Australian Government
Bureau of Meteorology

The Centre for Australian Weather and Climate Research
A partnership between CSIRO and the Bureau of Meteorology

CSIRO

A High-quality Historical Humidity Database for Australia

Chris Lucas

CAWCR Technical Report No. 024

July 2010

www.cawcr.gov.au

A High-quality Historical Humidity Database for Australia

Chris Lucas[1]

[1]*The Centre for Australian Weather and Climate Research*
- a partnership between CSIRO and the Bureau of Meteorology

CAWCR Technical Report No. 024

July 2010

ISSN: 1835-9884

National Library of Australia Cataloguing-in-Publication entry

Author: Lucas, Chris.

Title: A High-quality Historical Humidity Database for Australia [electronic resource] / Chris Lucas.

ISBN: 9781921605864 (pdf)

Series: CAWCR technical report; 24.

Notes: Included bibliography references and index.

Subjects: Humidity--Australia--Databases. Meteorology--Australia--Databases. Australia--Climate.

Dewey Number: 551.5710994

Enquiries should be addressed to:
Chris Lucas
Centre for Australian Weather & Climate Research
GPO Box 1289 Melbourne
Victoria 3001, Australia

C.Lucas@bom.gov.au

Copyright and Disclaimer

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

This study documents the creation of a high-quality homogeneous surface humidity dataset for Australia. The surface dewpoint data at 58 stations across Australia are homogenized for the time period from 1957 through 2003. The resulting high-quality dataset has monthly time resolution. To create the high quality series, data from nearby stations are amalgamated to create homogeneous reference series, which are then compared to the candidate station series to identify inhomogeneities, primarily through indirect statistical means. The methodology is fully described within the paper.

Typically, about five inhomogeneities (or breakpoints) are identified at each station. By design, many of these points have no obvious cause apparent in the individual station's metadata. However, a comparison with the metadata reveals the influence known disruptions to the data record such as site moves. A peak in the number of breakpoints is seen in the 1990s, when the observing network across Australia was modernized with the installation of Automatic Weather Stations. This switch to AWSs involved a change in humidity instrumentation. The newer instrumentation results in dewpoints of approximately 0.5^{o}C lower (in monthly medians) at many stations. The adjustments made to each of the 58 stations are documented in an Appendix.

A preliminary climatology of surface humidity for Australia is also presented. Nationally, anomalies of monthly median dewpoint are positively correlated with rainfall anomalies (r~0.6). Dewpoint anomalies are also found to weakly (but significantly) lead rainfall anomalies by about six months. The source of this apparent relation is currently unknown. Long-term trends in humidity are also investigated. Nationally, dewpoint has been increasing by about 0.1^{o}C per decade over this record. The value is in general agreement with the trends identified in global studies of humidity. The trend value also varies regionally, with smaller trends (but still mostly positive) noted in southern parts of Australia.

1 INTRODUCTION

The science of climatology initially began as primarily a bookkeeping exercise – essentially an attempt to quantify the ‘statistics of weather’. But climate can be more accurately defined as ‘the thermodynamic/ hydrodynamic status of the global boundary conditions that determine the concurrent array of weather patterns’ (Bryson 1997). Since the mid-20th century, the science has expanded to encompass the study of seasonal and interannual climate variability, decadal to millennial climate fluctuations, long-term changes in the mean and variability characteristics, climate extremes and seasonality. Climate is defined on multiple spatial scales, from local micro-climates to planetary-scale circulation patterns (MacGregor 2006).

Crucial for this endeavour is the acquisition of high-quality datasets. To accurately assess the behaviour of the climate system over long time scales, the data need to be in *relative homogeneity*. In other words, the dataset needs to have artificial trends and changes due to factors like changing instruments, moving locations of the observations and differences in observational techniques removed. This is but a sampling of the factors that can impact the interpretation of long time series of climate data. For a more complete discussion of the methodologies that have been used to homogenize datasets, see the review of Peterson et al. (1998). Homogenized datasets -- primarily temperature and precipitation -- have been created using a variety of homogenization techniques. In Australia, homogenized high-quality datasets of maximum and minimum temperatures and precipitation have been created (Nicholls et al. 2006). More recently, a national database of monthly total pan-evaporation has been homogenized (Jovanovic et al. 2007).

An important meteorological variable which has generally not been homogenized is water vapour. While it is nominally only a ‘trace gas’, water vapour is of fundamental importance in the atmosphere. Its relative concentration impacts the thermodynamic, dynamic and radiative characteristics of the atmosphere on all time and space scales. Accurate measurement of its concentration and a thorough understanding of its variability are essential for understanding atmospheric circulations ranging from the micro-scale to the climate.

In the past decade, several examinations of surface humidity using broad databases have been made. Gaffen and Ross (1999) and Robinson (1998, 2000) have investigated the surface humidity climatology and trends over the United States during the 1961-1990 period. Wang and Gaffen (2001) looked at surface humidity and temperature in China for the second half of the 20th century. Dai (2006) gridded humidity observations globally from 1975 to early 2005 and examined the trends over broad regions. Willett (2007) and Willett et al. (2007) describe a globally homogenized and gridded humidity dataset, although the resolution is only $5^o x 5^o$.

This paper reports on the creation of a high-quality humidity database for Australia. The variable chosen to represent humidity in this study is dewpoint, defined as the temperature to which a parcel of moist air must be cooled, at constant pressure and moisture content, in order to reach saturation. Another moisture variable, vapour pressure or specific humidity, could easily have been chosen; moisture variables are easily convertible from one form to another. The choice of dewpoint introduces some slight mathematical difficulties (e.g. its not readily average-able), but has the advantage of having familiar units (^{o}C or K) and having a easily understandable physical interpretation. It is in common use around the world, both professionally and in the wider public.

The time period covered in this study extends from 1957 through 2003; fifty-eight stations are selected for inclusion. All states and territories are represented. The data have been homogenized following the basic procedures described by Peterson and Easterling (1994) and Easterling and Peterson (1995). However, the characteristics of the data here meant that their algorithms could not be followed exactly.

This dataset has many potential uses. One use that is pursued here is a confident look at the variations in humidity associated with interannual variability and at any long–term trends. The humidity data also have many other applications, including input to fire-weather calculations, vegetation and drought studies along with an assessment of hydrological risks.

In the text that follows, an overview of humidity observations made by the Australian Bureau of Meteorology (the Bureau) is given. The data sources are described, as are the broad-scale characteristics of the data. The main portions of the paper focus on the extensive quality control and homogenization techniques employed to insure the database is of highest quality possible. This includes a detailed description of the technique, an evaluation of the methodology and a validation of the results. A preliminary climatology of surface humidity is also presented, including an analysis of the interannual variability and long-term trends in dewpoint. In an Appendix, detailed information pertaining to the adjustments made by the homogenization procedure for each individual station is presented.

2 HOMOGENIZATION IN BRIEF

The goal of data homogenization is to remove the effects of station discontinuities -- for example, those caused by changes in station location and observation procedures -- from a time series of a variable (dewpoint in this case) at a given *candidate station.* The review by Peterson et al. (1998) shows that there are a variety of approaches that can be followed when undertaking a project of this nature, but few (if any) standardized methods applicable to all situations. Approaches for identifying inhomogeneities can be 'direct', for example using documented changes to station and/or measurement characteristics (i.e. *metadata*) or 'indirect', where statistical methods are used to infer the presence of artificial changes to the time series. In this study, indirect statistical methods are primarily used, but this is supplemented and informed by the use of metadata and instrument comparisons. In theory, objective statistical methods should identify all significant inhomogeneities. The experience here indicates that the metadata are often incomplete and the older records are difficult to access. The methodology used in this study for detecting the inhomogeneities is briefly discussed here; a detailed discussion is given later in the paper.

To homogenize the record at a candidate station, it is compared to a *reference series* free from inhomogeneities. Since few, if any such stations exist in the records, a composite reference series must be created from *reference stations*. These are nearby stations with records of reasonable quality and length and a humidity climate similar to the candidate station. Some leeway exists in the definition of 'nearby'; many remote Australian stations simply do not have any suitable stations within 200-300 km, forcing the selection of less-than-ideal reference stations. At a given candidate station, between 4 and 9 reference stations are chosen to create the reference series.

At the candidate and reference stations, time series of morning (0800 or 0900 LST) monthly median dewpoint are seasonally averaged (e.g. DJF, MAM…). The long-term seasonal means are removed from these series to create seasonal anomalies. These are the basic time series used in this analysis. To create the composite reference series, the technique described by Peterson and Easterling (1994) is generally followed. In this method, a consensus *difference series*, the difference of a given point from the previous in the series, is derived from a weighted average of the difference series at the reference stations. The consensus series is then integrated backward in time to create a composite homogeneous reference series. The reference series is subtracted from the candidate series. This time series is subsequently used to identify inhomogeneities in the data. The techniques used to accomplish this are discussed further in later sections of the paper.

3 DATA

3.1 Candidate stations

Data from 58 stations across Australia were selected for the final analysis. These stations are the so-called *candidate stations*, where the homogenization and full quality control procedures described in subsequent sections is applied. These stations cover nearly the entire spatial extent of Australia (Fig. 1), with some gaps. The stations were chosen with data quality and spatial coverage in mind. As a starting point, the stations used in the high-quality maximum and minimum temperature databases of Trewin (2001) were selected. As the procedure developed here is quite labour-intensive, this initial set of stations was further narrowed to avoid having too many stations in climatologically similar areas while still creating a national coverage. Stations in Trewin's database with poor humidity records were also removed. Other stations not included in Trewin's database were included in this data set in order to fill in spatial gaps in the coverage. The majority of the stations selected are associated with meteorological offices or larger airports, where the observations are generally more reliable. The secondary stations are often post offices or other cooperative observer sites that are generally less reliable and of lower time resolution early in the record.

