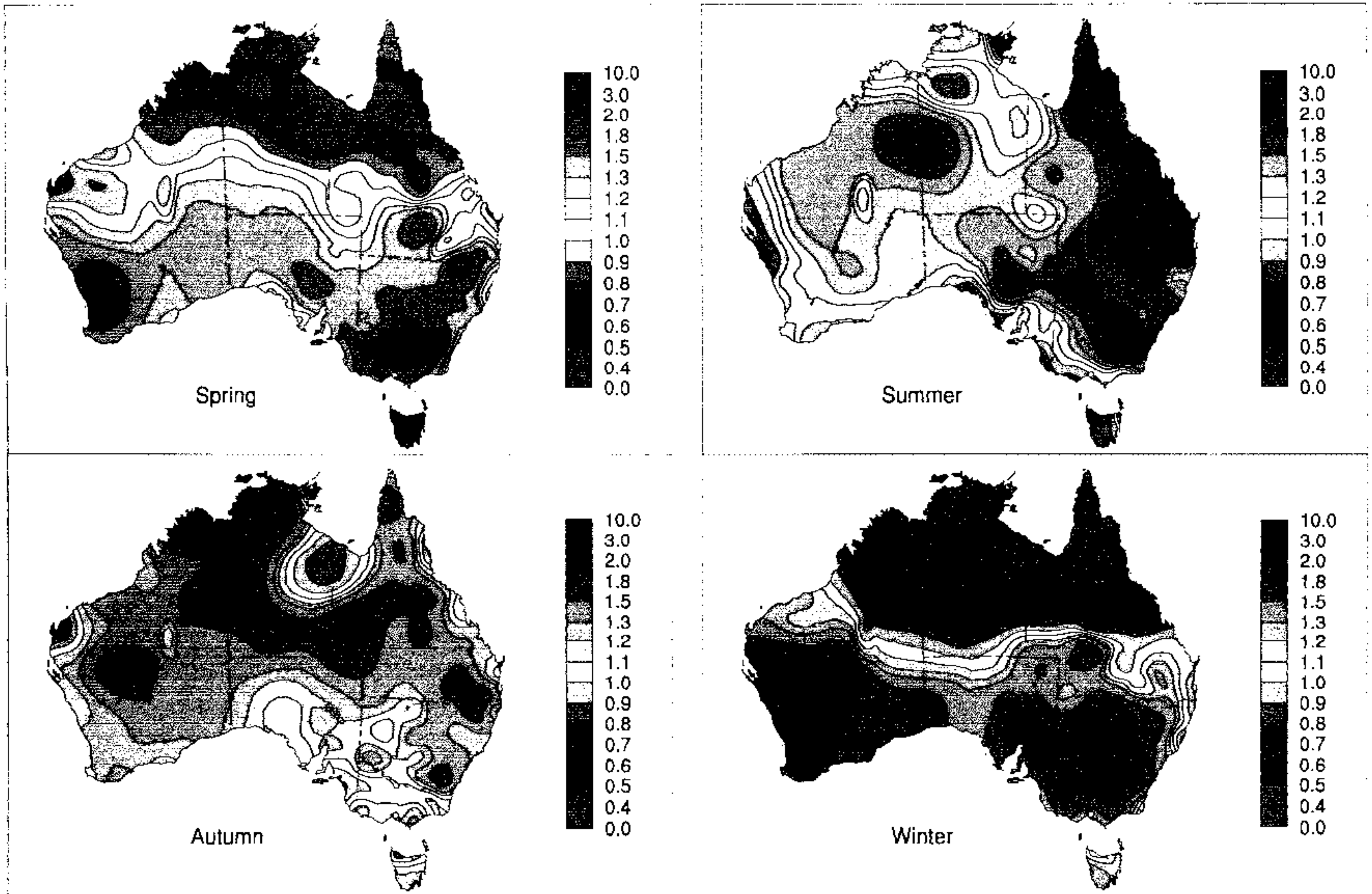


Fig. 9.2a. SOI tercile 1/tercile 3 event frequency ratio, maxima above 90th percentile, simultaneous

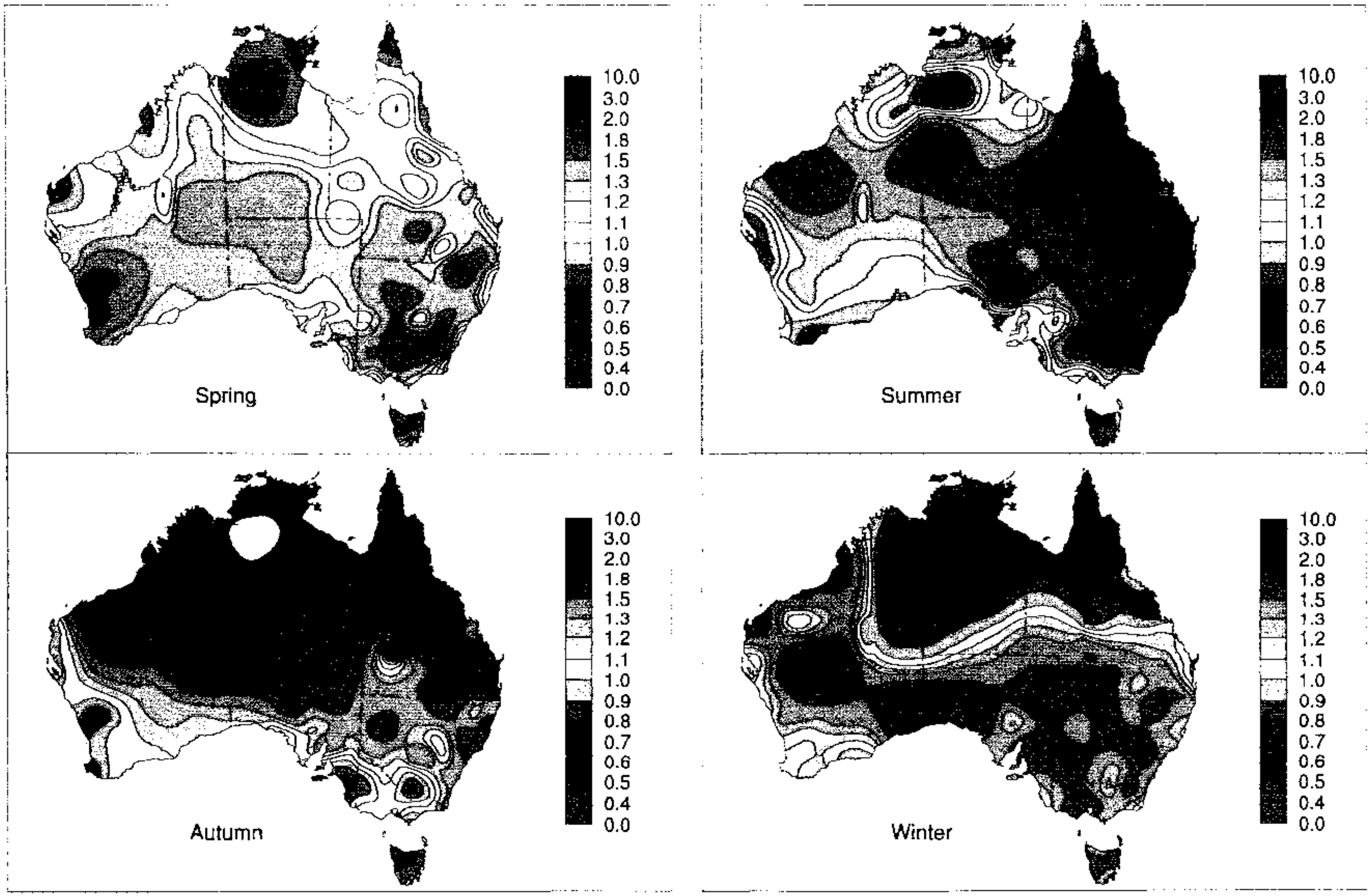


Fig. 9.2b. SOI tercile 1/tercile 3 event frequency ratio, maxima above 90th percentile, lag

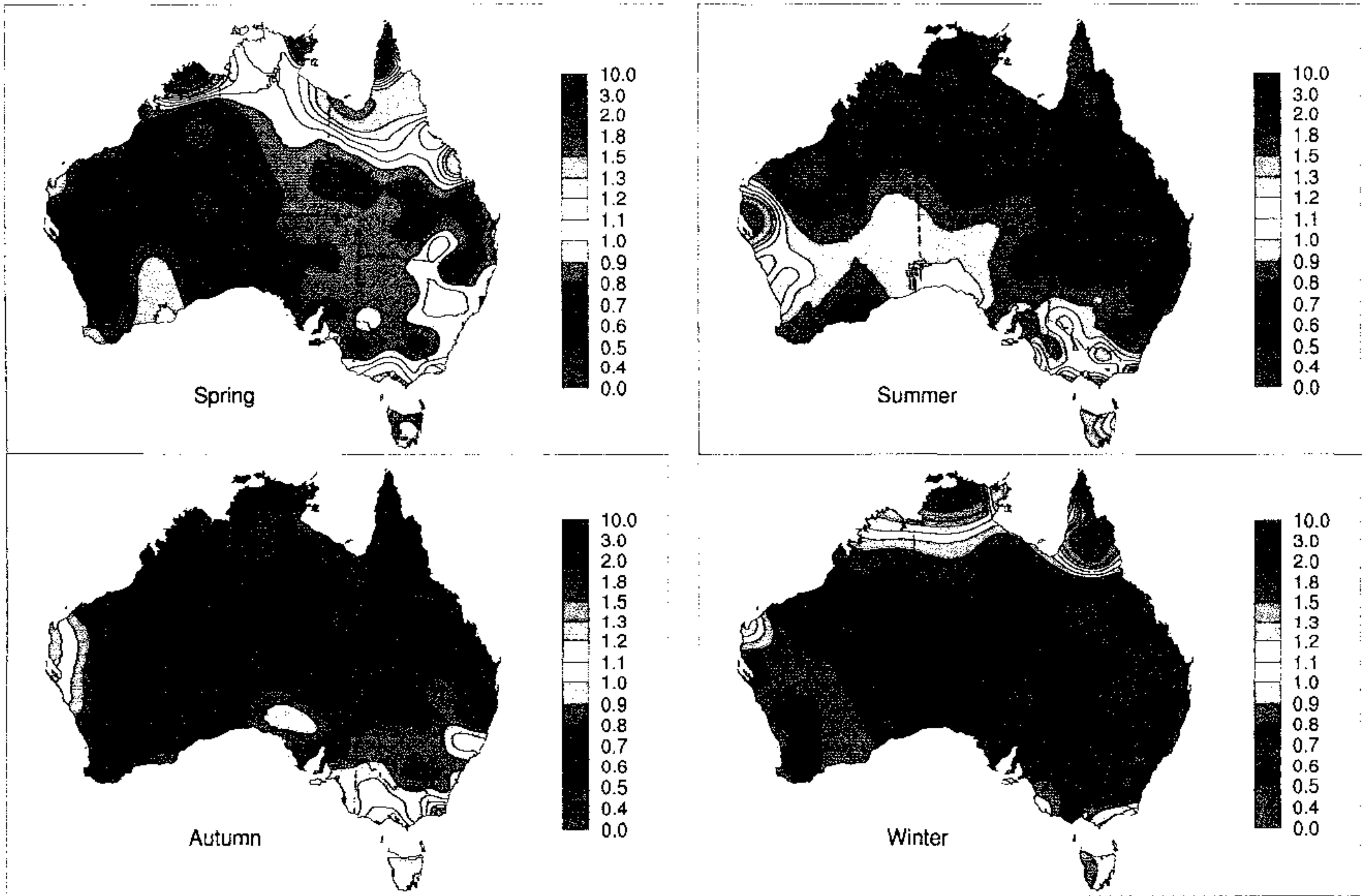


Fig. 9.2c. SOI tercile 1/tercile 3 event frequency ratio, maxima below 10th percentile, simultaneous