The initial data record at the selected stations consists of observations of temperature, dewpoint, wet bulb temperature and surface pressure. Figure 2 indicates the approximate diurnal sampling of the stations as well as the extent of the record and any gaps in the data set. The stations generally have records extending from 1957 through 2003, although some start later. The number of observations varies from 2 to 8 a day. There is a brief period during the first Daylight Savings Time (DST) in 1972-3 when up to 12 observations a day were reported at a few stations, due to apparent confusion about what time people were supposed to report. Generally speaking, when there are but two observations per day, these are typically made at 0900 and 1500 *local* time[1]. In fact, these are the key observation times across much of Australia; all stations report at these times, regardless of the total number of daily observations, and at many stations, only data at those times were digitized prior to 1987. On the figure, the thickest bars represent 8-times-a-day 'SYNOP' observations.

[1] Hence during periods with DST, the solar time of the observations is 0800 and 1400, an hour earlier than in non-DST periods.

Fig. 1 *Names and locations of candidate stations used in the analysis. Details of the candidate stations are found in Appendix A.*

All stations which have had an Automatic Weather Station (AWS) installed currently report at this full rate[2]. A small number of stations, such as Cabramurra, have only 1 observation a day for much of the record. In the figure below, the number of observations per day is computed as the round quotient of the total number of observations divided by the number of days on which observations are made in a month. Any short-term ‘blips’ in the figure likely represent a month with some missing data rather than a change in the scheduling of the observation program, which is generally consistent over longer time scales. Some other shortcomings in the data set are also indicated in Fig. 2. Months with missing data are seen as sections taken out of the bar. These are usually just for a month or two at a time, although occasionally periods of missing data can extend for several years. A period of missing data is quite often present in the early 1970s. This is seen in 10 of the candidate stations and is even more prevalent in the reference station data. The reason for this ‘70s Gap’ is unknown. The effects of the missing data on this analysis are discussed later in the text.

---

[2] Most AWSs report data at a much higher rate than 3-hourly, up to 1 minute resolution in many cases.

3.2 Reference Stations

To create a homogeneous reference series, data from nearby reference stations are used. A large number of reference stations were considered for inclusion; the majority were considered unsuitable for a variety of reasons. The location of the chosen reference stations is shown by the crosses in Fig. 3, and Appendix B provides a listing and geographic details of these stations. The reference station data is of the same general format as the candidate stations data; surface measurements of temperature and humidity, along with surface pressure. The biggest difference between candidate and reference stations lies in the quality of the data. Reference stations tend to be more sporadic in their record and have generally lower-quality data. Stations with longer term records were most sought after; new AWS stations installed since the expansion of the observing system began in the 1990s were generally not considered. That said, there are instances where a station with a short record, particularly earlier in the record and/or in more remote regions, is crucial to the augmenting the reference series used in the homogenization. More details on the selection, quality control and use of the reference station data is provided in the section describing the homogenization procedure.

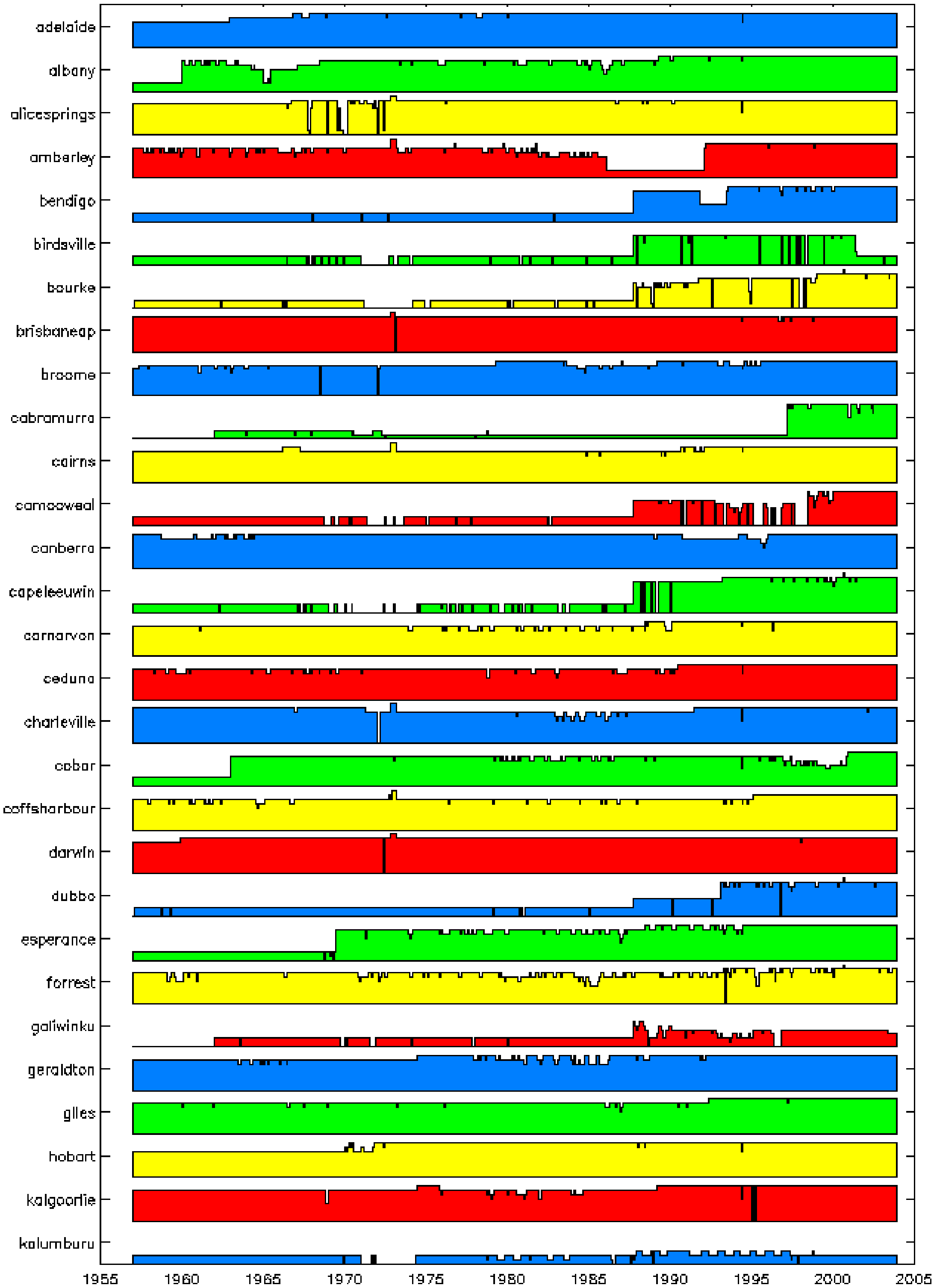


Fig. 2 *Graphical representation of the data availability at each station. The height of the bar shows the average (by month) number of observations per day. The highest level generally represents 8 observations a day. At stations in QLD and NT a short period in 1972-3 shows up to 12 observations per day associated with the introduction of daylight savings time. No colour indicates a period of missing observations. The smaller bar seen at many stations is 2 observations a day, generally at 0900 and 1500. The different colours are included to differentiate between the stations and have no other meaning.*

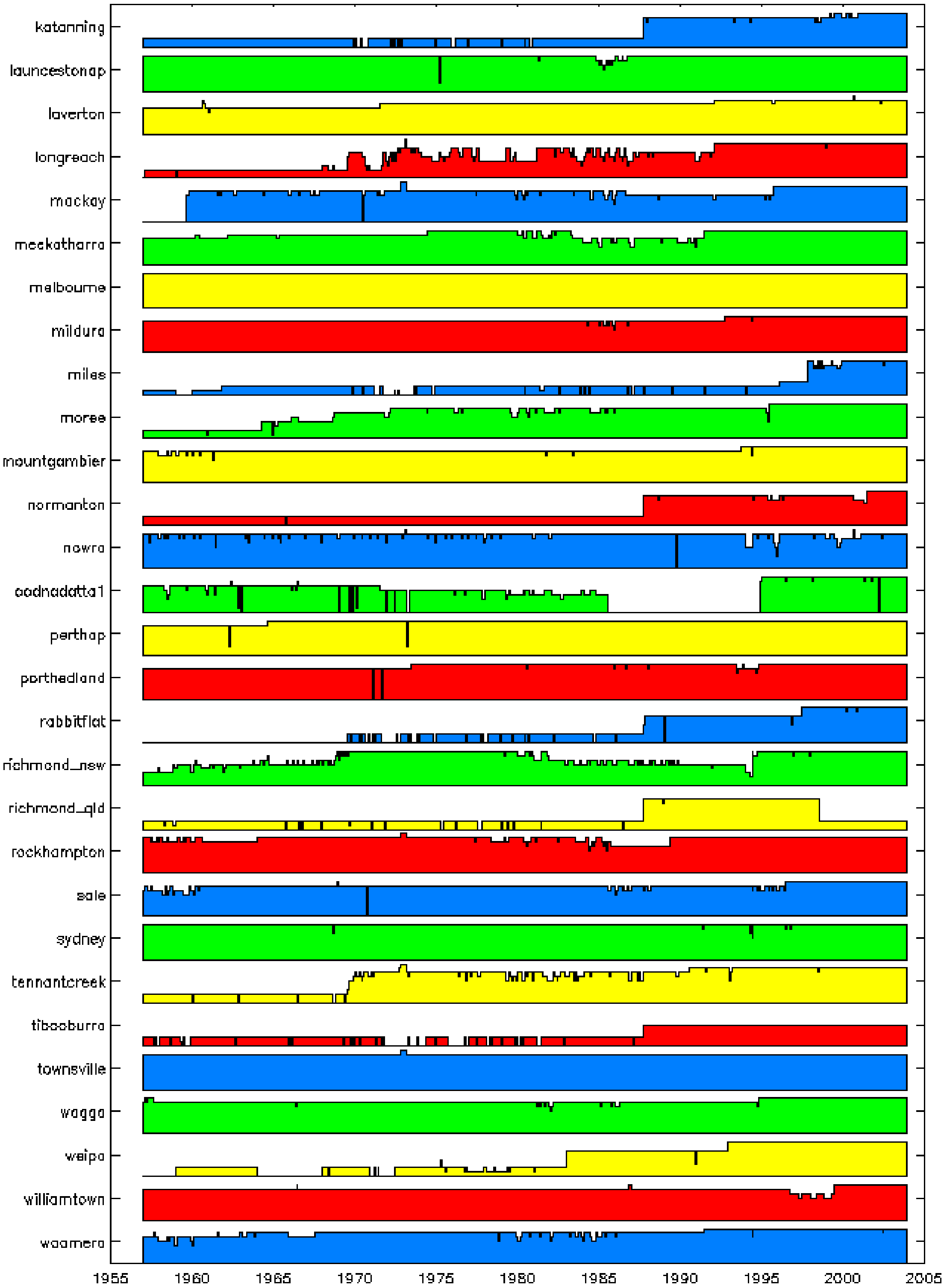


Fig. 2 continued.

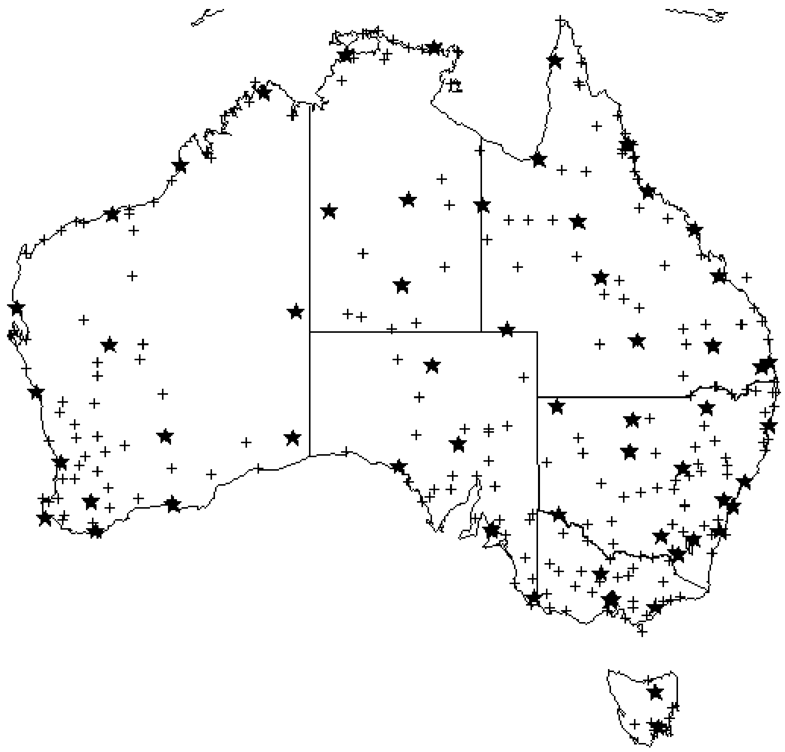


Fig. 3 *Location of candidate (stars) and reference (crosses) stations used in this study. Reference station names and geographic coordinates are given in Appendix B.*

4 DEWPOINT COMPUTATION AND MEASUREMENT

4.1 Psychrometric Method

In Australia, the psychrometric method is most often used to measure humidity in the atmosphere. In this method, the actual amount of vapour in the air is determined from two separate, but simultaneous temperature measurements: 1.) the ambient air temperature and 2.) the wet-bulb temperature. A value for station pressure is also required. These measurements are used in the semi-empirical psychrometric formula

$$e = e_w - Ap(T - T_w) \, ,$$

where e is the actual vapour pressure (i.e. the saturation vapour pressure at the dewpoint), e_w is the vapour pressure at the wet-bulb temperature T_w, p is the pressure, T is the ambient air temperature and A is the psychrometric constant. Vapour pressures are converted to and from their associated temperatures using the approximation derived by Alduchov and Eskridge (1996):

$$e = 6.1094 \exp\left(\frac{17.625T}{T + 243.04}\right) .$$

The psychrometric constant *A* defined above is a critical term and a major source of uncertainty in the calculation. From a purely thermodynamic standpoint, $A = C_p(\varepsilon L)^{-1} \approx 6.46\times10^{-4}$ K^{-1} at 0^{o}C. However, the value of this 'constant' when making real-world measurements varies considerably based on a number of factors.

Perhaps most important of these factors is the ventilation of the instruments and/or their shelter. Figure 4 shows schematically the response of *A* to changes in the ventilation. At low ventilation speeds, *A* is high. As the ventilation increases *A* decreases asymptotically. Other factors of importance in determining *A* are the screen configuration, the shape of the wet bulb and the wick length and cleanliness

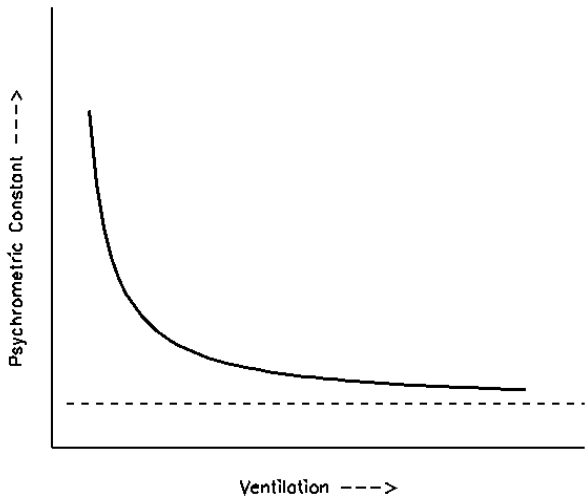


Fig. 4 *Schematic diagram showing the variation of psychrometric coefficient A with changes in the ventilation of the instrument.*

Psychrometric measurements made by the Bureau of Meteorology use 'naturally ventilated' screens, with values of *A* recommended by the World Meteorological Organizations (WMO) Commission for Instruments and Methods of Observation (CIMO) to be 7.7 - 8.0x10^{-4} K^{-1} for wet-bulb temperatures in excess of 0^{o}C (CIMO 1996). The standard Bureau value is 7.886x10^{-4} K^{-1} falls within this range, and is used in all calculations in this study.

4.2 Humidity Instruments used by the Bureau

Two separate temperature measurements are required to calculate dewpoint using the psychrometric method: the dry-bulb or air temperature and the wet-bulb temperature. The wet bulb temperature is defined as the temperature a parcel of air obtains when water is evaporated into it until saturation occurs. Measuring the wet-bulb requires that the sensing element is kept wet. This is achieved by placing a closely-fitting cotton (or similar) wick around the sensing element to maintain an even covering of water. The wick is attached to a reservoir of (distilled) water, to insure that it remains wet. The wick should be kept clean and changed on a frequent basis to insure accurate measurements (CIMO 1996).

Historically, the primary instruments used to measure humidity have been mercury-in-glass (Hg) thermometers. These are standard instruments which derive temperature by measuring the rise and fall of a column of mercury as it expands and contracts with changes in temperature. These instruments were used over most of the country until the gradual introduction of AWSs, beginning in earnest in the early-1990s. They are still in use in many AWSs, as supplemental readings. Five stations in the dataset exclusively used Hg thermometers in 2003.

Most AWSs in the humidity database use values derived from platinum resistance thermometers (PRTs), which work by measuring the temperature–dependent change in the resistance of a conductor, in this case platinum. The instruments used in Australia are manufactured by Rosemount, and are referred to as ‘temperature probes’. AWSs using PRTs rely on the psychrometric method to measure humidity, with a dry- and wet-bulb probe. Of the 58 stations in the dataset, 39 use PRTs in 2003. The type of instrument in use during 2003 at each station is noted in Appendix A.

At more remote stations, military bases and other stations where staff are not on hand to maintain the instruments (particularly the wet-bulb thermometer), electrical humidity measurements are made using a humidity probe (HP). These instruments were also installed at places where the wet bulb temperature regularly goes below 0^{o}C to avoid uncertainty resulting from the different vapour pressures over ice and water. This instrument does not require the techniques of psychrometry, but instead measures the humidity directly by measuring the change in capacitance of a thin film, a quantity dependent on the RH. These devices typically have a larger uncertainty in their measurement and are generally not reliable in the long term as they are subject to hysteresis and drift after exposure to very high RH and cloud (e.g. Strangeways 2001). Through 2003, the majority of AWSs with HPs installed used devices manufactured by Rotronics of Switzerland. Ten of the stations in the dataset used HPs in 2003.

Lucas (2006)[3] examined the relative bias in the humidity measurements between these different types of instruments. Using the Hg thermometers as a standard, both PRTs and HPs were found to produce lower readings of dewpoint. The typical size of this bias was -0.5^{o}C for PRTs and -0.3^{o}C for HPs. It should be noted that this is a relative bias; it cannot be stated unequivocally which measurement is the correct one. For the PRTs, this bias arises as a result of the mischaracterization of *A*, the psychrometric coefficient. For the HPs, the bias is largely related to the characteristics of climate – ambient humidity and rainfall impact the performance of the instrument.

The Bureau’s “sitesDB” metadata database also indicates that other instruments have been used to measure humidity at different times and different stations. Before the 1990s, many stations used hygrographs or thermohygrographs to record humidity as well. Other stations show the use of psychrometers and hair hygrometers in their records. In general, these instruments were not the ‘official’ measurement, but rather a supplemental one to the Hg thermometer standard.

[3] Because of the relative obscurity of this reference and its importance to the results here, the report is reproduced in Appendix C for easy reference.

5 QUALITY CONTROL AND HOMOGENIZATION

In this section, an explanation of the manual quality control methods applied to the data is discussed. A detailed description of the homogenization is also shown.