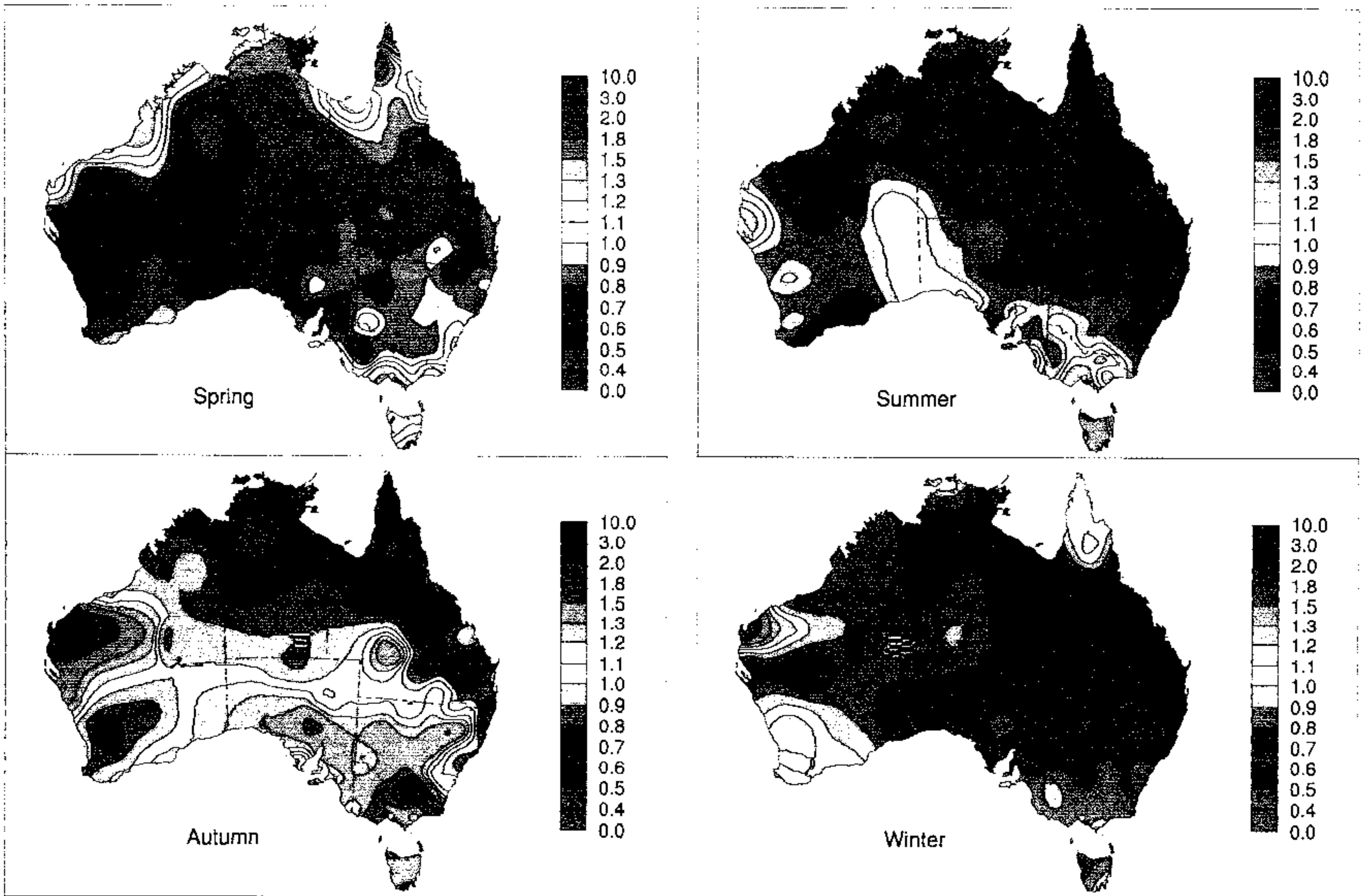


Fig. 9.2d. SOI tercile 1/tercile 3 event frequency ratio, maxima below 10th percentile, lag

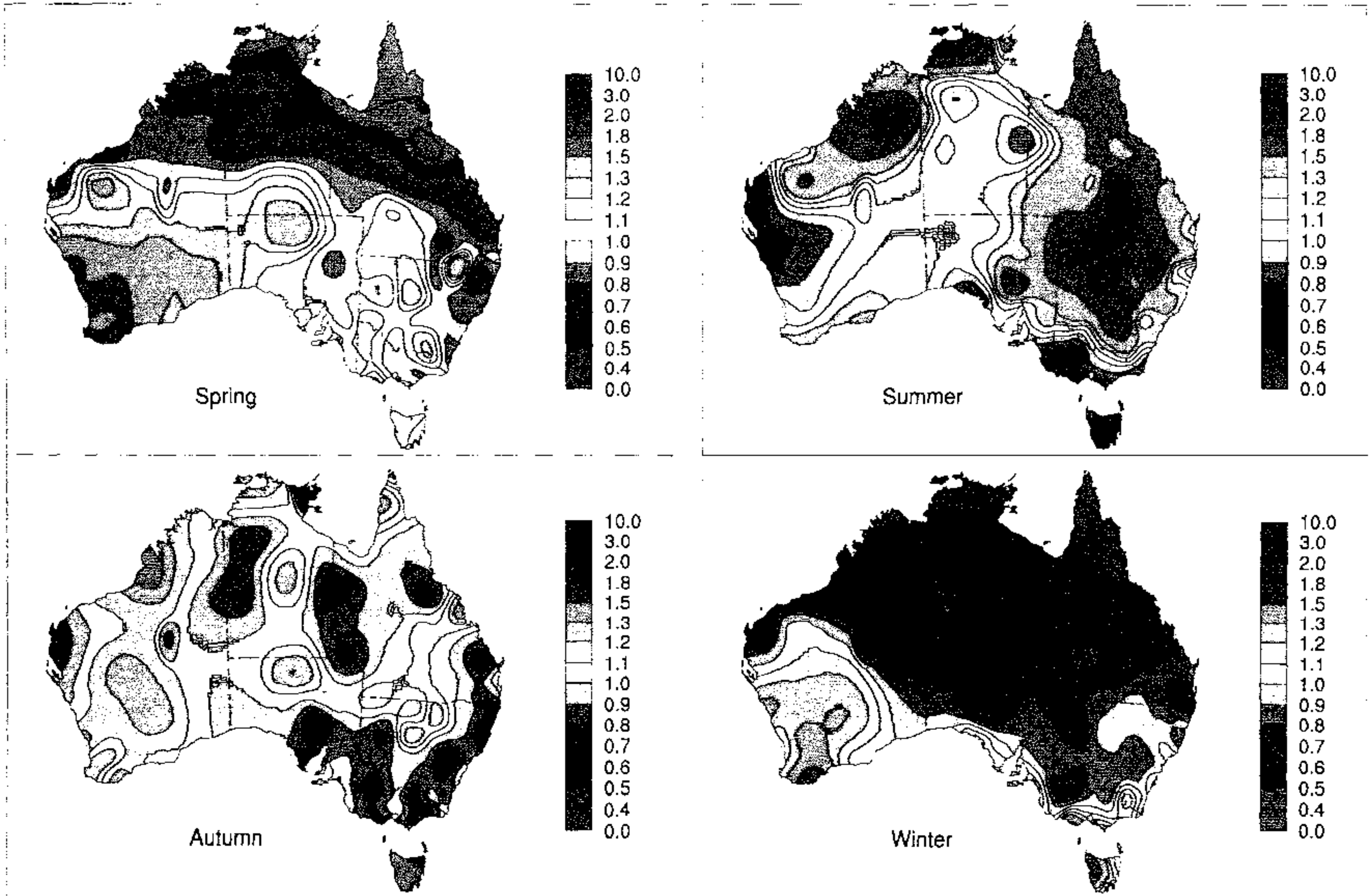


Fig. 9.2e. SOI tercile 1/tercile 3 event frequency ratio, minima above 90th percentile, simultaneous

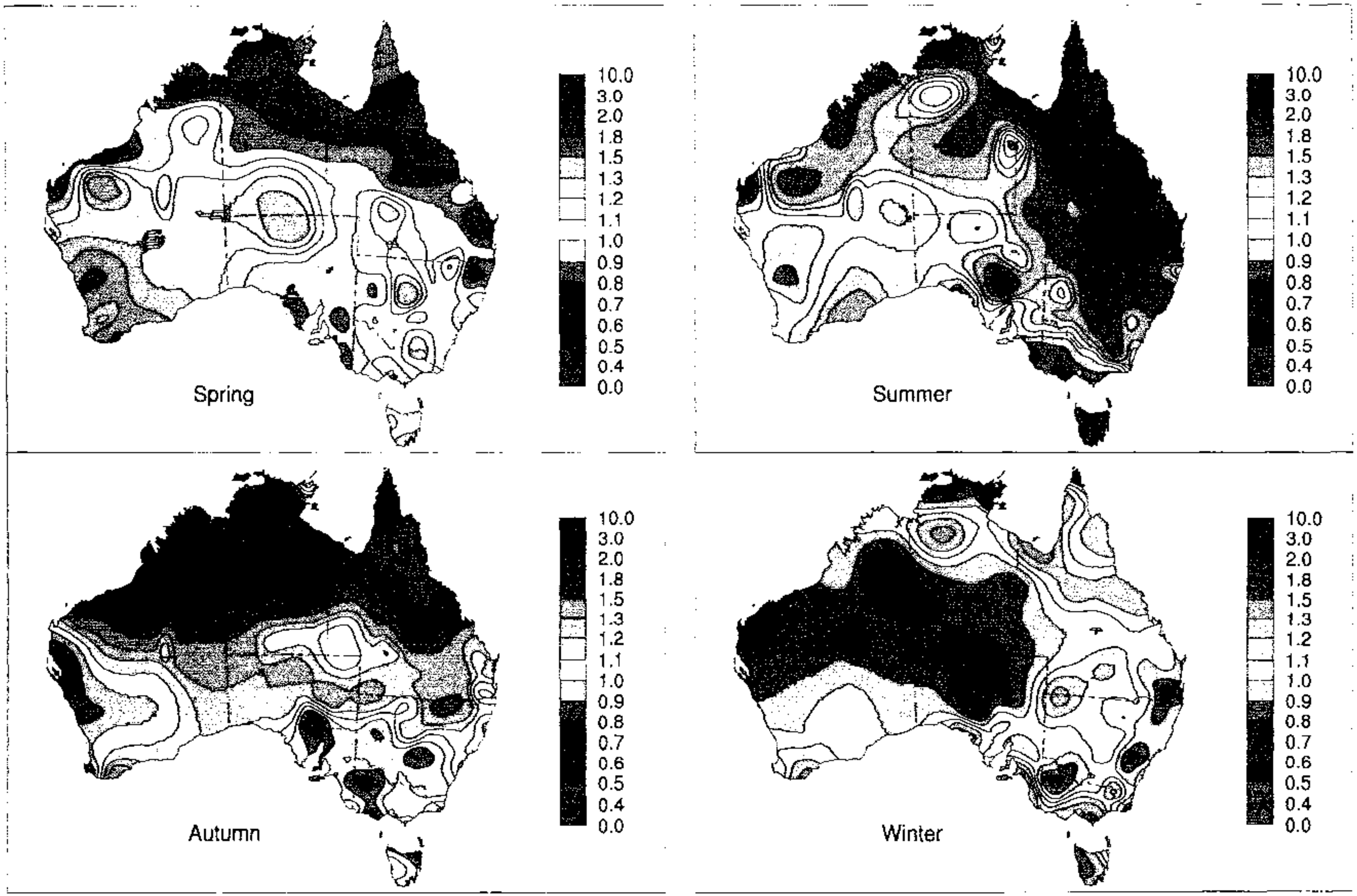


Fig. 9.2f. SOI tercile 1/tercile 3 event frequency ratio, minima above 90th percentile, lag

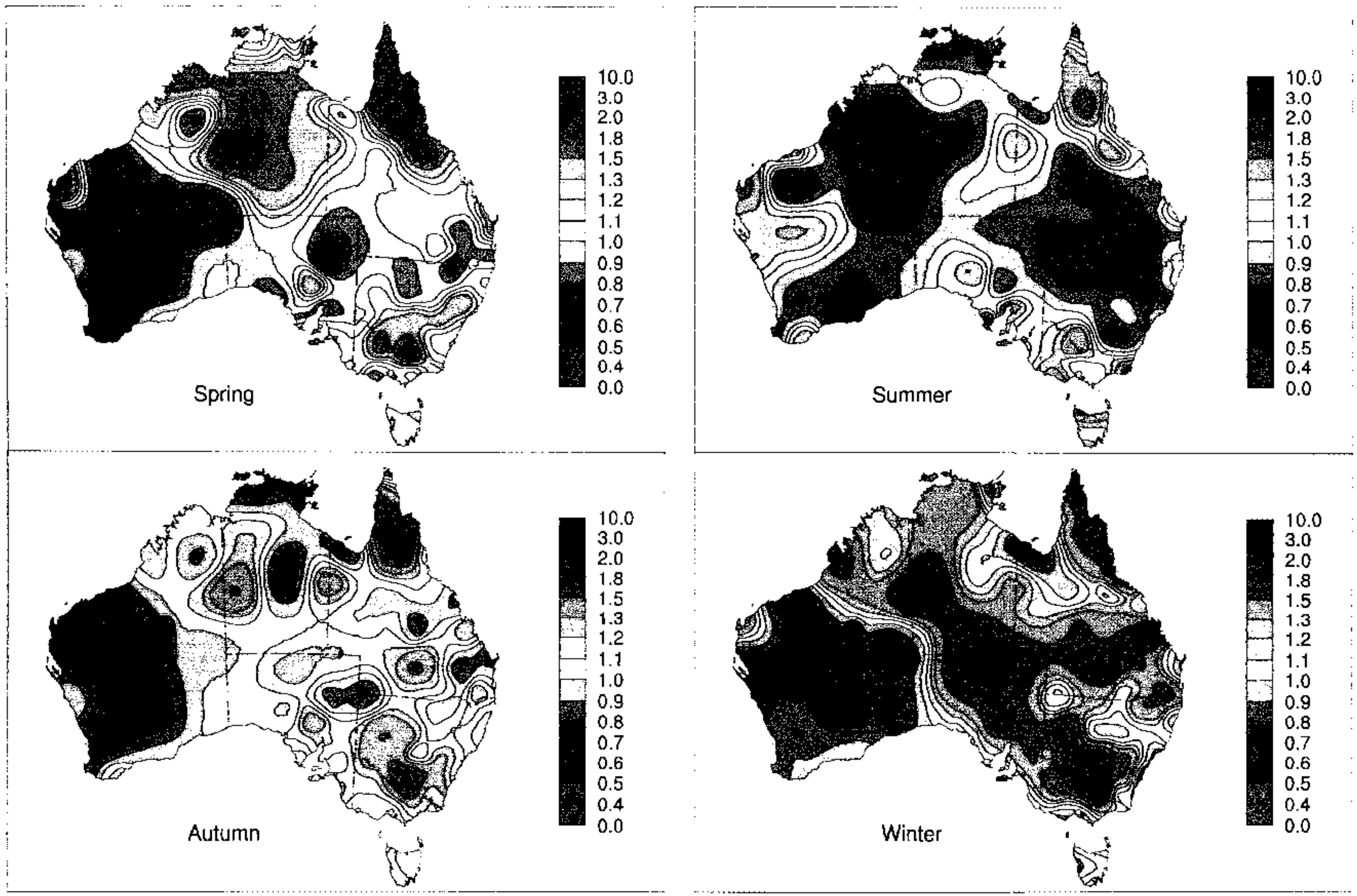


Fig. 9.2g. SOI tercile 1/tercile 3 event frequency ratio, minima below 10th percentile, simultaneous