5.1 Recomputing dewpoint

In the original records, there are several shortcomings in the data which require correction. Apparently, Bureau practice in the pre-computer days was to report dewpoint rounded to the nearest whole degree. This is functionally equivalent to assuming a non-constant value of *A*. To remedy this, all dewpoints are recomputed using the accepted Bureau standard of *A* (= $7.886 \times 10^{-4}\ K^{-1}$) from the wet-bulb and temperature readings and recorded to the nearest tenth of a degree. This calculation requires an estimate of station pressure. During times when a measured value is not available, a typical value based on the altitude of the station is input instead.[4] Further, in the event of either the wet-bulb temperature or dewpoint missing, the missing one is recomputed from the available observations. When this occurs with the rounded values of dewpoints, possible errors of ±0.5 degrees are introduced. If both humidity readings are missing, the observation is reported as missing

5.2 Error identification and removal

Before homogenization begins it is important to apply some basic quality control to the data. The wet-bulb temperature measurement is a complex procedure, with many opportunities for errors to arise. The identification and removal of suspect measurements in the data set is crucial to the success of the homogenization. This step is done manually. While there are automatic criteria that could be applied to the problem, it is difficult to successfully detect errors if they aren't extreme. Similarly, too broad a criterion will remove good data from the set. The procedure here is to combine automated methods with a consideration of the meteorology of time and place of the suspicious point to help identify whether it is a valid observation. The general procedure is described more thoroughly below.

Broadly speaking, there are two main types of errors in the data; those due to spikes and those due to so-called tracking errors. Spikes are generally errors that take the form shown in Fig. 5; a single point (or at most a few) which stands out in a series that is otherwise consistent with expected behaviour. Spikes arise from several different sources: insufficiently moist wet-bulb; poor instrument ventilation (low wind speeds) or a dirty wick (dust or smoke in observations). Most often, no apparent cause is obvious.

[4] For pressure errors of 25 hPa, this assumption introduces errors of up to ±0.5 degrees (negative dewpoint error when pressure error is positive) at 'typical' moisture levels. These errors can become quite large (say 5-10^{o}C) when the dewpoint below -20^{o}C or so. The errors tend towards zero as saturation is approached.

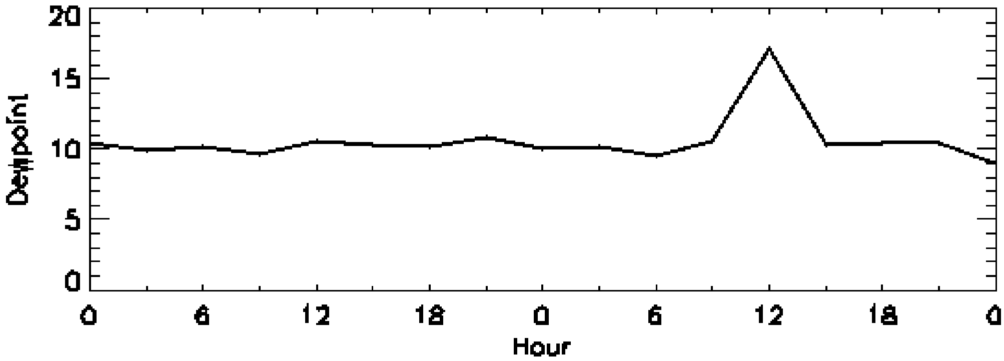


Fig. 5 *Schematic diagram of a 'spike'.*

Tracking errors are where the dewpoint and wet-bulb temperature 'track' the air temperature over an extended period of time (days to weeks). There can either be an offset or all three temperatures are equal. The source of this error is incomplete wetting of the wet-bulb (or none!). There should be some positive correlation in the diurnal variations of dry- and wet bulb temperatures. However, for dewpoint and air temperature, there is most often a negative correlation in the diurnal trends – dewpoint is lowest when air temperature is highest. (Real positive correlations between the two do occur, but most often in wetter, cooler conditions). To identify periods of tracking, extended periods when a positive correlation between dewpoint and air temperature is observed are manually identified. Figure 6 shows an example from April 1959 in Alice Springs. Tracking errors were recorded for four separate periods in the last half of this month (dates: 14-16, 18-21, 23-26, and 29-30 April). A spike is indicated on 22 April.

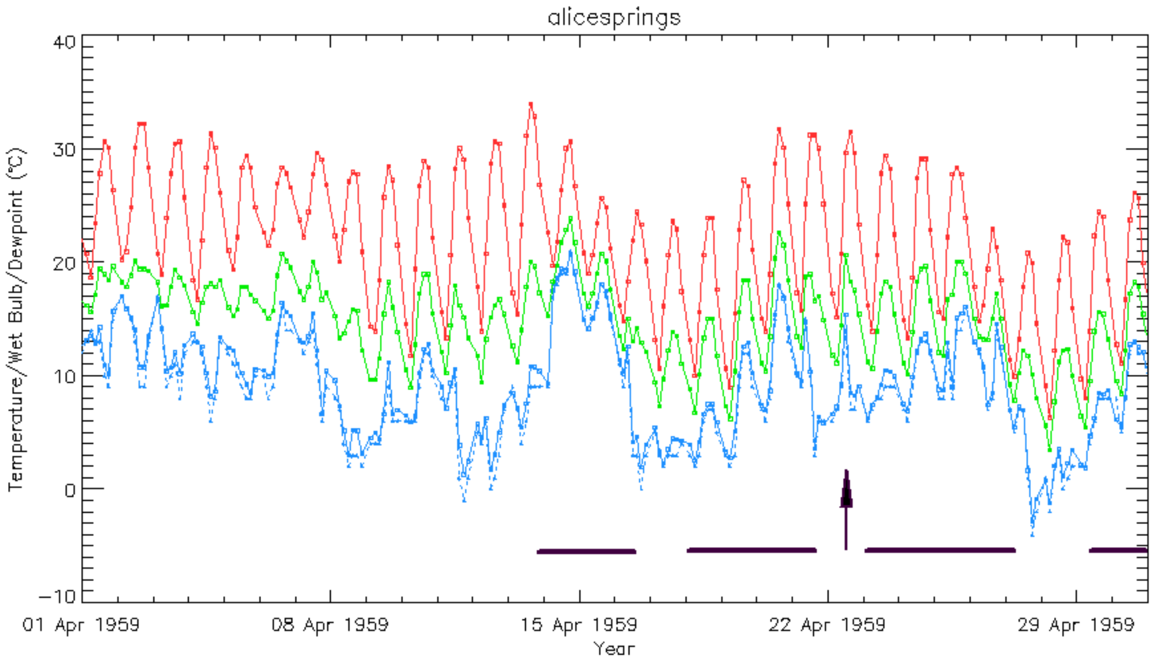


Fig. 6 *Alice Springs, NT time series trace for April 1959. Shown are air temperature (red), wet-bulb temperature (green) and dewpoint (blue). Both the original (blue dashed) and recalculated (blue solid) dewpoints are shown. Horizontal black bars indicate tracking errors; the arrow shows the spike.*

To assist in the identification of suspicious points, observations of rainfall ('precipitation since last observation'), wind speed and direction and 'present weather' data are collected to help establish the prevailing meteorological conditions at a given time. When a point is identified as potentially in error, either spikes or tracking, these data along with the temperature and moisture variables and their overall tendencies and climatology for a given month are examined to determine the meteorological veracity of the observation in question. If the weather conditions reasonably support the possibility of a given observation, it is left in the final data set. Otherwise, it is flagged as 'bad' and removed from later processing. An error log is maintained for each station; comments regarding the nature of the identified errors are noted in the log.

Two separate procedures are used to identify these in errors in the data. The first procedure is automated, designed to catch the unrealistic extremes. It involves sorting all observations of dewpoint for a given month and examining the top and bottom 1% (the tails) of the distribution. This whole subset of data doesn't need to be examined; the observations 'fall into line' reasonably quickly. This method is quite effective at identifying and eliminating the most extreme outliers.

The second procedure is more time consuming. It involves the examination of plots and the manual selection of outliers. Initially, annual plots are examined. On these plots, it is relatively straightforward to identify the months which contain potentially suspicious points. Months in a given year which are a bit suspicious are examined in more detail using the general methodology described above. Undoubtedly, many points which are really in error will be noted as good, as this method will only pick out the points which 'stand out' from the background. Generally, a conservative approach is taken and the observations are taken at face value whenever possible.

As an example, consider a situation where a sharp increase in dewpoint is observed for one three-hourly observation, followed by a return to the more generally prevailing conditions at the next observation, as depicted at 1200 of the second day in Fig. 5. The first check would be to compare with the overall distribution for the month of the observation. If this value were within reasonable bounds of the distribution (say, within three standard deviations or so for an upward spike, more for a downward spike), then the prevailing weather scenario would be considered. If this observation had precipitation just before or during the time it was made, this would be considered plausible and the observation retained. Another common possibility is the onset of a sea breeze at a near-coastal station, indicated by a shift in wind direction to an onshore flow.

Some stations simply show an unusual spike at certain times, which only become apparent after some examination of long series of observations. Generally a note will be made of this when it occurs. If no plausible weather scenario can be concocted, then the point is flagged as bad. For example, if the wind speed coinciding with the dewpoint jump was reported as CALM, this point would be thrown out, as that suggests an erroneously high humidity measurement associated with poor ventilation of the wet bulb, and hence an incorrect value of the psychrometric constant.

5.3 The details of homogenization

A broad overview of the homogenization process is given above. Generally, the technique for the creation and testing of climatological reference series detailed in Peterson and Easterling (1994) and Easterling and Peterson (1995) are followed. However, the unique characteristics of this data required these techniques to be adapted, particularly those involved in creating the reference series. In the remainder of this section, the details of this process will be enumerated. The procedure will be illustrated using the homogenization of the Perth AP site as an example.

1. The initial stages of the homogenization are somewhat 'documentary' in nature. In these steps, the Bureau's electronic metadata database (sitesDB) is invaluable. There are two main documentation tasks.