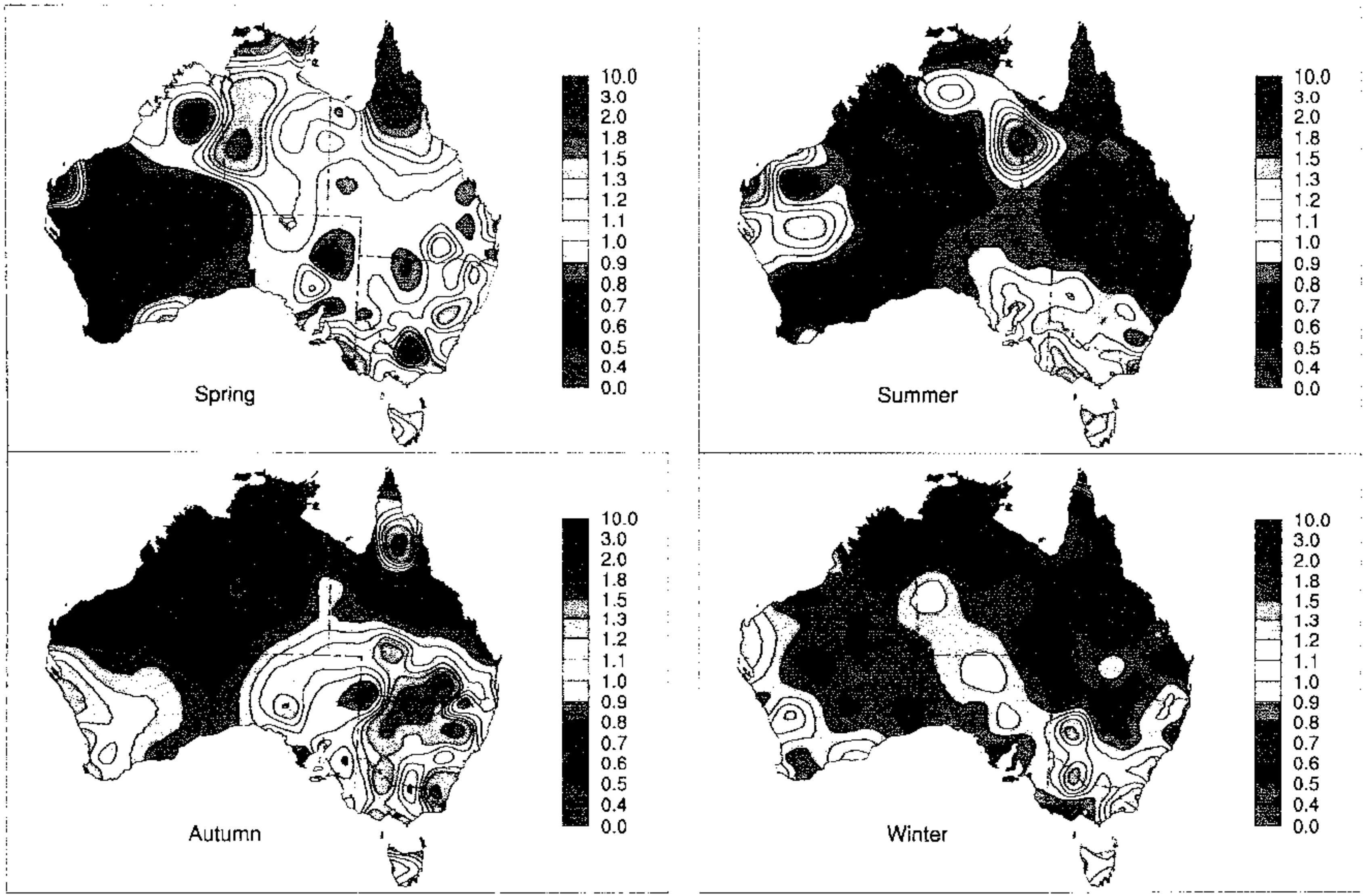


Fig. 9.2h. SOI tercile 1/tercile 3 event frequency ratio, minima below 10th percentile, lag

for New South Wales east of the Great Dividing Range and far eastern Gippsland, with values locally reaching -0.5 in several places. At lag, the positive/negative pattern is similar to that for the simultaneous correlations, but the correlations themselves are much weaker, although -0.3 is still reached at scattered locations through southern Australia and 0.4 on Cape York Peninsula.

Figs. 9.2a and 9.2b show the relative sensitivities of the frequency of extreme high maxima to the SOI. As expected, the geographical patterns of the ratios largely mirror the correlations discussed above. The simultaneous winter pattern is particularly striking. The ratio is below 0.5 over most of the region north of 20°S, and above 2.0 in much of south-western Western Australia and inland New South Wales. These indicate shifts in probabilities of extreme high maxima exceeding 2:1 (in either direction) between El Niño and La Niña conditions. However, as for the winter correlations, these relationships are much weaker at lag.

Other regions and seasons where the ratios are above 1.5 are:

- Much of Tasmania, Victoria, inland New South Wales and south-western Western Australia in spring, both simultaneously and at lag.
- Most of Queensland (apart from the tropical coast) and New South Wales in summer, with greater sensitivities (widely exceeding 2.0 in Queensland, and reaching 3.0 in places) at lag than simultaneously.
- Most of tropical Australia at lag in autumn, with sensitivities exceeding 2.0 in most of north-western Australia. Such ratios are also observed more locally simultaneously in northern Western Australia and the western Northern Territory.

Ratios below 0.7 are less common. Apart from the aforementioned very low values in the tropics during winter, low simultaneous ratios (mostly 0.5-0.7) occur in spring over the region north of 18°S, but those ratios are somewhat higher at lag. These results suggest that, over Australia as a whole, extreme high temperature events are most likely during El Niño events.

9.3.2. Low maximum temperatures

Figs. 9.1e and 9.1f show the simultaneous and lag correlations between the SOI and the frequency of maxima above the 10^{th} percentile. In spring, simultaneous and lag correlations are negative over most of Australia, except for parts of northern Australia, southern Victoria and parts of Tasmania. However, the correlations only reach –0.3 in small isolated areas, mostly in Western Australia. The correlations are slightly stronger at lag than they are simultaneously, with values locally reaching –0.5 at Halls Creek and isolated Queensland stations also reaching –0.3. Isolated stations on the northern coastline have correlations exceeding 0.3.

As for high maxima, negative correlations dominate most of Australia in summer, although the focus of the strongest correlations is further north and west. Simultaneous correlations are below –0.3 over almost all of Queensland, the Northern Territory and tropical Western Australia, reaching –0.6 in the far north. At lag the correlations are slightly weaker but are still below –0.3 over much of Queensland and the Northern Territory. Positive correlations are mostly confined to the south-east, covering Tasmania (where they reach 0.3 locally), most of Victoria and adjoining parts of New South Wales and South Australia. The area of positive correlations in the south-east is more extensive for low maxima than it is for high maxima, and it is interesting to note that some stations near the NSW/Victorian border show positive correlations near 0.3 for low maxima, but negative correlations near –0.3 for high maxima, indicating enhanced (suppressed) variability of temperature at both ends of the distribution in El Niño (La Niña) years. This may be associated with positive pressure anomalies over the South Tasman Sea, and consequent north-easterly gradient wind anomalies over south-eastern Australia, in La Niña years (Drosdowsky and Williams, 1991; Jones and Simmonds, 1994).

In autumn, negative simultaneous correlations are observed over most of Australia. They are mostly weak, with –0.3 reached only in the northern half of Queensland, parts of the Northern Territory and the Kimberley region of Western Australia. In contrast to the situation for high maxima, the correlations are even weaker at lag, and (mostly weak) positive correlations cover substantial parts of the continent, 0.3 being reached locally in Victoria.

Winter correlations are negative over almost all of Australia except the far north, both simultaneously and at lag. Unlike the other extreme variables in winter, the correlations at lag are of similar or greater strength to those found simultaneously, except that the strong positive correlations found simultaneously in the far north (locally exceeding 0.5 on Cape York Peninsula) disappear at lag. Simultaneous values below –0.3 are found at scattered locations through inland eastern Australia, whilst at lag they are found over much of Queensland (except for Cape York), reaching –0.5 near Brisbane.

Figs. 9.2c and 9.2d show the relative sensitivities of the frequency of extreme low maxima to the SOI. The relative sensitivity of the frequency of low maxima to the SOI is, on balance, generally greater than those found for similar correlations for high maxima. Ratios below 0.7 are found in the following areas:

- Widespread areas in a belt across the central latitudes of Australia in spring.
- Most of Queensland, the Northern Territory and northern Western Australia in summer. The areas are more extensive, and stronger, at lag than they are simultaneously, extending southwards into northern New South Wales are with values below 0.5 in the Top End of the Northern Territory.
- Most of Western Australia (except for the west and south coasts), the Northern Territory, Queensland and northern South Australia for simultaneous values in autumn, with ratios as low as 0.4 in the northern Northern Territory. As with the correlations, the pattern weakens considerably at lag, with values below 0.7 mostly confined to the region north of 20°S.
- Large areas of central and eastern Australia in winter (reaching 0.5 in inland southern Queensland). Unlike the correlations, the pattern for ratios is somewhat weaker at lag than it is simultaneously (at lag ratios below 0.7 are mostly confined to Queensland and northern New South Wales), but the weakening of the relationship is still much less distinct than it is for the other three extremes.

Simultaneous ratios above 1.5 are only found at isolated stations, mostly in the far north in winter and spring. At lag, the one season where coherent areas with ratios above 1.5 occur is autumn, where they are found over much of Victoria and adjacent southern inland New South Wales, parts of Tasmania, and the Pilbara and Gascoyne regions of Western Australia.

9.3.3. High minimum temperatures

Figs. 9.1g and 9.1h show the simultaneous and lag correlations between the SOI and the frequency of minima above the 90th percentile. In spring, correlations are positive in most of tropical Australia, both simultaneously and at lag. Simultaneous values above 0.3 occur over most of the area north of a line from Brisbane to the Kimberley, reaching as high as 0.7 on Cape York Peninsula. The positive/negative boundary is in a similar location at lag but the positive correlations are weaker, only reaching 0.3 in the far north. Negative correlations between –0.3 and –0.5 occur in south-western Western Australia, with near-zero correlations over most of the remaining extratropics.

Negative correlations occur over most of Australia in summer. They are stronger at lag than simultaneously, with values below –0.3 covering most of Queensland and inland New South Wales. Positive correlations, both simultaneously and at lag, occur in Victoria, Tasmania and the south-east of South Australia, exceeding 0.3 at some mainland coastal stations and in much of Tasmania.

Simultaneous correlations in autumn are weak throughout Australia, although positive correlations cover the south-east south of 30°S, with values reaching 0.3 at a few stations. At lag, however, negative correlations cover almost all of mainland Australia, and are below –0.3 over almost all of the tropics and extratropical Queensland (reaching –0.6 in central Queensland). Interestingly, the change between the simultaneous and lag patterns is the reverse of that which occurs for low maxima.

In winter, positive correlations occur over most of Australia, except for southern Western Australia and the coasts of Victoria and South Australia, and exceed 0.3 over extensive areas of the tropics. However, these correlations disappear almost completely at lag, with values between 0.2 and –0.2 at almost all stations.

Figs. 9.2e and 9.2f show the relative sensitivities of the frequency of extreme high minima to the SOI. Notable features include:

- The very low ratios found simultaneously in winter and spring in the far north of Australia. Ratios are below 0.5 in both seasons at numerous stations, are below 0.7 over most of the tropics, and fall as low as 0.2 on Cape York Peninsula. These low ratios are also found at lag in spring, but not in winter.
- There are extensive areas with ratios at lag exceeding 1.5 in both summer and autumn. In summer those ratios occur over most of Queensland, northern and central New South Wales and some northern coastal areas of the Northern Territory and Western Australia. In autumn they cover the entire tropics. In both cases the ratios exceed 2.0 over substantial regions and 3.0 at a few stations. These patterns are also found simultaneously in summer, but not in autumn.
- Ratios drop below 0.7 in summer, both simultaneously and at lag, in summer in southern Victoria and Tasmania. Conversely, in winter this is the only portion of the country with ratios approaching 1.5.
- Simultaneous ratios exceed 1.5 in spring in south-western Western Australia, and are still well above 1 (although mostly dropping to 1.3-1.4) at lag.

9.3.4. Low minimum temperatures

Figs. 9.1k and 9.1l show the simultaneous and lag correlations between the SOI and the frequency of minima above the 10^{th} percentile. In spring, the only areas with strong correlations ($|r| > 0.3$) are parts of inland southern and central Western Australia, where correlations are between –0.3 and –0.5, and two small areas where positive correlations exceed 0.3: Cape York Peninsula and an area on either side of the NSW/Victoria border. The simultaneous and lag patterns are similar.

Weak simultaneous correlations are also a feature of summer. Whilst negative correlations are widespread in Western Australia, they only reach –0.3 at a few widely scattered stations. Positive correlations are found in much of south-eastern Australia but only reach 0.3 at some exposed coastal stations in Victoria and Tasmania. At lag, the pattern is somewhat different with negative correlations over most of Australia except for Victoria and Tasmania, but values are still generally above –0.3, with that threshold being reached in several areas in northern Western Australia, the Northern Territory and inland southern Queensland.