    - Create a station history for the candidate stations. SitesDB is examined and changes to humidity instrumentation, sites moves and the like are noted for future reference. Unfortunately, these station histories are not complete, as sitesDB has not been fully 'seeded' with historical data at this time. The data do exist in paper form, but are not readily accessible. These paper records are generally not used in this study. Hence, before about 1997 the historical data are woefully incomplete, although some useful information is available. The upshot of this is that sources of earlier inhomogeneities will most likely not be documented.

    - Compile a list of nearby potential reference stations for all the candidate stations. The distance used as 'nearby' varies, depending on the density of stations near the candidate station. In all cases it is between 250 and 700 km. In general, reference stations with extended records are preferred. The general rule is to consider stations whose records extend back to before 1985, excluding most of the AWS stations installed since the 1990s. While this is the ideal, necessity dictates that stations with shorter records be used on occasion, particularly when they occur earlier in the record. Hence, some long-closed stations with shorter records are included. This initial list of stations is further modified by excluding stations with dissimilar humidity climates (i.e. different seasonal means or variations), determined by comparing seasonal means. Exceptions to this last 'rule' occur when there is a paucity of otherwise quality observations either temporally or spatially. Figure 7 shows the identified possible reference stations for Perth. There are 54 possible stations, a higher than normal number. These stations range from 10 to 466 km distant from the airport.

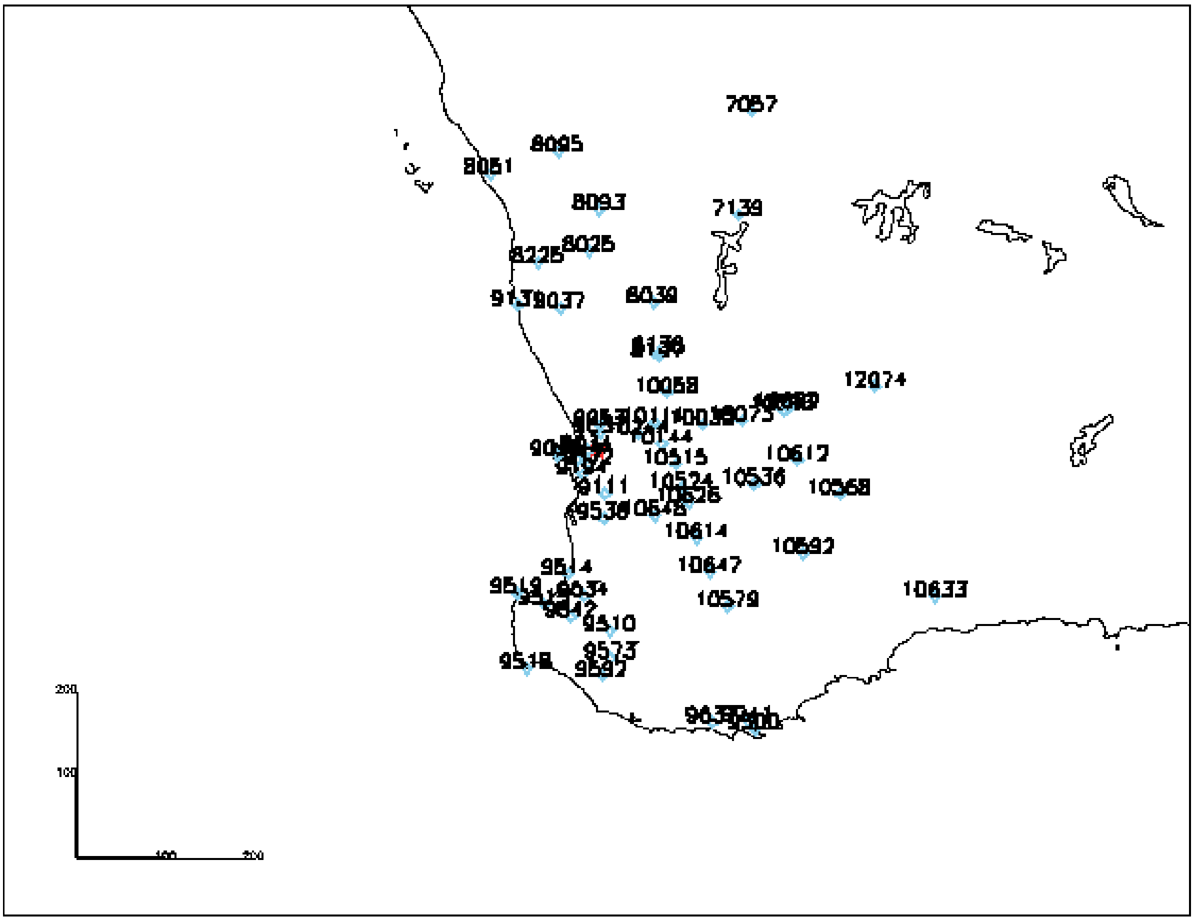


Fig. 7 *Map of all potential reference stations for Perth (red star).Shown are the station numbers. Refer to Table 1 for the station names.*

2. In the next step, we prepare the time series at both candidate and reference stations to be used in the analysis. The first step is a monthly frequency analysis using daily data *from 0900 only*. After 1972, when Daylight Saving Time was instituted across much of Australia, observations at 0800 Standard Time are included as well. These times are chosen so as to eliminate any potential sampling differences and to minimize the influence of diurnal variability. The 1500 observation could be chosen here, but it is much more subject to turbulence and mixing associated with boundary layer processes which generally peak in the afternoon.

   The *monthly median* value of dewpoint is chosen for subsequent calculations. Where a gap of one month is present in the time series, the value for that month is filled in by linear interpolation. Longer gaps are kept missing. For the homogenization exercise, the time series are further processed into seasonal series (seasons: DJF, MAM, JJA, SON) by averaging the three monthly median values in a given season. Annual series have too few points to perform a meaningful homogenization and monthly series were too noisy and gave unclear results. The seasonal series were a compromise between these two extremes. Further, seasonal means (computed independently for each station) are removed to give a seasonal anomaly time series. A comparison of the monthly median, seasonally- and annually-averaged time series is shown in Fig. 8.

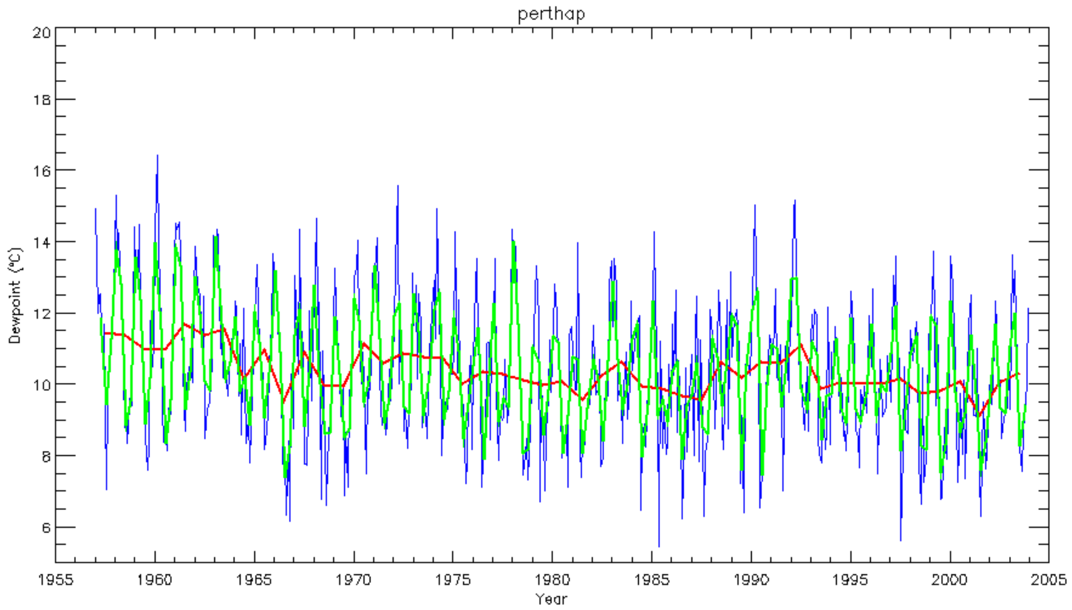


Fig. 8 *Time series of monthly (blue), seasonally- (green) and annually-averaged (red) median dewpoint at Perth AP. The basic quality control has been applied, but the data are not homogenized.*

3. A simple-minded automatic quality control is performed on the individual reference series to remove outlier points. A standard z-score, as used in the significance testing of means (e.g. Panofsky and Brier 1968), is computed for the time series and all points with abs(z) > 2.576 are removed. This corresponds to a two-sided probability of one percent for lying outside a normally distributed distribution. This will occasionally remove a few legitimate extreme observations, but this is unlikely to significantly impact the seasonal means. Further, potential reference stations were removed from consideration or selectively-edited on a case-by-case basis to eliminate poor or 'overly-influential' data which were not detected during this automated procedure. This procedure is not applied to the candidate stations, as extreme points are identified and removed during the basic quality control phase.

4. With the data prepared, the homogenization procedure is ready to begin in earnest. Following the methodology of Peterson and Easterling (1994), difference series (alternatively but equally called the derivative series) are computed for each candidate and reference series using the seasonal anomaly data. This series is simply the value at a given time minus the value at the previous time. Figure 9 shows this quantity for Perth AP. As discussed in Peterson and Easterling (1994), these series are useful for identifying discontinuities in the data.

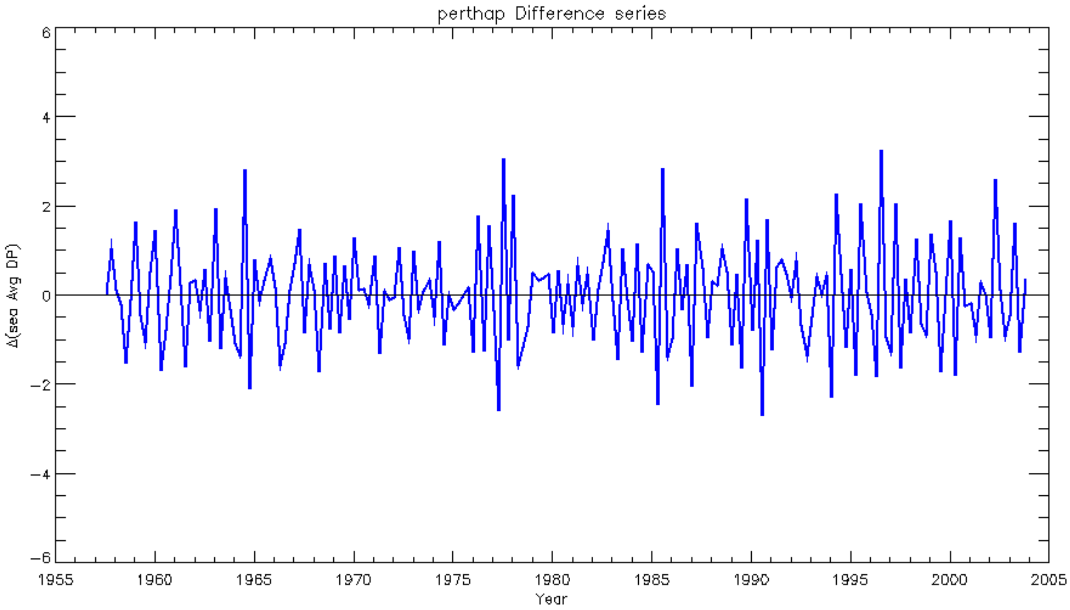


Fig. 9 *Difference series at Perth AP.*

Using these series, correlation coefficients between the candidate station and the corresponding reference stations are computed. Other statistics computed are correlation coefficients between seasonal anomaly candidate series and each seasonal anomaly reference series and the number of matching points in the time series. As more fully discussed in the next item, these calculations inform the decision of which reference stations to keep and (in part) the amount of influence each station has in determining the final series.

5. In the next steps, the composite reference series is constructed. This involves choosing the reference stations used in the composite, calculating the reference series and identifying which solution is 'best'. This is an iterative process, with different combinations of reference stations used until a satisfactory solution is found. This choice is subjective, but by applying a set of consistent guidelines some of the arbitrariness can be avoided.

   There are many factors to consider when deciding on the stations to be included in the final set. Following Easterling and Peterson (1995) (hereafter EP95), between five and ten reference stations should ideally be chosen. The experience here also suggests this to be the case. It is important to ensure that the selected stations have reasonable quality and display an internal consistency with the other reference stations making up the series. Also, stations should be chosen such that, to the degree possible, they are evenly distributed in time.

   - Quantitative (but arbitrary) criteria were devised to help provide an objective basis to assist in choosing the 5-10 reference stations. These criteria are: 1.) difference series correlation >0.7; 2.) time series correlation > 0.6; and 3.) at least 130 points in the difference series (out of 187 possible). These variables are combined into two different 'scores'. The first score multiplies the two correlations and the number of points; the second just multiplies the two correlations together. While these criteria were adhered to wherever possible, at many candidate stations there were few reference stations (or even none) which met these standards. In these cases, the scores are useful in picking out the higher quality stations in the record. Examples of these statistics are shown in Table 1.

- On occasion it is necessary to choose stations which don't meet the above criteria in order to fill in gaps in the temporal coverage. Most reference series contain some of these 'non-criteria' reference stations. Generally, these tend toward not meeting the above criteria on the length of the series, rather than on the correlation-aspect. They are too short, not of poor quality.

6. A consensus difference series for each candidate station is formed using weighted averages (Fig. 10). Averages are weighted by the individual reference/candidate difference-series correlation and an inverse exponential distance function. The e-folding scale of the exponential weight is set to 255 km. This distance is somewhat arbitrary, but the sensitivities to this and other factors were examined, with the broad conclusion that a moderately-sized scale is better than one either smaller or larger. Generally, the effects of the weighting-scale are small overall in the majority of cases. With the weighting, there is a need to attempt to 'balance' the stations based on distance from the candidate site, especially those that are very close. Small distances have a large weight and any errors at those stations have a disproportionate effect on the consensus if another station is not nearby to balance. Initially, all the potential reference stations (at a given candidate station) are included in this average.

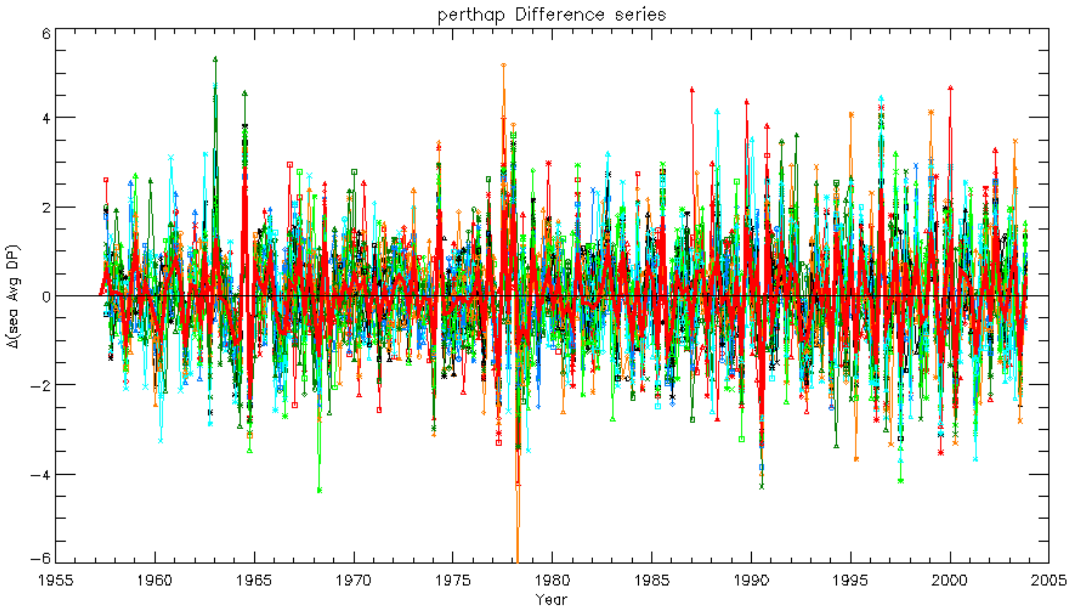


Fig. 10 *Difference series for all potential reference stations at Perth AP. The thick red line is the consensus reference series for this case.*

Table 1 *Sample of the statistics used in the station selection procedure for Perth AP. Shown are the station ID and name, the distance (km) from Perth AP, the number of points and correlations with the candidate series for the difference series and the raw time series and the two scores described in the text. Stations chosen for the final solution are highlighted in bold; italics indicate stations that are part of the 'base set'.*

Station ID	Station Name	Distance	Diff		Raw TS		score	Score 2
			N	corr	N	corr		
9034	**perthro**	**11**	**139**	**0.830**	**140**	**0.791**	**91.34**	**0.6572**
9172	**jandakotaero**	**21**	**51**	**0.926**	**53**	**0.863**	**40.77**	**0.7993**
9053	*pearceraaf*	*29*	*154*	*0.765*	*156*	*0.574*	*67.62*	*0.4391*
9194	*medinarescent*	*36*	*80*	*0.856*	*81*	*0.604*	*41.34*	*0.5168*
9038	*rottnestislandlh*	*46*	*102*	*0.789*	*104*	*0.720*	*58.01*	*0.5687*
9111	*karnet*	*58*	*132*	*0.690*	*141*	*0.581*	*52.90*	*0.4008*
9131	jurienbay	201	124	0.690	130	0.494	42.28	0.3409
9538	**dwellingup**	**87**	**186**	**0.753**	**187**	**0.688**	**96.35**	**0.5180**
9514	bunburypo	159	31	0.579	43	0.569	10.21	0.3295
9534	**donnybrook**	**183**	**140**	**0.700**	**143**	**0.577**	**56.53**	**0.4038**
9842	jarrahwood	210	104	0.618	107	0.582	37.41	0.3597
9510	bridgetown1	226	162	0.504	167	0.128	10.45	0.0645
9573	manjimup	259	180	0.664	183	0.499	59.65	0.3314
9592	pemberton	280	184	0.541	186	0.410	40.76	0.2215
9518	capeleeuwin	283	143	0.584	152	0.614	51.32	0.3589
8137	*wonganhills*	*135*	*142*	*0.748*	*145*	*0.618*	*65.57*	*0.4618*
8138	wonganhillsresstn	140	112	0.600	116	0.307	20.63	0.1842
10579	katanning1	245	174	0.579	179	0.401	40.44	0.2324
10592	**lakegrace1**	**267**	**142**	**0.722**	**145**	**0.637**	**65.34**	**0.4601**
10568	hyden	281	112	0.649	119	0.443	32.15	0.2871
8039	dalwallinu1	195	153	0.656	162	0.311	31.21	0.2040
8225	eneabba	244	120	0.665	122	0.451	36.02	0.3001
8025	carnamah	249	105	0.567	115	0.420	25.00	0.2381
8093	morawa	302	108	0.600	118	0.456	29.54	0.2736
8051	*geraldton*	*369*	*186*	*0.706*	*187*	*0.670*	*87.99*	*0.4730*
8095	mullewa	380	116	0.602	121	0.294	20.56	0.1772
10111	northam	73	87	0.621	101	0.482	26.05	0.2994
10144	*yorkpo*	*74*	*109*	*0.700*	*119*	*0.694*	*52.99*	*0.4861*
10058	goomalling	107	70	0.696	78	0.630	30.70	0.4386
10035	*cunderdin1*	*124*	*154*	*0.718*	*163*	*0.497*	*54.95*	*0.3568*
10073	kellerberrin	169	152	0.571	164	0.233	20.22	0.1330
10093	merredinresstn	218	88	0.629	96	0.659	36.48	0.4145
10092	merredin	224	122	0.617	132	0.512	38.49	0.3155
10515	**beverley**	**92**	**102**	**0.776**	**110**	**0.643**	**50.96**	**0.4996**
10524	brookton	109	105	0.663	115	0.604	42.04	0.4004
10648	**wanderingcomp**	**106**	**168**	**0.794**	**171**	**0.653**	**87.09**	**0.5184**
10626	*pingelly*	*124*	*119*	*0.740*	*123*	*0.607*	*53.43*	*0.4490*
10614	*narrogin*	*159*	*104*	*0.798*	*112*	*0.727*	*60.33*	*0.5801*
10536	*corrigin*	*184*	*179*	*0.732*	*183*	*0.579*	*75.89*	*0.4240*
10647	wagin	200	105	0.610	113	0.515	32.99	0.3142
9519	capenaturaliste	200	172	0.527	175	0.298	27.04	0.1572
12074	southerncross	326	172	0.519	178	0.441	39.32	0.2286

7. A homogeneous reference series is computed by integrating the consensus difference series backwards in time (i.e. start at the most recent value). The required initial value needed for the integration is obtained by assuming that the most recent observations of the candidate series are unbiased and otherwise correct. This is generally not true and is addressed later in step 10.