In autumn there is a marked contrast between the simultaneous and lag patterns. The simultaneous correlations are weakly positive over most of the country except for the western half of Western Australia, and exceed 0.3 over parts of Victoria, southern New South Wales and northern Queensland. At lag, however, values are negative over most of the mainland, and are near or below -0.3 over much of the tropics. Over New South Wales and northern Victoria, the frequency of minima below the 10^{th} percentile in years with a summer SOI in tercile 2 is generally somewhat above the frequency in years when it is in either tercile 1 or 3, one of the few examples of a substantial anomaly being associated with near-neutral SOI conditions.

Positive simultaneous correlations occur in winter over most of Australia, other than the southern two-thirds of Western Australia. They exceed 0.3 over a broad belt stretching from Victoria to the Northern Territory, reaching 0.5 in northern Victoria and southern New South Wales. These positive correlations, however, disappear almost completely at lag, with most of the continent instead being dominated by weak negative correlations, and stronger correlations (-0.3 to –0.5) being found in the northern half of Queensland, particularly near the Gulf of Carpentaria.

In general, the correlations for low minima, particularly at lag, are weaker (in both directions) than those found for the other three extreme temperature parameters.

Figs. 9.2g and 9.2h show the relative sensitivities of the frequency of extreme low maxima to the SOI. The most striking feature of these is the high ratios observed simultaneously through most of the eastern two-thirds of Australia in winter – and the almost complete absence of high ratios over this area at lag. Simultaneously, extensive areas have ratios exceeding 1.5, with values as high as 2.5 in southern New South Wales; at lag, only isolated stations even exceed 1.3. These results mirror those for the correlations described above.

Ratios below 0.7 are found at lag through substantial parts of northern Australia in all seasons except spring. For simultaneous ratios, though, such values are only found in this region in summer, when they extend to an area centred on the NSW/Queensland border. Ratios between 0.5 and 0.7 are also found over much of the southern half of Western Australia in spring.

The results for ratios of low minima show less spatial coherence than for the other three parameters. Some of this lack of coherence is the result of individual anomalous seasons (e.g. Camooweal in summer 1994/95) which may be indicative of undetected data quality problems. Low minimum temperatures are, however, generally more dependent on local factors such as topography and site condition (Bootsma, 1976; Kalma et al., 1986, 1992; see also section 3.2) than other extremes, and it might be expected that this would contribute to a reduced spatial coherence of the patterns shown in Figs. 9.2g and 9.2h.

9.4. Discussion and implications

Many of the results found for extreme temperatures are consistent with those previously found for mean temperatures and noted in section 9.1. In particular, the negative correlation between summer temperatures (especially maxima) and the SOI through much of northern and eastern Australia affects most of the frequency distribution of temperature fairly uniformly. This is also true of the negative correlations between the SOI and maximum and minimum temperatures in southern Western Australia in spring.

There are, however, a number of locations where there are substantial differences between the influence of the SOI on different parts of the frequency distribution. A particularly notable example of this occurs for maximum temperatures in Victoria, particularly southern Victoria, in spring and summer. Two cases characteristic of this are Laverton (144°44' E, 37°52' S) in spring (where most percentile points up to the 75th show weak positive simultaneous correlations, but there is a negative correlation of –0.48 for the 90th and 95th percentiles), and Rutherglen (146°30' E, 36°06' S) in summer (where there is a simultaneous correlation of 0.26 for the 10th percentile, but –0.35 for the 90th). This suggests that, in Victoria, El Niño (La Niña) conditions are associated with enhanced (suppressed) variability of maximum temperatures, at both ends of the frequency distribution, in spring and summer. When viewed in a spatial sense, it is perhaps not surprising that the area of negative correlations in spring and summer extends further south for extreme high temperatures than it does for median temperatures (Figs. 9.1c/d), as extreme high temperatures in Victoria are generally associated with airstreams of northerly origin and the maximum temperatures in such airstreams might be expected to be influenced by conditions in the source regions for the air, further north.

Another region where such effects are noticeable is northern Australia in winter and, to a lesser extent, in spring. Here, it is La Niña that is associated with enhanced temperature variability, with increased frequencies of both extreme low maxima and high maxima. Two examples of this occur at Halls Creek (where the simultaneous SOI correlations in winter are –0.13 for the 10^{th} percentile and 0.43 for the 90^{th}) and Camooweal (-0.25 and 0.45 respectively).

A striking result is the marked seasonal reversal of the maximum temperature/SOI relationships in northern Australia between winter and summer. This is noticeable throughout the frequency distribution, particularly in northern Queensland. A good example is Palmerville, where the simultaneous SOI/temperature frequency correlations are between 0.44 and 0.64 for all percentiles in winter, increase to 0.48-0.66 for the July-September period (not mapped), and are still weakly positive in spring (0.00-0.36), but fall to -0.43- -0.57 in summer and –0.57 - -0.63 for the January-March quarter. The negative correlations in summer can be associated with enhanced rainfall and cloud cover during the tropical wet season in La Niña years (Drosdowsky and Williams, 1991), but an explanation for the positive correlations in winter and spring is less obvious.

There are few instances of substantial anomalies being associated with near-neutral (tercile 2) SOI values, the most extensive instance being for low minima in autumn, which occur with increased frequency in New South Wales and northern Victoria in years when the summer SOI is near neutral. In general, the observed frequencies of extreme events, for all parameters, in tercile 2 are intermediate between those in terciles 1 and 3, although there are some instances where an anomaly is confined to one of the three terciles (for example, the negative correlation between the SOI and the frequency of extreme high maxima in winter in south-eastern Australia reflects a increased frequency of such events in El Niño years, with frequencies in tercile 2 being similar to those in tercile 3).

The results obtained in section 9.3 indicate that an SOI-based scheme has potentially useful skill in the seasonal forecasting of extreme temperatures some parts and seasons of Australia. This is particularly true of maximum temperatures (both high and low). The weakest results are for low minimum temperatures, suggesting that a scheme based on the SOI alone has limited potential for the forecasting of extreme low temperatures. As extreme low temperatures, particularly outside the regular frost season, are of great importance for some types of agriculture, as illustrated by the estimated agricultural losses of $200 million in a frost in Victoria in October 1998 (Bureau of Meteorology, 1998a) this is a somewhat disappointing result.

Possible future extensions of the analysis

There are a number of ways in which this analysis could be extended further at a later date. Stone and Auliciems (1992) defined five phases of the SOI (consistently positive/negative/near zero, rapidly rising, rapidly falling). It would be possible to use these phases, rather than SOI terciles, as categories into which to stratify extreme temperature occurrences. This is likely to have particular potential for those seasons and parameters for which there is a dramatic difference between the simultaneous and lag patterns, as occurs in autumn and winter for some variables.

Another possible extension would be to incorporate information of sea surface temperatures in the Indian Ocean, as well as the tropical Pacific (for which the SOI is used as a surrogate), in the analysis. Two empirical orthogonal functions (EOFs), corresponding approximately to sea surface temperatures in the two oceans, are used in the Australian Bureau of Meteorology's current operational scheme for the seasonal forecasting of Australian rainfall and mean temperature (Drosdowsky and Chambers, 1998; Jones, 1998). A possible drawback to repeating the analysis of extreme temperature frequencies in different Pacific/Indian Ocean temperature categories is that the number of categories could become rather large (using three terciles of the two EOFs, for example, would result in nine categories), which in turn would result in fairly small samples in each category when only 40 years of record are available from most stations.

The 'autumn predictability barrier', and comparisons with previous studies

Except for low maxima, the correlations were generally substantially weaker (and ratios closer to 1) at lag than they were simultaneously in winter, but not in the other three seasons. This is consistent with the well-known 'autumn predictability barrier' of the El Niño-Southern Oscillation phenomenon itself (e.g. Torrence and Webster, 1998); the SOI shows much less persistence from the Southern Hemisphere autumn into winter than it does in any of the other seasons.

A particularly interesting result in winter is that there are, in general, weak negative correlations between the autumn SOI and the frequency of minima above the 10th percentile in winter in most of Queensland. At first glance, this appears to contradict the findings of Stone et al. (1996), who found negative correlations (mostly around -0.3) between the May SOI and the number of days with temperatures below specified thresholds at a number of Queensland stations. There are, however, at least four differences between the two studies:

(a) The analysis in this chapter uses the three-month mean SOI for the March-May period, whereas Stone et al. use the single-month value for May. This difference may be significant in light of the previously-noted tendency for rapid changes in the SOI during that period.

(b) The analysis in this chapter mostly uses data from the 1957-96 period, whereas most stations used by Stone et al. had data from the 1910-93 period. Changes in the decadal-to-multidecadal timescale in the climate (Power et al., 1999a), and, in particular, in the relationship between the SOI and various climatic variables in Australia, possibly associated with the Interdecadal Pacific Oscillation (Power et al., 1999b), are well-known to have taken place. In particular, Lough (1997) found substantial changes in the correlation between the SOI and mean minimum temperatures for Queensland in the April-September period between 1931-50

(0.63) and 1975-95 (0.22). It would not be surprising if this weakening of the SOI-minimum temperature relationship were also observed for extreme temperatures.

(c) As shown in Chapters 7 and 8, there has been a very strong downward trend in the frequency of low minimum temperatures in Queensland over the 1957-96 period. There has also been a tendency towards an increased frequency of low autumn SOI values towards the end of this period. Six of the last 10 years of the record had an autumn SOI in tercile 1 (including five in succession between 1991 and 1995), compared with 9 of the 30 years between 1957 and 1986. It is possible that an SOI-temperature relationship here has been masked by the effects of general climate change. (A consequence, if this is indeed the case, is that this suggests that the observed downward trend in the frequency of low minimum temperatures would have been even stronger were it not for the behaviour of the SOI over this period).

(d) The data sets used by Stone et al. were not adjusted for inhomogeneities. Whilst this is likely to affect conclusions about the trends in temperatures that they found, it should have a limited impact on the SOI-temperature relationship, as any bias in temperatures during a section of the record will affect observations during that period under both high and low SOI conditions.

The possibility of decadal-to-interdecadal variability in the nature of the SOI-extreme temperature relationship is a particularly intriguing one. The 40 years of record available from most stations for this study is insufficient to carry out an assessment of this, but it is an area of considerable potential for future study once more pre-1957 daily data are digitised over the coming years.

Chapter 10
Conclusion

The central conclusion of this thesis is that the frequency of extreme high temperatures, both maxima and minima, in Australia has increased over the period between 1957 and 1996, and that the frequency of extreme low temperatures has decreased. These results hold across most seasons, and in most regions, and are valid for all of the thresholds tested, both fixed and relative (percentile-based). The strongest observed trends are, in general, the decreasing trends in the frequency of extreme low minimum temperatures, and the weakest are the increasing trends in the frequency of extreme high maximum temperatures. This suggests a decline in temperature variability over Australia during the 1957-1996 period, superimposed upon a general warming trend of mean temperatures over that period.

The declining trend in the frequency of extreme low temperatures is especially marked in Queensland, where the annual frequency of minima below the 10^{th} percentile fell by 47% between 1957 and 1996, with the decline reaching 50% in winter. This is a dramatic change, being of comparable magnitude to those projected for New South Wales (accompanying a much larger warming of mean temperatures than that observed so far in Queensland) by 2050 by the CSIRO climate model (Hennessy et al., 1998).

It was found in Chapter 6 that the frequency distributions of Australian daily maximum and minimum temperatures were most effectively represented by a compound Gaussian distribution, being a composite of two or three individual Gaussian distributions. Using this distribution, it was found that the observed change in temperature over the 1957-1996 period was reflecting an increase in the means of both the cooler and warmer parts of the frequency distribution, suggesting that the changes, over Australia as a whole, represent warming of all air masses in the Australian region (both continental and maritime), rather than a general circulation change (although the question of whether changes in circulation have been responsible for anomalous changes at individual stations remains unaddressed).

In Chapter 9, numerous relationships were found between the frequency of extreme temperatures and the Southern Oscillation Index. These relationships were particularly strong for extreme high maximum temperatures. With the exception of the relationship of autumn SOI with winter temperatures, many of these relationships remained robust at one season's lag. This suggests that there is considerable potential for the seasonal forecasting of extreme temperature probabilities, especially if the simple SOI-based scheme suggested by the work in Chapter 9 is refined to a more sophisticated system, based on principal components of Pacific and Indian Ocean temperatures, as is currently used by the Australian Bureau of Meteorology for seasonal forecasting of mean temperatures and total rainfall. The seasonal forecasting of extreme temperature probabilities, if it can be accomplished with a reasonable degree of skill, is of great interest to industries such as agriculture and energy generation.

The development of a high-quality daily temperature data set in Chapter 4 was a necessary precursor to the results obtained elsewhere in this study. It could form the basis of numerous future studies of Australian climate, especially if it can be extended backwards in time from its existing starting date of 1957 once a substantial amount of additional daily temperature data from the pre-1957 period has been digitized.

An area which will be of particular interest once sufficient data have been digitized is the interdecadal variability of extreme temperature frequencies, and of the extreme temperature-SOI relationship. Results obtained in Chapter 9 suggest the likelihood of substantial variability in the extreme temperature-SOI relationship on the interdecadal timescale, but a definitive answer awaits the availability of time series of greater length than the 40 years currently available.

The 1957-1996 period is a specific snapshot in time. The climate is changing continuously. The techniques presented in this thesis can be readily extended in time or space. Accordingly, they will be able to form the basis for the ongoing monitoring of trends in the frequency of extreme temperature events in Australia, and should also be adaptable globally, given the availability of sufficient data. A truly global study, and following ongoing global monitoring, of extreme temperature frequency, instead of an agglomeration of regional studies, may finally become feasible with the advent of the global GCOS Surface Network.

References

Alexandersson, H. 1986. Homogeneity test applied to precipitation data. *J. Climatol.*, 6, 661-675.

Alexandersson, H. and Moberg, A. 1997. Homogenization of Swedish temperature data. Part I: homogeneity test for linear trends. *Int. J. Climatol.*, 17, 25-34.

Allen, R.J. and DeGaetano, A.T. 2000. A method to adjust long-term temperature extreme series for nonclimatic inhomogeneities. *J. Climate*, 13, 3680-3695.

Andrews, K. 1994. *The consequences of heatwaves in Australia.* B.Sc (Hons.) thesis, Macquarie University.

Arnfield, J.D. 2001. A flexible system to manage and query NOAA station history information. *Preprints, 17th Conference on Interactive Information and Processing Systems for Meteorology, Oceanography and Hydrology, Albuquerque, 14-19 January 2001*, 468-476.

Auer, I., Böhm, R., Hagen, M. and Schöner, W. 1998. ALOCLIM – Austrian – Central European long-term climate – creation of a multiple homogenised long-term climate data set. *Proceedings, 2nd Seminar for Homogenisation of Surface Climatological Data, Budapest, 9-13 November 1998*, 47-65.

Baker, D.G. 1975. Effect of observation time on mean temperature estimation. *J. Appl. Meteor*, 14, 471-476.

Balling, R.C. and Idso, S.B. 1990. Effects of greenhouse warming on maximum summer temperatures. *Agric. Forest Meteor.*, 53, 143-147.

Balling, R.C., Skindlov, J.A. and Phillips, D.H. 1990. The impact of increasing summer mean temperatures on extreme maximum and minimum temperatures in Phoenix, Arizona. *J. Climate*, 3, 1491-1494.

Balling, R.C., Idso, S.B. and Hughes, W.S. 1992. Long-term and recent anomalous temperature changes in Australia. *Geophys. Res. Lett.*, 19, 2317-2320.

Barger, G.L. and Nyhan, J.C. (eds.). 1960. *Climatology at work.* U.S. Department of Commerce, 109 pp.

Barnes, S.L. 1964. A technique for maximising details in numerical weather map analysis. *J. Appl. Meteor.*, 3, 396-409.

Barnes, S.L. 1973. Mesoscale objective analysis using weighted time-series observations. *NOAA Tech. Memo. ERL NSSL-62*, National Severe Storms Laboratory, Norman, OK, 60 pp.

Barnes, S.L. 1994a. Applications of the Barnes objective analysis scheme. Part I: effects of undersampling, wave position, and station randomness. *J. Atmos. Oceanic Technol.*, 11, 1433-1448.

Barnes, S.L. 1994b. Applications of the Barnes objective analysis scheme. Part II: improving derivative estimates. *J. Atmos. Oceanic Technol.*, 11, 1449-1458.

Begert, M., Giroud, M., Kegel, R., Seiz, G., Koehli, V., Bochnicek, O., Fukasz, M., Nieplova, E. and Sramo, L. 1998. Operational homogenization of long-term climate data series at SMI and SHMI. *Proceedings, 2nd Seminar for Homogenisation of Surface Climatological Data, Budapest, 9-13 November 1998*, 177-184.

Bergström, H. 1990. The early climatological records of Uppsala. *Geog. Annaler*, 72A, 143-149.

Bernhofer, C. 1984. Jahreszeitliche und tägliche Variationen einer städtischen Wärmeinsel auf Grund von Topographie und Windverhältnissen. *Arch. Met. Geophys. Bioklimatol., Ser. B.*, 34, 121-139.

Blackburn, T. 1983. A practical method of correcting monthly average temperature biases resulting from differing times of observation. *J. Climate Appl. Meteor.*, 22, 328-330.

Blumenthal, C.S., Bekes, F., Batey, I.L., Wrigley, C.W., Moss, H.J., Mares, D.J. and Barlow, E.W.R. 1991. Interpretation of grain quality results from wheat variety trials with reference to high temperature stress. *Aust. J. Agric. Res.*, 42, 325-334.

Bolstad, P.V., Swift, L., Collins, F. and Régnière, J. 1998. Measured and predicted air temperatures at basin to regional scales in the southern Appalachian mountains. *Agric. Forest. Meteor.*, 91, 161-176.

Bootsma, A. 1976. Estimating minimum temperature and climatological freeze risk in hilly terrain. *Agric. Forest. Meteor.* 16. 425-443.

Bootsma, A. and Brown, D.M. 1989. Spring and autumn freeze risk in Ontario. *Climatol. Bull.*, 23, 43-59.

Bootsma, A. 1994. Long term (100 yr) climatic trends for agriculture at selected locations in Canada. *Climatic Change*, 26, 65-88.

Brinkmann, W.A.R. 1979. Growing season length as an indicator of climatic variations? *Climatic Change*, 2, 127-138.

Brinkmann, W.A.R. 1993. Development of an airmass-based regional climate change scenario. *Theor. Appl. Climatol.*, 47, 129-136.

Brooks, C.F. 1948. The climatic record: its content, limitations and geographical value. *Ann. Assoc. Am. Geog.*, 38, 153-168.

Brown, B.G. and Katz, R.W. 1995. Regional analysis of temperature extremes: spatial analog for climate change? *J. Climate*, 8, 108-119.

Bruhn, J.A., Fry, W.E. and Fick, G.W. 1980. Simulation of daily weather data using theoretical probability distributions. *J. Appl. Meteor.*, 19, 1029-1036.

Bryson, R.A. 1966. Air masses, streamlines and the boreal forest. *Geog. Bull.*, 8, 228-269.

Bureau of Meteorology. 1925. *Australian Meteorological Observer's Handbook*, Bureau of Meteorology, Melbourne, 172 pp.

Bureau of Meteorology. 1954. *Australian Meteorological Observer's Handbook*, Bureau of Meteorology, Melbourne, 148 pp.

Bureau of Meteorology. 1988. *Climatic averages: Australia.* Bureau of Meteorology, Melbourne, 536 pp.

Bureau of Meteorology. 1992. The BOM top 191. *Weather News*, 302, 24-25.

Bureau of Meteorology. 1995. *Australia's Reference Climate Stations*, Bureau of Meteorology, Melbourne, 4 pp.

Bureau of Meteorology. 1998a. *Monthly weather review, Victoria, October 1998*, Bureau of Meteorology, Melbourne, 32 pp.

Bureau of Meteorology. 1998b. *Gascoyne-Murchison climatic survey.* Bureau of Meteorology, Melbourne, 114 pp.

Butterworth, I. 1993. On the inhomogeneity of climatic temperature records at Darwin. *Res. Papers, Bureau of Meteorology, Northern Territory Region*, 107-110.

Changnon, D. and Laffey, S.C. 1994. Variations in the frequency and duration of days ≥ 32°C in the Southeast. *6th Conf. on Climate Variations, Nashville, 23-28 January 1994*, 182-184.

Changnon, S.A., Kunkel, K.E. and Reinke, B.C. 1996. Impacts and responses to the 1995 heat wave: a call to action. *Bull. Amer. Meteor. Soc.*, 77, 1497-1506.

Chappel, L.C. 1995. Tasmanian district average rainfall: a review of their application to climate trends. *Bull. Aust. Meteor and Ocean. Soc.*, 8, 27-31.

Colman, B. 1986. Winter climate of Juneau: a mean of contrasting regimes. *Natl. Wea. Dig.*, 11 (2), 29-34.

Colombo, A.F., Etkin, D. and Karney, B.W. 1999. Climate variability and the frequency of extreme temperature events for nine sites across Canada: implications for power usage. *J. Climate*, 12, 2490-2502.

Cooter, E.J. and LeDuc, S.K. 1995. Recent frost date trends in the north-eastern USA. *Int. J. Climatol.*, 15, 65-75.

Coughlan, M.J. 1979. Recent variations in annual-mean maximum temperatures over Australia. *Quart.J. Roy. Meteor. Soc.*, 105, 707-719.

Court, A. 1953. Temperature extremes in the United States. *Geog. Rev.*, 43, 39-49.

Court, A. and Salmela, H.A. 1963. Improbable weather extremes and measurement needs. *Bull. Amer. Meteor. Soc*, 44, 571-575.

Cressman, G.P. 1959. An operational objective analysis system. *Mon. Wea. Rev.*, 87, 367-374.

Crowder, R.B. 1995. *The Wonders of the Weather*. Australian Government Publishing Service, Canberra, 270 pp.

Crowe, R.B. 1990. Reconstruction of Toronto temperatures 1778-1840 using various United States and other data. *Climatol. Bull.*, 24, 28-50.

Crummay, F.A. 1986. Monitoring the homogeneity of UK climatological data. *Meteor. Mag.*, 115, 133-142.

Curran, E. and Grace, W. 1992. The exceptionally cool January of 1992 related to binormal temperature distribution. *Bull. Aust. Meteor. and Ocean. Soc.*, 5, 66-69.

Davis, N.E. 1972. The variability of the onset of spring in Britain. *Quart. J. Roy. Meteor. Soc.*, 98, 763-777.

Deacon, E.L. 1953. Climatic change in Australia since 1880. *Aust. J. Phys.*, 6, 209-218.

DeGaetano, A.T., Eggleston, K.L. and Knapp, W.W. 1994. Trends in extreme temperature events in the northeastern United States. *Preprints, 6th Conference on Climate Variations, Nashville, 23-28 January 1994*, 136-139.

DeLisi, M.P. and Shulman, M.D. 1984. An evaluation of heat wave occurrence in New Jersey. *Natl. Wea. Dig.*, 9 (2), 7-10.

Diamond, H.J. 2001. Status of the U.S. National Global Climate Observing System (GCOS) Program. *Preprints, 17th Conference on Interactive Information and Processing Systems for Meteorology, Oceanography and Hydrology, Albuquerque, 14-19 January 2001*, 497-500.

Diaz, H.F. and Quayle, R.G. 1980. The climate of the United States since 1895: spatial and temporal changes. *Mon. Wea. Rev.*, 108, 249-266.

Dodson, R. and Marks, D. 1997. Daily air temperature interpolated at high spatial resolution over a large mountainous region. *Clim. Res.*, 8, 1-20.

Domrös, M. 1976. Uber das Vorkommen von Frost auf Java/Indonesien, insbesondere in den Pengalengan Highlands. *Erdkunde*, 30, 97-108.

Donaldson, J. 1888. *Account of the Operations of the Weather Bureau and List of Stations*. Queensland Post and Telegraph Department report, 2 July 1888, 5 pp.

Donnel, C.A. 1912. The effect of the time of observation on mean temperatures. *Mon. Wea. Rev.*, 40, 708.

Downton, M.W. and Miller, K.A. 1993. The freeze risk to Florida citrus. Part II: temperature variability and circulation patterns. *J. Climate*, 6, 364-372.

Drosdowsky, W. and Williams, M. 1991. The Southern Oscillation in the Australian region. Part I: anomalies at the extremes of the oscillation. *J. Climate*, 4, 619-638.

Drosdowsky, W. and Chambers, L. 1998. Near global sea surface temperature anomalies as predictors of Australian seasonal rainfall. *BMRC Res. Report 65*, Bureau of Meteorology, Melbourne, Australia, 19 pp.

Dury, G.H. 1972. High temperature extremes in Australia. *Ann. Assoc. Am. Geog.*, 62, 388-400.

Easterling, D.R. and Peterson, T.C. 1992. Techniques for detecting and adjusting for artificial discontinuities in climatological time series: a review. *Preprints, Fifth International Meeting on Statistical Climatology, 22-26 June 1992, Toronto*, J28-J32.

Easterling, D.R. and Peterson, T.C. 1995. A new method for detecting undocumented discontinuities in climatological time series. *Int. J. Climatol.*, 15, 369-377.

Easterling, D.R., Peterson, T.C. and Karl, T.R. 1996. On the development and use of homogenized climate datasets. *J. Climate*, 9, 1429-1434.

Easterling, D.R., Horton, B., Jones, P.D., Peterson, T.C., Karl, T.R., Parker, D.E., Salinger, M.J., Razuvayev, V., Plummer, N., Jamason, P. and Folland, C.K. 1997. Maximum and minimum temperature trends for the globe. *Science*, 277, 364-367.

Easterling, D.R., Evans, J.L., Groisman, P.Y., Karl, T.R., Kunkel, K.E. and Ambenje, P. 2000. Observed variability and trends in extreme climate events: a brief review. *Bull. Amer. Meteor. Soc*, 81, 417-425.

Ellis, W. 1890. On the difference produced in the mean temperature derived from daily maximum and minimum readings, as depending on the time at which the thermometers are read. *Quart. J. Roy. Meteor. Soc.*, 16, 213-218.

Essenwanger, O. 1954. Probleme der Häufigkeitsanalyse. *Meteor. Rundsch.*, 7, 85-88.

Essenwanger, O. 1955. Zur Realität der Zerlegung von Häufigkeitsverteilungen in Normalkurven. *Arch. Meteor. Geophys. Bioklimatol., Ser.B.* , 7, 49-59.

Essenwanger, O. 1963. Die Beziehung zwischen dem mittleren Jahresmaximum and dem mittleren Tagesmaximum der Lufttemperatur im wärmsten Monat. *Meteor. Rundsch.*, 16, 154-156.

Fantoli, A. 1958. La più alta temperatura del mondo. *Riv. Met. A.M.*, 18(3), 53-63.