8. Once the reference series is computed, it is used to produce the 'candidate minus reference' series. This time series is the main source of input for identifying discontinuities in the data. This is done using the procedure and test statistic described

by EP95. In this methodology, the longer time series is broken into smaller sub-series by systematically removing a single point from the series and comparing the total sum of squares from two regressions on the split series with the sum of squares from a regression on the whole series. For the procedure here, the split regressions have the slope set to zero, as this better represents the ‘step function’-type discontinuities that are expected in this data set. This ratio of sum of squares is converted into score, and an F-test (e.g. Panofsky and Brier 1968) is performed. The significance level for keeping a potential discontinuity (called ‘plev’ here) is variable, but is generally set at 0.03. This value was chosen as it identifies a reasonable number of realistic discontinuities, without issuing too many false alarms. The significance of individual discontinuities is tested using t-tests and the Wilcoxon rank-sum test (e.g. Panofsky and Brier 1968). These tests are done for the 16 points (4 years) on either side of the discontinuity (or however many are available). A further restriction is applied that discontinuities must be at least 2 years (8 points) apart.

9. The information gathered in steps 6 through 8 is used simultaneously to evaluate the solutions and determine the best mix of stations. Determining of the ‘best’ solution is somewhat subjective. In general, the evaluation is made by plotting the consensus reference series and the component series, and doing a visual comparison. By carefully considering all the available information, overly influential points and problem stations can be identified. This is used to refine the list of stations, allowing many different combinations to be tried.

   The iterative procedure is briefly illustrated below. As a first step, all stations are used in the analysis. Being a major metropolitan area, Perth has 55 available reference stations, a relatively high number. Table 1 summarizes this station’s data. Seven stations (9034, 9053, 9538, 8137, 10592, 8051, 10648) meet all the criteria noted in point 5. Seven more meet the correlation criteria (9172, 9194, 9038, 10144, 10515, 10614, 10626), but are a bit short on the length. Four others (9111, 9534, 10035, 10536) are ‘close’, falling just a bit short on the correlation criteria. Call these 18 stations the ‘base set’, as these are (apparently) the highest quality reference stations available for Perth AP. They certainly make a good starting point for further refinement and illustrate the issues to be addressed

   Figure 11 shows the seasonal dewpoint anomaly time series for the base set. In general, a good correspondence between the reference and candidate stations is seen. This is not unexpected, as these stations were selected for their high correlations. Despite the automated quality control applied (step 3), some stations demonstrate different behaviour for periods of time. A few examples: Pingelly (10626; dark blue squares) shows strongly positive dewpoints in 1986, where every other station is negative; Cunderdin1[5] (10035; orange triangles) shows many occasions where the series deviates from the more typical behaviour. Other examples abound. Considering the frequency and severity of such points is one factor in deciding on the final station set.

5 The ‘1’ on the name indicates a station which had more than one location. This is the first occurrence of the station, before the installation of the AWS.

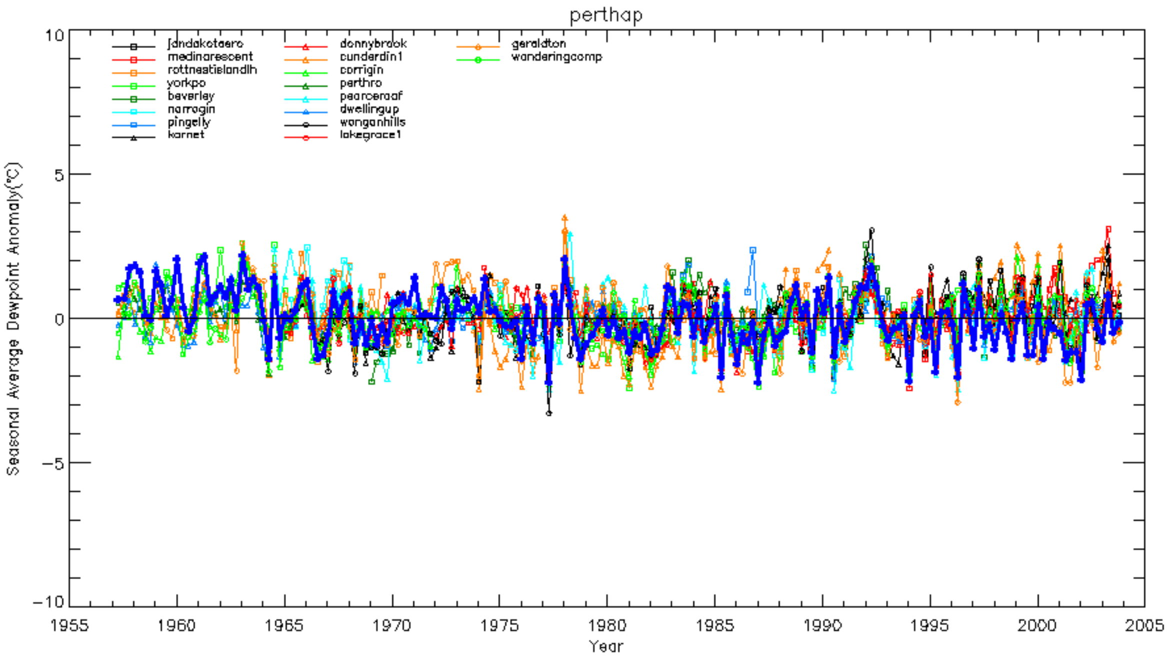


Fig. 11 *Seasonal dewpoint anomaly time series at Perth AP (thick blue line) and the 18 'base set' stations (thin lines and legend).*

Figure 12 shows the 'candidate minus reference' time series for the 'base set' solution. It is close to the 'all stations' solution (not shown). The positive values at the start of the series and slight negative at the end suggests that the negative trend in the raw dewpoint series (Fig. 7) is a result of inhomogeneities in the data; compared to the composite reference series the early dewpoints are too high and later dewpoints too low. Three significant breakpoints are identified, in MAM 1963, JJA 1972 and DJF 1997. The latter breakpoint coincides with a change in the station location and the beginning of the AWS epoch (see Appendix A and later discussion). These are significant using both the t-test and the non-parametric statistical tests. By comparing these series among the various stations sets, the influence of individual stations can be estimated. This helps in the final reference station selection.

Data quality is not the only issue to consider when choosing stations. Ensuring as even a distribution as possible through time is also important. Figure 13 shows the times when valid observations are available at the 'base set' of stations. This pattern is typical. Even at a station with a large number of stations to draw from, getting enough quality stations early in the record (say, in the 1960s) can be difficult. Also problematic is a frequent gap in observations in the early-1970s (i.e. the 70s Gap described earlier). At a large number of reference stations (and some candidate stations, too!), the dewpoint observations are missing or sporadic. For whatever reason, these records have simply not been included in the electronic archive. This problem is seen at nine of the fifteen 'base set' stations open during this time at Perth. It is widespread throughout the country. No region is immune.

Also a factor in final station selection is the distance of a reference station from the candidate station. Closer is generally better, as these stations should more closely follow the behaviour of the dewpoint at the candidate station. A distant station in a group of otherwise close stations will only have a small influence due to the weighting. This can be a positive, allowing less similar stations only to have strong influence where stations are otherwise missing.