Fekete, L. 1987. Frost conditions in Hungary in the periods of late spring and early autumn. *Hungary. Orszagos Meteorologiai Szolgalat, Beszamolok az 1985-ben vegzett tudomanyos kutatasokrol*, 147-158.

Fisher, R.A. and Tippett, L.H.C. 1927. Limiting forms of the frequency distribution of the largest or smallest member of a sample. *Proc. Camb. Phil. Soc.*, 24, 180-190.

Flocas, A.A. and Angouridakis, V.E. 1979. Extreme values analysis of air temperature over Greece. *Arch. Meteor. Geophys. Bioklimatol., Ser. B.*, 27, 47-57.

Foley, J.C. 1945. Frost in the Australian region. *Bulletin 32*, Bureau of Meteorology, Melbourne, 142 pp.

Folland, C.K., Miller, C., Bader, D., Crowe, M., Jones, P., Plummer, N., Richman, M., Parker, D.E., Rogers, J. and Scholefield, P. 1999. Workshop on Indices and Indicators for Climate Change, Asheville, NC, USA, 3-6 June 1997. Report of Breakout Group C: Temperature indices for climate extremes. *Climatic Change*, 42, 31-43.

Frich, P. 1993. Homogeneity problems in Danish and Greenlandic temperature time series. *Preprints, 8th Conference on Meteorological Observations and Instrumentation, Anaheim, 17-22 January 1993*, J39-42.

Frich, P., Alexandersson, H., Ashcroft, J., Dahlström, B., Demarée, G.R., Drebs, A., van Engelen, A.F.V., Førland, E.J., Hanssen-Bauer, I., Heino, R., Jónsson, T., Jonasson, K., Keegan, L., Nordli, P.Ø., Schmidt, T., Steffensen, P., Tuomenvirta, H. and Tveito, O.E. 1996. *North Atlantic Climatological Dataset (NACD Version 1) - Final Report*, Scientific Report, 96-1, Danish Meteorological Institute, Copenhagen, 60 pp.

Gall, R., Young, K., Schotland, R. and Schmitz, J. 1992. The recent maximum temperature anomalies in Tucson: are they real or an instrumental problem? *J. Climate*, 5, 657-665.

Gershunov, A. and Barnett, T.P. 1998. ENSO influence on intraseasonal extreme rainfall and temperature frequencies in the contiguous United States: observations and model results. *J. Clim.*, 11, 1575-1586.

Gerstengarbe, F-W., Werner, P.C., Busold, W., Ruge, U. and Wegener, K-O. 1993. Katalog der Grosswetterlagen Europas nach Paul Hess und Helmuth Brezowski 1881-1992, 4., vollständig neu bearbeite Auflage. *Berichte des Deutsche Wetterdiensts*, 113, Deutsche Wetterdienst, Offenbach, 249 pp.

Goulter, S. 1991. Some aspects of the distribution of frost over New Zealand. *Weather and Climate*, 11, 105-115.

Grace, W., Curran, E. and Burrows, K. 1991. Modelling daily maximum temperatures at coastal localities. *Extended abstracts, Conference on Agricultural Meteorology, Melbourne, 17-19 July 1991*, Bureau of Meteorology, Melbourne.

Grace, W. and Curran, E. 1993. A binormal model of frequency distributions of daily maximum temperature. *Aust. Meteor. Mag.* 42. 151-161.

Gruza, G., Rankova, E., Razuvaev, V. and Bulygina, O. 1999. Indicators of climate change for the Russian Federation. *Climatic Change*, 42, 219-242.

Gumbel, E.J. 1958. *Statistics of Extremes*, Columbia University Press, New York, 375 pp.

Hansen, J., Johnson, D., Lacis, A., Lebedeff, S., Lee, P., Rind, D. and Russell, G. 1981. Climate impact of increasing atmospheric carbon dioxide. *Science*, 213, 957-965.

Hansen, J. and Lebedeff, S. 1987. Global trends of measured surface air temperature. *J. Geophys. Res.*, 92D, 13345-13372.

Hansen, J. and Lebedeff, S. 1988. Global surface air temperatures: update through 1987. *Geophys. Res. Lett.*, 15, 323-336.

Hardin, J.W. and Upson, R.B. 1993. Estimation of the global average temperature with optimally weighted point gauges. *J. Geophys. Res.*, 98D, 23275-23282.

Hasselblad, V. 1966. Estimation of parameters for a mixture of normal distributions. *Technometrics*, 8, 431-444.

Heino, R. 1994. *Climate in Finland during the period of meteorological observations*. Finnish Meteorological Institute, Helsinki, 210 pp.

Heino, R., Brazdil, R., Førland, E., Tuomenvirta, H., Alexandersson, H., Beniston, M., Pfister, C., Rebetez, M., Rosenhagen, G., Rosner, S. and Wibig, J. 1999. Progress in the study of climatic extremes in northern and central Europe. *Climatic Change*, 42, 151-181.

Henderson, K.G. and Muller, R.A. 1997. Extreme temperature days in the south-central United States. *Clim. Res.*, 8, 151-162.

Hennessy, K.J. and Pittock, A.B. 1995. Greenhouse warming and threshold temperature events in Victoria, Australia. *Int. J. Climatol.*, 15, 591-612.

Hennessy, K.J., Whetton, P.H., Katzfey, J.J., McGregor, J.L., Jones, R.N., Page, C.M. and Nguyen, K.C. 1998. *Fine-resolution climate change scenarios for New South Wales: annual report 1997-98.* NSW Environment Protection Authority, Sydney, 48 pp.

Hennessy, K.J., Suppiah, R. and Page, C.M. 1999. Australian rainfall changes, 1910-1995. *Aust. Meteor. Mag.*, 48, 1-14.

Hershfield, D.M. 1974. The frequency of freeze-thaw cycles. *J. Appl. Meteor.*, 13, 348-354.

Hevesi, J.A., Istok, J.D. and Flint, A.L. 1992. Precipitation estimation in mountainous terrain using multivariate geostatistics. Part I: structural analysis. *J. Appl. Meteor.*, 31, 661-676.

Hinds, W.T. and Rotenberry, J.T. 1979. Relationship between mean and extreme temperatures in diverse microclimates. *Ecology*, 60, 1073-1075.

Horton, E.B., Folland, C.K. and Parker, D.E. 2001. The changing incidence of extremes in worldwide and Central England temperatures to the end of the twentieth century. *Climatic Change*, 50, 267-295.

Hudson, G. and Wackernagel, H. 1994. Mapping temperature using kriging with external drift: theory and an example from Scotland. *Int. J. Climatol.*, 14, 77-91.

Hulme, M. 1994. The cost of climate data: a European experience. *Weather*, 49, 168-175.

Hutchinson, M.F. 1986. Methods of generation of weather sequences. In A.H. Bunting (ed.), *Agricultural Environments: characterisation, classification and mapping*, CAB International, Wallingford, 149-157.

Hutchinson, M.F. 1991. The application of thin plate smoothing splines to continent-wide data assimilation. *BMRC Research Report 27*, Bureau of Meteorology, Melbourne, 104-113.

Intergovernmental Panel on Climate Change. 1990. *Climate Change: The IPCC Scientific Assessment.* Cambridge University Press, Cambridge, 365 pp.

Intergovernmental Panel on Climate Change. 1995. *Climate change 1995: The science of climate change.* Cambridge University Press, Cambridge, 572 pp.

Intergovernmental Panel on Climate Change. 2001. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the IPCC.* Cambridge University Press, Cambridge, 881 pp.

Janowiak, J.E. and Bell, G.D. 1999. Interannual differences in the distribution of daily wintertime temperatures, precipitation and snowfall in the United States. *Preprints, 8^{th} Conference on Climate Variations, Denver, 13-17 September 1999*, 1-5.

Jayanthi, S. 1973. The extreme values analysis of maximum and minimum temperatures over India. *Indian J. Met. Geophys.*, 24, 367-370.

Jenkinson, A.F. 1955. The frequency distribution of the annual maximum (or minimum) values of meteorological elements. *Quart. J. Roy. Meteor. Soc.*, 81, 158-171.

Jones, D.A. and Simmonds, I. 1994. A climatology of Southern Hemisphere anticyclones. *Climate Dyn.*, 10, 333-348.

Jones, D.A. and Weymouth, G.T. 1997. An Australian monthly rainfall data set. *Technical Report 70*, Bureau of Meteorology, Melbourne, 19 pp.

Jones, D.A. 1998. The prediction of Australian land surface temperatures using near global sea surface temperature patterns. *BMRC Res. Report 70*, Bureau of Meteorology, Melbourne, Australia, 48 pp.

Jones, D.A. and Beard, G. 1998. Verification of Australian monthly district rainfall totals using high resolution gridded analyses. *Aust. Meteor. Mag.*, 47, 41-54.

Jones, D.A. 1999. Characteristics of Australian land surface temperature variability. *Theor. Appl. Climatol.* 63. 11-31.

Jones, D.A. and Trewin, B.C. 2000a. On the relationships between the El Niño-Southern Oscillation and Australian land surface temperature. *Int. J. Climatol.* 20. 697-719.

Jones, D.A. and Trewin, B.C. 2000b. The spatial structure of monthly temperature anomalies over Australia. *Aust. Meteor. Mag.*, 49, 261-276.

Jones, P.A. 1991. Historical records of cloud cover and climate for Australia. *Aust. Meteor. Mag.*, 39, 181-189.

Jones, P.A. and Henderson-Sellers, A. 1992. Historical records of cloudiness and sunshine in Australia. *J. Climate,* 5, 260-267.

Jones, P.D, Wigley, T.M.L. and Kelly, P.M. 1982. Variations in surface air temperatures, part I, Northern Hemisphere: 1881-1980. *Mon. Wea. Rev.*, 110, 59-70.

Jones, P.D., Raper, S.C.B., Bradley, R.S., Diaz, H.F., Kelly, P.M. and Wigley, T.M.L. 1986a. Northern Hemisphere surface air temperature variations: 1851-1984. *J. Climate Appl. Meteor.*, 25, 161-179.

Jones, P.D., Raper, S.C.B. and Wigley, T.M.L. 1986b. Southern Hemisphere surface air temperature variations: 1851-1984. *J. Climate Appl. Meteor.*, 25, 1213-1230.

Jones, P.D., Raper, S.C.B., Goodess, C.M., Cherry, B.S.G. and Wigley, T.M.L. 1986c. *Grid point surface air temperature data set for the Southern Hemisphere*, U.S. Department of Energy, Report TR027, Washington D.C., 79 pp.

Jones, P.D. 1988. Hemispheric surface air temperature variations: recent trends and an update to 1987. *J. Climate*, 1, 654-660.

Jones, P.D. 1994. Hemispheric surface air temperature variations: a reanalysis and an update to 1993. *J. Climate* , 7, 1794-1802.

Jones, P.D. and Briffa, K.R. 1995. Growing season temperatures over the former Soviet Union. *Int. J. Climatol.*, 15, 943-959.

Jones, P.D., Horton, E.B., Folland, C.K., Hulme, M., Parker, D.E. and Basnett, T.A. 1999. The use of indices to identify changes in climatic extremes. *Climatic Change,* 42, 131-149.

Kalma, J.D., Laughlin, G.P., Caprio, J.M. and Hamer, P.J.C. 1992. *The Bioclimatology of Frost: its occurrence, impact and protection*, Springer-Verlag, Berlin, 144 pp.

Kalma, J.D., Laughlin, G.P., Green, A.A. and O'Brien, M.T. 1986. Minimum temperature surveys based on near-surface air temperature measurements and airborne thermal scanner data. *J. Climatol.* 6. 413-430.

Karl, T.R., Williams, C.N., Young, P.J. and Wendland, W.M. 1986. A model to estimate the time of observation bias associated with monthly mean maximum, minimum and mean temperatures for the United States. *J. Climate Appl. Meteor.*, 25, 145-160.

Karl, T.R. and Williams, C.N. 1987. An approach to adjusting climatological time series for discontinuous inhomogeneities. *J. Climate Appl. Meteor.* , 26, 1744-1763.

Karl, T.R., Diaz, H.F. and Kukla, G. 1988. Urbanization: its detection and effect in the United States climate record. *J. Climate*, 1, 1099-1123.

Karl, T.R., Williams, C.N., Quinlan, F.T. and Boden, T. A. 1990. United States Historical Climatology Network (HCN) serial temperature and precipitation data. *U.S. Dept. of Energy, Environmental Sciences Division, Pub. No. 3404*, 1123 pp.

Karl, T.R., Kukla, G., Razuvayev, V.N., Changery, M.J., Quayle, R.G., Heim, R.R., Easterling, D.R. and Fu, C.B. 1991. Global warming: evidence for asymmetric diurnal temperature change. *Geophys. Res. Lett.*, 18, 2253-2256.

Karl, T.R., Knight, R.W. and Plummer, N. 1995a. Trends in high-frequency climate variability in the twentieth century. *Nature*, 377, 217-220.

Karl, T.R., Derr, V.E., Easterling, D.R., Folland, C.K., Hofmann, D.J., Levitus, S., Nicholls, N., Parker, D.E. and Withee, G.W. 1995b. Critical issues for long-term climate monitoring. *Climatic Change*, 31, 185-221.

Karl, T.R. and Knight, R.W. 1997. The 1995 Chicago heat wave: how likely is a recurrence? *Bull. Amer. Meteor. Soc.*, 78, 1107-1119.

Karl, T.R. and Easterling, D.R. 1999. Climate extremes: selected review and future research directions. *Climatic Change*, 42, 309-325.

Karl, T.R., Nicholls, N. and Ghazi, A. 1999.. CLIVAR/GCOS/WMO Workshop on Indices and Indicators for Climate Extremes: workshop summary. *Climatic Change*, 42, 3-7.

Katz, R.W. and Farago, T. 1989. Applications of the theory of extreme values in climatology. *Proceedings, 4th International Meeting on Statistical Climatology, Rotorua, New Zealand, 27-31 March 1989*, 223-226.

Katz, R.W. and Brown, B.G. 1992. Extreme events in a changing climate: variability is more important than averages. *Climatic Change*, 21, 289-302.

Katz, R.W. 1993. Towards a statistical paradigm for climate change. *Clim. Res.*, 2, 167-175.

Kestin, T.S. 2000. *Variations of Australian climate and extremes*, Ph. D thesis, Monash University.

Klein, W.H. and Hammons, G.A. 1975. Maximum/minimum temperature forecasts based on model output statistics. *Mon. Wea. Rev.*, 103, 796-806.

Koch, S.E., DesJardins, M. and Kocin, P.J. 1983. An interactive Barnes objective map analysis scheme for use with satellite and conventional data. *J. Climate Appl. Meteor.*, 22, 1487-1503.

Kohler, M.A. 1949. On the use of double-mass analysis for testing the consistency of meteorological records and for making required adjustments. *Bull. Amer. Meteor. Soc.*, 30, 188-189.

Laing, J. 1977. Maximum summer temperatures recorded in Glaisher stands and Stevenson screens. *Meteor. Mag.*, 106, 220-228.

Lamb, H.H. 1950. Types and spells of weather around the year in the British Isles: annual trends, seasonal structure of the year, singularities. *Quart. J. Roy. Meteor. Soc.*, 76, 393-438.

Lamb, H.H. 1977. *Climate present, past and future. Vol. 2: Climatic history and the future.* Methuen, London, 836 pp.

Lavery, B., Kariko, A. and Nicholls, N. 1992. A historical rainfall data set for Australia. *Aust. Meteor. Mag.*, 40, 33-39.

Lawrence, E.N. 1952. Estimation of weekly frost risk using weekly minimum temperatures. *Meteor. Mag.* 81, 137-141.

Lehman, R.L. 1987. Probability distributions of monthly degree-day variables at U.S. stations, Part 1, Estimating the mean value and variance from temperature data. *J. Climate Appl. Meteor.*, 26, 329-340.

Linforth, D. 1995. Letter to the editor. *Bull. Aust. Meteor. and Ocean. Soc.*, 8, 32.

Logue, J.J. 1986. Comparison of wind speeds recorded simultaneously by a pressure-tube anemograph and a cup-generator anemograph. *Meteor. Mag.*, 115, 178-185.

Longton, J.F. 1975. *Record Maximum Temperature-Cloncurry.* Unpublished note to the Director of Meteorology, lodged on file at Bureau of Meteorology, Melbourne.

Lorenc, A.C. 1981. A global three-dimensional multivariate statistical interpolation scheme. *Mon. Wea. Rev.*, 109, 701-721.

Lorenc, A.C. 1986. Analysis methods for numerical weather prediction. *Quart. J. Roy. Meteor. Soc.*, 112, 1177-1194.

Lough, J.M. 1995. Temperature variations in a tropical-subtropical environment: Queensland, Australia, 1910-1987. *Int. J. Climatol.* 15. 77-95.

Lough, J.M. 1997. Regional indices of climate variation: temperature and rainfall in Queensland, Australia. *Int. J. Climatol.* 17. 55-66.

McBride, J.L. and Nicholls, N. 1983. Seasonal relationships between Australian rainfall and the Southern Oscillation. *Mon. Wea. Rev.* 111. 1998-2004.

McGuffie, K., Henderson-Sellers, A., Holbrook, N., Kothavala, Z., Balachova, O. and Hoekstra, J. 1999. Assessing simulations of daily temperature and precipitation variability with global climate models for present and enhanced greenhouse climates. *Int. J. Climatol.*, 19, 1-26.

Manley, G. 1953. The mean temperature of Central England, 1698-1952. *Quart. J. Roy. Meteor. Soc.*, 79, 242-261.

Manley, G. 1974. Central England temperatures: monthly means 1659 to 1973. *Quart. J. Roy. Meteor. Soc.*, 100, 389-405.

Manton, M.J., Della-Marta, P.M., Haylock, M.R., Hennessy, K.J., Nicholls, N., Chambers, L.E., Collins, D.A., Daw, G., Finet, A., Gunawan, D., Inape, K., Isobe, H., Kestin, T.S., Lefale, P., Leyu, C.H., Lwin, T., Maitrepierre, L., Ouprasitwong, N., Page, C.M., Pahalad, J., Plummer, N., Salinger, M.J., Suppiah, R., Tran, V.L., Trewin, B., Tibig, I. and Yee, D. 2001. Trends in extreme daily rainfall and temperature in southeast Asia and the south Pacific: 1961-1998. *Int. J. Climatol.*, 21, 269-284.

Marchenko, A.S. and Minakova, L.A. 1980. Probabilistic model of air temperature time series. *Meteor. i Gidrol.*, 1980 (9), 39-47.

Maronna, R. and Yohai, V.J. 1978. A bivariate test for the detection of a systematic change in mean. *J. Am. Stat. Assoc.*, 73, 640-645.

Mearns, L.O., Katz, R.W. and Schneider, S.H. 1984. Extreme high-temperature events: changes in their probabilities with changes in mean temperature. *J. Climate Appl. Meteor.*, 23, 1601-1613.

Mearns, L.O., Schneider, S.H., Thompson, S.L. and McDaniel, L.R. 1990. Analysis of climate variability in general circulation models: comparison with observations and changes in variability in 2 x CO_2 experiments. *J. Geophys. Res.*, D95, 20469-20490.

Mearns, L.O., Rosenzweig, C. and Goldberg, R. 1991. Changes in climate variability and possible impacts on wheat yields. *20th Conference on Agricultural and Forest Meteorology, Salt Lake City, 10-13 September 1991*, J1-J6.

Meehl, G.A., Zwiers, F., Evans, J., Knutson, T., Mearns, L. and Whetton, P. 2000. Trends in extreme weather and climate events: issues related to modelling extremes in projections of future climate change. *Bull. Amer. Meteor. Soc.*, 81, 427-436.

Merriam, C.F. 1937. A comprehensive study of the rainfall on the Susquehanna Valley. *Trans. Amer. Geophys. Union*, 18, 471-476.

Mills, G.A., Weymouth, G., Jones, D., Ebert, E.E., Manton, M., Lorkin, J. and Kelly, J. 1997. A national objective daily rainfall analysis system. *BMRC Techniques Development Reports, 1*, Bureau of Meteorology, Melbourne, 30 pp.

Mitchell, J.M. 1958. Effect of changing observation time on mean temperature. *Bull. Amer. Meteor. Soc.*, 39, 83-89.

Mitchell, J.M. 1961. The measurement of secular temperature change in the United States, *U.S. Weather Bureau Research Paper No. 43*, U.S. Department of Commerce, 80 pp.

Moberg, A. and Alexandersson, H. 1997. Homogenization of Swedish temperature data. Part II: Homogenized gridded air temperature compared with a subset of global gridded air temperature since 1861. *Int. J. Climatol.*, 17, 35-54.

Morris, C.J.G. and Simmonds, I. 2000. Associations between varying magnitudes of the urban heat island and the synoptic climatology in Melbourne, Australia. *Int. J. Climatol.*, 20, 1931-1954.

Morris, C.J.G., Simmonds, I. and Plummer, N. 2001. Quantification of the influences of wind and cloud on the nocturnal urban heat island of a large city. *J. Appl. Meteor.*, 40, 169-182.

Neild, R.E., Richman, H.N. and Seeley, M.W. 1979. Impacts of different types of temperature change on the growing season for maize. *Agric. Meteor.* , 20, 367-374.

Nese, J.M. 1993. A spatial and temporal climatology of eastern United States temperature extremes: 1901-1986. *Preprints, 8th Conference on Applied Climatology, Anaheim, 17-22 January 1993*, 107-108.

Nese, J.M. 1994. Systematic biases in manual observations of daily maximum and minimum temperature. *J. Climate*, 7, 834-842.

Nicholls, N. 1995. Long-term climate monitoring and extreme events. *Climatic Change*, 31, 231-245.

Nicholls, N., Lavery, B., Fredriksen, C., Drosdowsky, W. and Torok, S. 1996a. Recent apparent changes in relationships between the El Niño - Southern Oscillation and Australian rainfall and temperature. *Geophys. Res. Lett.*, 23, 3357-3360.

Nicholls, N., Tapp, R., Burrows, K. and Richards, D. 1996b. Historical thermometer exposures in Australia. *Int. J. Climatol.*, 16, 705-710.

Nicholls, N. 2000. An artificial trend in district average rainfall in the Snowy Mountains. *Aust. Meteor. Mag.*, 49, 255-258.

Nicholls, N. 2001. The insignificance of significance testing. *Bull. Amer. Meteor. Soc.*, 82, 981-986.

Nichols, E.S. 1934. Time limits of the day as affecting records of minimum temperature. *Mon. Wea. Rev.*, 62, 337-340.

Nordli, P.Ø., Alexandersson, H., Frich, P., Førland, E.J., Heino, R., Jonsson, T., Tuomenvirta, H. and Tveito, O.E. 1997. The effect of radiation screens on Nordic time series of mean temperature. *Int. J. Climatol.*, 17, 1667-1681.

Nordli, P.Ø. 1998. Adjustments of Norwegian monthly means of daily minimum temperature. *Proceedings, 2nd Seminar for Homogenisation of Surface Climatological Data, Budapest, 9-13 November 1998*, 87-95.

Parker, D.E. 1981. Early meteorological observations for Sitka, Alaska. *Meteor. Mag.* 110, 161-163.

Parker, D.E., Legg, T.P. and Folland, C.K. 1992. A new daily central England temperature series, 1772-1991. *Int. J. Climatol.*, 12, 317-342.

Parker, D.E. 1994. Effects of changing exposure of thermometers at land stations. *Int. J. Climatol.*, 14, 1-31.

Parry, M.L. and Carter, T.R. 1985. The effect of climatic variations on agricultural risk. *Climatic Change*, 7, 95-110.

Pearson, E.S. and Hartley, H.O. (eds.). 1976. *Biometrika tables for statisticians, Vol.2.* Cambridge University Press, Cambridge, 404 pp.

Perry, A.H. and Mayes, J. 1998. The Lamb weather type catalogue. *Weather*, 53, 222-229.

Peterson, T.C. and Easterling, D.R. 1994. Creation of homogeneous composite climatological reference series. *Int. J. Climatol.*, 14, 671-679.

Peterson, T, Daan, H. and Jones, P. 1997. Initial selection of a GCOS surface network. *Bull. Amer. Meteor. Soc.* 78, 2145-2152.

Peterson, T.C. and Vose, R.S. 1997. An overview of the Global Historical Climatology Network temperature database. *Bull. Amer. Meteor. Soc.*, 78, 2837-2849.

Peterson, T.C., Karl, T.R., Jamason, P.F., Knight, R. and Easterling, D.R. 1998a. First difference method: maximizing station density for the calculation of long-term global temperature change. *J. Geophys. Res.*, 103D, 25967-25974.

Peterson, T.C., Easterling, D.R., Karl, T.R., Groisman, P., Nicholls, N., Plummer, N., Torok, S., Auer, I., Boehm, R., Gullett, D., Vincent, L., Heino, R., Tuomenvirta, H., Mestre, O., Szentimrey, T., Salinger, J., Førland, E.J., Hanssen-Bauer, I., Alexandersson, H., Jones, P. and Parker, D. 1998b. Homogeneity adjustments of *in situ* atmospheric climate data: a review. *Int. J. Climatol.*, 18, 1493-1517.

Petrovic, P. 1998. Measurement precision as a cause of inhomogeneity in weather data time series. *Proceedings, 2nd Seminar for Homogenisation of Surface Climatological Data, Budapest, 9-13 November 1998*, 161-169.

Petrovic, S. and Soltis, J. 1985. Extrémne teploty vzduchu na vybraných miestach Slovenska za obdobie 1931-1980. *Met. Zprávy*, 38, 65-71.

Pittock, A.B. 1975. Climatic change and the patterns of variation in Australian rainfall. *Search*, 6. 498-504.

Pittock, A.B. 1988. Actual and anticipated changes in Australia's climate. In: *Greenhouse: planning for climate change*, CSIRO Publications, Melbourne, 35-51.

Plummer, N. 1995. *Recent changes in temperature variability and extremes over Australia*, M.Sc thesis, Monash University.

Plummer, N., Lin, Z. and Torok, S. 1995. Trends in the diurnal temperature range over Australia since 1951. *Atmos. Res.* 37, 79-86.

Plummer, N., Salinger, M.J., Nicholls, N., Suppiah, R., Hennessy, K.J., Leighton, R.M., Trewin, B., Page, C.M. and Lough, J.M. 1999. Changes in climate extremes over the Australian region and New Zealand during the twentieth century. *Climatic Change*, 42, 183-202.

Policansky, D. 1977. The winter of 1976-77 and the prediction of unlikely weather. *Bull. Amer. Meteor. Soc.*, 58, 1073-1074.

Potter, K.W. 1981. Illustration of a new test for detecting a shift in mean in precipitation series. *Mon. Wea. Rev.*, 109, 2040-2045.

Power, S., Tseitkin, F., Mehta, V., Lavery, B., Torok, S. and Holbrook, N. 1999a. Decadal climate variability in Australia during the twentieth century. *Int. J. Climatol.* 19. 169-184.

Power, S., Casey, T., Folland, C., Colman, A. and Mehta, V. 1999b. Inter-decadal modulation of the impact of ENSO on Australia. *Climate Dyn.* 15. 319-324.

Quayle, E.T. 1929. Long-range rainfall forecasting from tropical (Darwin) air pressure. *Proc. Roy. Soc. Victoria*, 41, 160-164.

Quayle, R.G., Easterling, D.R., Karl, T.R. and Hughes, P.Y. 1991. Effects of recent thermometer changes in the cooperative station network. *Bull. Amer. Meteor. Soc.*, 72, 1718-1723.

Ratcliffe, R.A.S., Weller, J. and Collison, P. 1978. Variability in the frequency of unusual weather over approximately the last century. *Quart.J. Roy. Meteor. Soc.*, 104, 243-255.

Rebetez, M. and Beniston, M. 1997. Observational and numerical investigations of changes in climatological extremes in terms of shifts in means. *Preprints, 7th Conference on Climate Variations, Long Beach, 2-7 February 1997*, J105-J107.

Revfeim, K.J.A. 1990. Daily observations: necessity, ritual or imposition? *Int. J. Climatol.*, 10, 105-110.

Rhoades, D.A. and Salinger, M.J. 1993. Adjustment of temperature and rainfall records for site changes. *Int. J. Climatol.*, 13, 899-913.

Richards, D., Wilson, G., How, K.S., Kang, S., Tan, A. and Cheung, S. 1992. *Comparison of temperature measures*. Department of Mathematics, Swinburne University of Technology, Melbourne, 176 pp.

Robinson, D.A. 1990. The United States cooperative climate-observing systems: reflections and recommendations. *Bull. Amer. Meteor. Soc.*, 71, 826-831.

Rumbaugh, W.F. 1934. The effect of time of observation on mean temperature. *Mon. Wea. Rev.*, 62, 375-376.

Salinger, M.J. 1988. Climatic warming: impact on the New Zealand growing season and implications for temperate Australia. In: *Greenhouse: planning for climate change*, CSIRO Publications, Melbourne, 564-575.

Salinger, M.J. 1997. Indices and indicators of changes in extreme events in the South Pacific: preliminary results from New Zealand. In: *CLIVAR/GCOS/WMO Workshop on Indices and Indicators for Climate Extremes, Asheville, 3-7 June 1997.*

Savin, R., Stone, P.J. and Nicolas, M.E. 1996. Responses of grain growth and malting quality of barley to short periods of high temperature in field studies using portable chambers. *Aust. J. Agric. Res.*, 47, 465-477.

Savin, R. and Nicolas, M.E. 1999. Effects of timing of heat stress and drought on growth and quality of barley grains. *Aust. J. Agric. Res.*, 50, 357-364.

Schaal, L.A. and Dale, R.F. 1977. Time of observation temperature bias and "climatic change". *J. Appl. Meteor.*, 16, 215-222.

Seaman, R.S. 1982. A systematic description of the spatial variability of geopotential and temperature in the Australian region. *Aust. Meteor. Mag.*, 30, 133-141.

Sevruk, B. and Hamon, W.R. 1984. International comparison of national precipitation gauges with a reference pit gauge. *WMO Instrument and Observing Methods Report, No. 17*, World Meteorological Organization, Geneva, 136 pp.

Shaw, R.H. 1983. Estimates of yield reductions in corn caused by water and temperature stress. In *Crop reactions to water and temperature stresses in humid, temperate climates*, C.D. Raper and P.J. Kramer (eds.), Westview Press, Boulder, 374 pp.: 49-66.

Shein, K.A. 1998. The role of metadata in climate data homogeneity. *Proceedings, 2nd Seminar for Homogenisation of Surface Climatological Data, Budapest, 9-13 November 1998*, 195-201.

Shepard, D. 1968. A two-dimensional interpolation function for irregularly-spaced data. *Proceedings, 1968 ACM National Conference*, 517-524.

Shepherd, D.J. 1991. The effect of site changes on climatic records: a Tasmanian example. *Met. Note 194*, Bureau of Meteorology, Melbourne, 13 pp.

Simmonds, I. and Kaval, J. 1986. Day-of-the-week variation of rainfall and maximum temperature in Melbourne, Australia. *Arch. Meteor. Geophys. Bioklimator., Ser. B*, 36, 317-330.

Simmonds, I. and Keay, K. 1997. Weekly cycle of meteorological variations in Melbourne and the role of pollution and anthropogenic heat release. *Atmos. Env.*, 31, 1589-1603.

Skaar, J., Hegg, K., Moe, T. and Smedstud, K. 1989. WMO international hygrometer comparison. *WMO Instrument and Observing Methods Report, No. 38*, World Meteorological Organization, Geneva, 246 pp.

Slutz, R.J., Lubker, S.J., Hiscox, J.D., Woodruff, S.D., Jenne, R.L., Joseph, D.H., Steurer, P.M. and Elms, J.D. 1985. *Comprehensive Ocean-Atmosphere Data Set: release 1*. Climate Research Program, ERC, Boulder, 262 pp.

Sneyers, R. 1969. Les plus fortes gelées enregistrées en Haute Belgique comparées à celles d'Uccle (Bruxelles). *Arch. Meteor. Geophys. Bioklimatol., Ser. B.*, 17, 73-84.

Solow, A.R. 1987. Testing for climate change: an application of the two-phase regression model. *J. Climate Appl. Meteor.*, 26, 1401-1405.

Stepanova, N.A. 1958. On the lowest temperatures on earth. *Mon. Wea. Rev.*, 86, 6-10.

Stephens, M.A. 1970. Use of the Kolmogorov-Smirnov, Cramér-von Mises and related statistics without extensive tables. *J. R. Statis. Soc.*, B 32, 115-122.

Stern, H. 2001. The application of weather derivatives to mitigate the financial risk of climate variability and extreme weather events. *Aust. Meteor. Mag.*, 50, 171-182.

Stone, R. and Auliciems, A. 1992. SOI phase relationships with rainfall in eastern Australia. *Int. J. Climatol.* 12. 625-636.

Stone, R., Nicholls, N. and Hammer, G. 1996. Frost in northeast Australia: trends and influences of phases of the Southern Oscillation. *J. Climate* 9. 1896-1909.

Szentimrey, T. 1998. Multiple analysis of series for homogenization (MASH). *Proceedings, 2nd Seminar for Homogenisation of Surface Climatological Data, Budapest, 9-13 November 1998*, 27-46.

Takle, E.S. and Bian, X. 1993. Preliminary evaluation of temperature means, extremes and variability, and their relation to agricultural yields. *Preprints, 8th Conference on Applied Climatology, Anaheim, 17-22 January 1993*, 32-37.

Tarleton, L.F. and Katz, R.W. 1993. Effect of urban heat island on temperature variability and extremes. *Preprints, 8th Conference on Applied Climatology, Anaheim, 17-22 January 1993*, J104-J107.

Tattelman, P. and Kantor, A.J. 1976a. Atlas of probabilities of surface temperature extremes, Pt. 1, Northern Hemisphere. *U.S. Air Force Geophysics Lab, Hanscom AFB, Environmental Research Papers, 557,* 35 pp.

Tattelman, P. and Kantor, A.J. 1976b. Atlas of probabilities of surface temperature extremes, Pt. 2, Southern Hemisphere. *U.S. Air Force Geophysics Lab, Hanscom AFB, Environmental Research Papers, 588,* 34 pp.

Taubenheim, J. 1989. An easy procedure for detecting a discontinuity in a digital time series. *Z. Meteor.*, 39, 344-347.

Thiessen, A.H. 1911. Precipitation averages for large areas. *Mon. Wea. Rev.*, 39, 1082-1084.

Thom, H.C.S. 1973. The distribution of wet bulb temperature depression. *Arch. Meteor. Geophys. Bioklimatol., Ser. B*, 21, 43-54.

Thompson, R.D. 1973a. The contribution of airflow circulations to local temperatures and rainfall in the New England area, New South Wales, Australia. *Arch. Meteor. Geophys. Bioklimatol., Ser. B.*, 21, 175-188.

Thompson, R.D. 1973b. Some aspects of the synoptic mesoclimatology of the Armidale district, New South Wales, Australia. *J. Appl. Meteor.*, 12, 578-588.

Tiago de Oliveira, J. 1986. Extreme values and meteorology. *Theor. Appl. Climatol.*, 37, 184-193.

Torok, S.J. 1996. *The development of a high quality historical temperature data base for Australia.* PhD thesis, School of Earth Sciences, Faculty of Science, University of Melbourne.

Torok, S.J. and Nicholls, N. 1996. A historical annual temperature dataset for Australia. *Aust. Meteor. Mag.*, 45, 251-260.

Torok, S.J., Morris, C.J.G., Skinner, C. and Plummer, N. 2001. Urban heat island features of southeast Australian towns. *Aust. Meteor. Mag.*, 50, 1-14.

Torrence, C. and Webster, P.J. 1998. The annual cycle of persistence in the El Niño-Southern Oscillation. *Quart. J. Roy. Meteor. Soc.* 124. 1985-2004.

Toth, Z. and Szentimrey, T. 1990. The binormal distribution: a distribution for representing asymmetrical but normal-like weather elements. *J. Climate,* 3, 128-136.

Tuomenvirta, H., Alexandersson, H., Drebs, A., Frich, P. and Nordli, P. Ø. 2000. Trends in Nordic and Arctic temperature extremes and ranges. *J. Climate* 13, 977-990.

U.S. Weather Bureau. 1965. *World weather records 1951-1960: Part I, North America*, U.S. Weather Bureau, Washington, D.C., 538 pp.

van Loon, H. and Williams, J. 1978. The association between mean temperature and interannual variability. *Mon. Wea. Rev.*, 106, 1012-1017.

Vedin, H. 1990. Frequency of rare weather events during periods of extreme climate. *Geog. Annaler*, 72A, 151-155.

Vincent, L. 1998. A technique for the identification of inhomogeneities in Canadian temperature series. *J. Climate*, 11, 1094-1104.

von Lengerke, H.J. 1978. Frost in den Nilgris, Klimtologische und okologische Beobachtungen in den kalten Tropen Sudindiens. *Erdkunde*, 32, 10-28.

Vose, R. S., Schmoyer, R.L., Steurer, P.M., Peterson, T.C., Heim, R., Karl, T.R. and Eischeid, J. 1992. *The Global Historical Climatology Network: long-term monthly temperature, precipitation, sea level pressure, and station pressure data.* ORNL/CDIAC-53, NDP- 041. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Wagner, D. 1996. Scenarios of extreme temperature events. *Climatic Change*, 33, 385-407.

Wahba, G. and Wendelberger, J. 1980. Some new mathematical methods for variational objective analysis using splines and cross-validation. *Mon. Wea. Rev.*, 108, 1122-1143.

Whetton, P.H., Hennessy, K.J., Katzfey, J.J., McGregor, J.L., Jones, R.N. and Nguyen, K. 2000. *Fine resolution assessment of enhanced greenhouse climate change in Victoria. Annual report 1997-98: climate averages and variability based on a transient CO_2 simulation*, CSIRO Atmospheric Research, Melbourne, 50 pp.

Whittle, B. 2001. World temperature record. *Weather*, 56, 113.

Wilks, D.S. 1992. Adapting stochastic weather generation algorithms for climate change studies. *Climatic Change*, 22, 67-83.

Wilks, D.S. 1999. Multisite downscaling of daily precipitation with a stochastic weather generator. *Clim. Res.*, 11, 125-136.

Willmott, C.J. and Robeson, S.M. 1995. Climatologically aided interpolation (CAI) of terrestrial air temperature. *Int. J. Climatol.*, 15, 221-229.

World Meteorological Organization. 1966. *Climatic Change.* Technical Note 79, WMO 195, TP 100.

World Meteorological Organization. 1983. *Guide to climatological practices*, WMO, Geneva, 278 pp.

Wragge, C. 1892. *Meteorological Report For 1888, 1889, 1890, 1891.* Report presented to both houses of the Queensland Parliament, Brisbane.

Zhai, P., Sun, A., Ren, F., Liu, X., Bo, G. and Zhang, Q. 1999. Changes of climate extremes in China. *Climatic Change*, 42, 203-218.

Zheng, X. and Basher, R. 1995. Thin-plate smoothing spline modeling of spatial climate data and its application to mapping South Pacific rainfalls. *Mon. Wea. Rev.*, 123, 3086-3102.

Zwiers, F.W. and Kharin, V.V. 1998. Changes in the extremes of the climate simulated by CCC GCM2 under CO_2 doubling. *J. Climate*, 11, 2200-2222.

Listing of personal communications

(institutions Australian unless stated)

Peter Bate	Northern Territory Regional Office, Bureau of Meteorology
Peter Burr	University of New England, Armidale
Nick Clarkson	Queensland Department of Primary Industries
David Evans	Observations and Engineering Branch, Bureau of Meteorology
Rod Hutchinson	National Climate Centre, Bureau of Meteorology
David Jones	National Climate Centre, Bureau of Meteorology
Alex Kariko	Bureau of Meteorology Research Centre
Stephen Lellyett	NSW Regional Office, Bureau of Meteorology
Per Øyvind Nordli	Det Norske Meteorologiske Institut (DNMI), Oslo, Norway
Neil Plummer	National Climate Centre, Bureau of Meteorology
Scott Power	National Climate Centre, Bureau of Meteorology
Doug Shepherd	Tasmania/Antarctica Regional Office, Bureau of Meteorology
Simon Torok	Tyndall Centre, University of East Anglia, U.K.
Peter Whetton	CSIRO Atmospheric Research
Kelvin Wong	National Climate Centre, Bureau of Meteorology