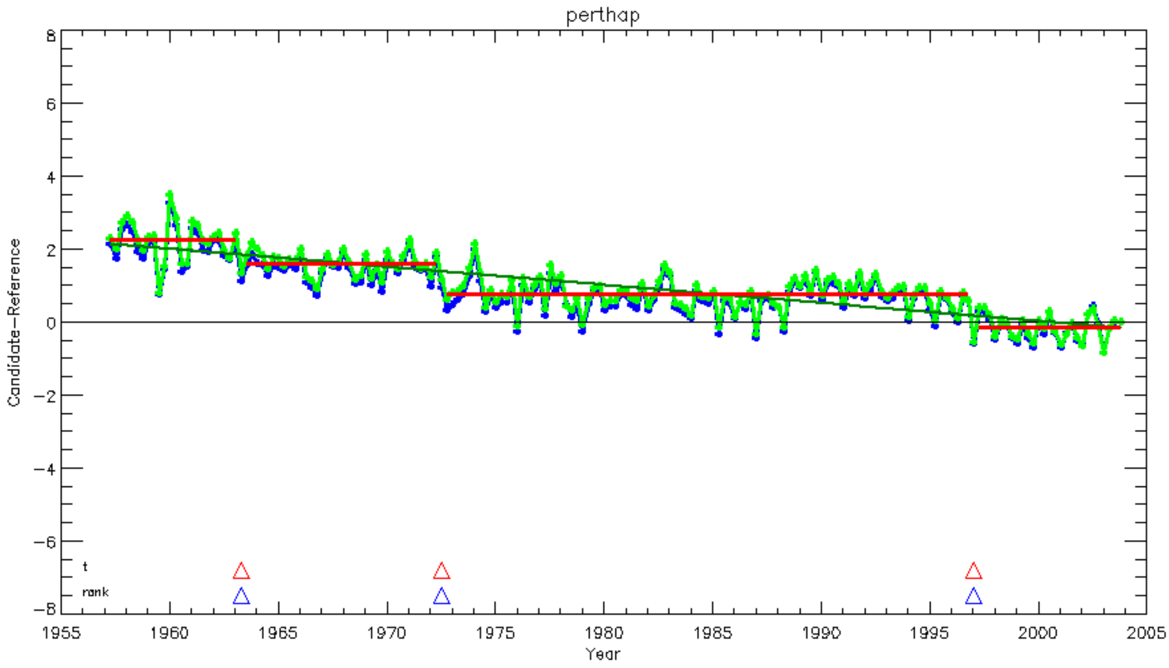


Fig. 12 *'Candidate minus reference' series for the 'base set' solution. Green line is the 'weighted' solution, blue line is the 'unweighted' solution (very close in this case). Red lines are the sub-series where the dewpoint is homogeneous. Breakpoints are noted at the bottom of the chart, with the results of the two significance tests. Red symbols are the t-test; blue are the non-parametric rank sum tests. Triangles indicate significance, crosses show non-significance and circles mean there is not enough data to perform the non-parametric test.*

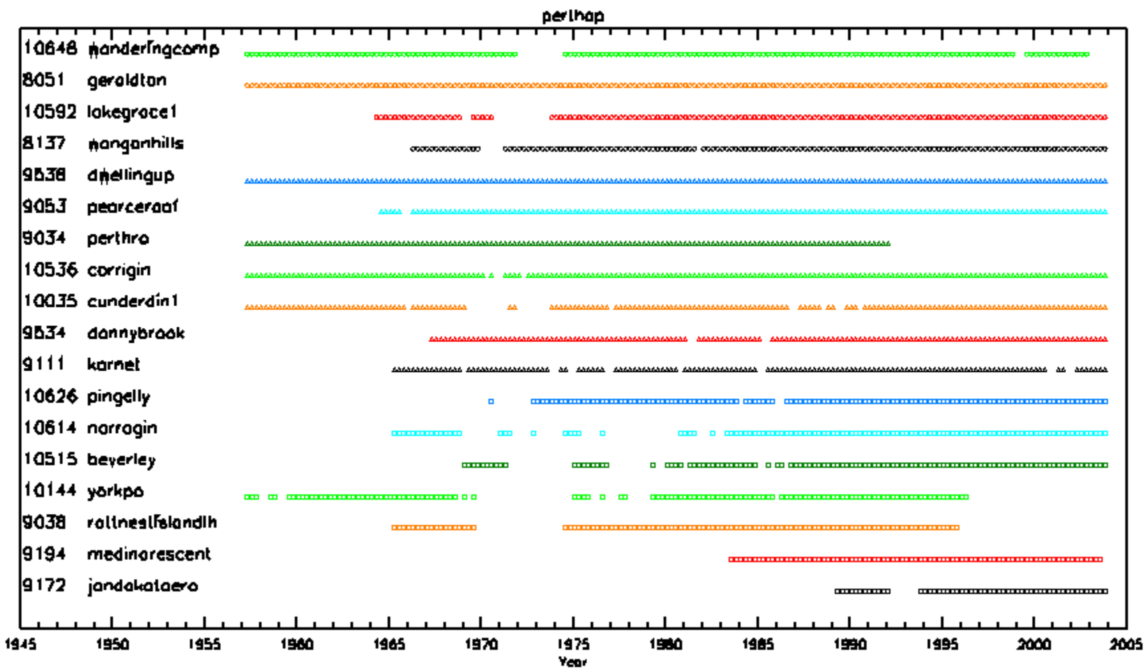
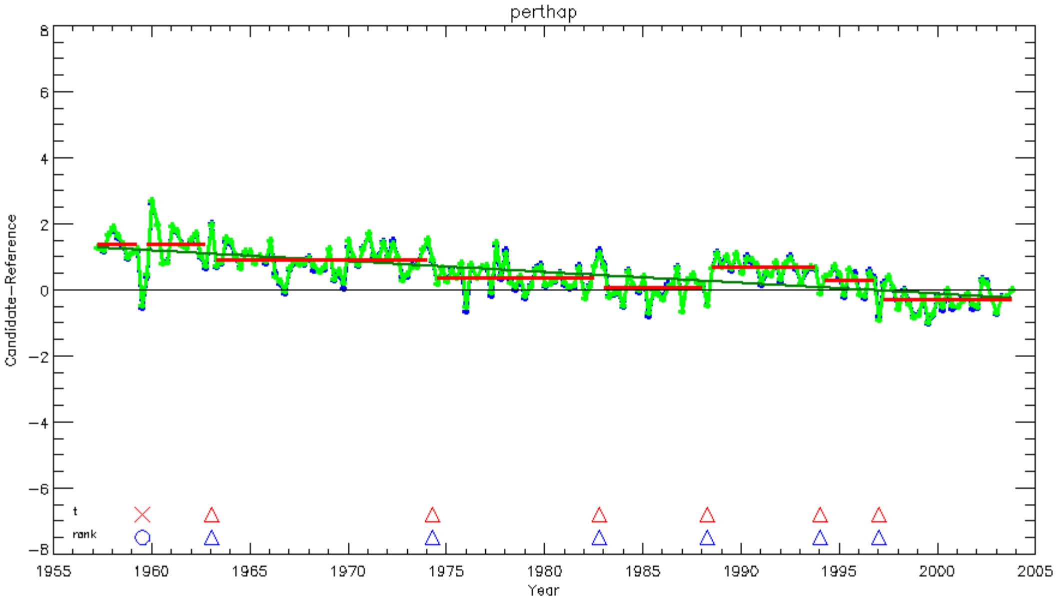


Fig. 13 *Availability of valid observations at the 'base set' stations as a function of time.*

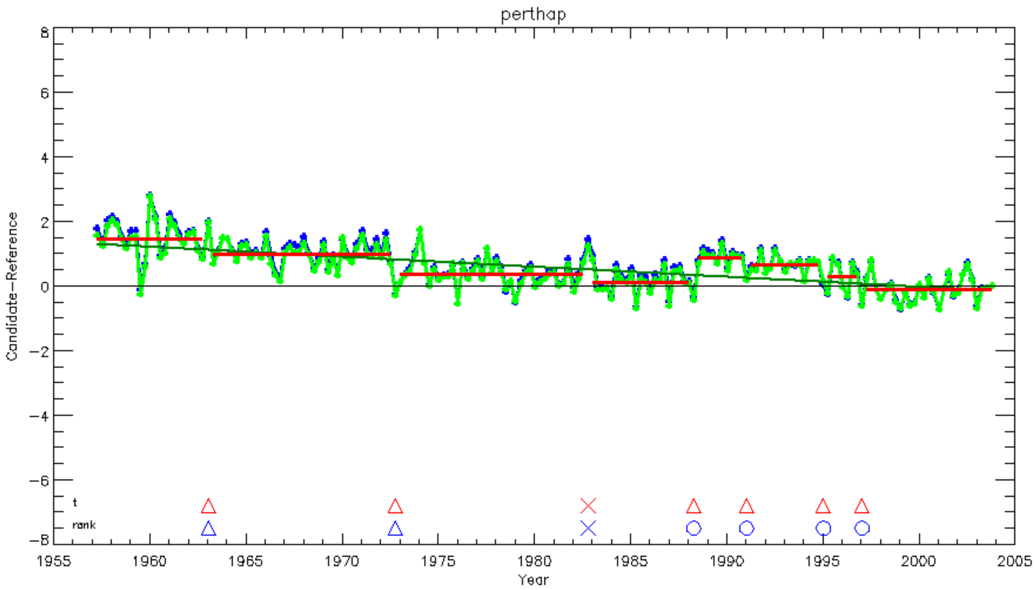
From this point, the process simply becomes of trial and error. In the example here at Perth, we must eliminate stations until we find the desired number that produces a reliable solution. In this case, a starting point involves eliminating the stations that have obviously inconsistent behaviour. Diagrams fashioned after Fig. 11 are useful here, to identify these stations. For example, the stations noted above are readily eliminated. Eventually through this process of trial and error, two possible (and similar) sets are chosen. Set 1 is (9034, 10648, 9538, 10515, 10592, 8137, 10536) and Set 2 is (9034, 9172, 9538, 9534, 10648, 10515, 10592). Each set has seven stations, five of which are common between the two.

The ‘candidate minus reference’ series for the two sets are depicted in Fig. 14. The seasonal dewpoint anomaly plots for the two sets are shown in Fig. 15. Overall, the two possibilities give very similar results, and neither is radically different from the ‘base set’ solution in Fig. 12. There are more breakpoints in these solutions and the negative trend, while still present, is not as strong.

While the solutions of the two sets are generally the same, subtle (and not so subtle!) differences are present. An equal number of breakpoints are present, but they are indicated at different times. Set 1 has a non-significant change in 1959; set 2 has a change suggested in 1991. The SON82 breakpoint is present in both sites, but is not-significant in set 2, due to a smaller magnitude of the change. The post-1997 period has a more negative mean in set 1. In the 1990s, the series appears to be a bit noisier in set 2. Looking at seasonal anomaly time series (Fig. 15) indicates that this variance is due to Corrigin (10536). In late 1972, the negative excursion in set 2 is much greater than in set 1, due to the behaviour at Wongan Hills (8137). This highlights the pitfalls of the ‘70s Gap’. A bad point at a far away station has undue influence because of the shortfall of good data during this period.

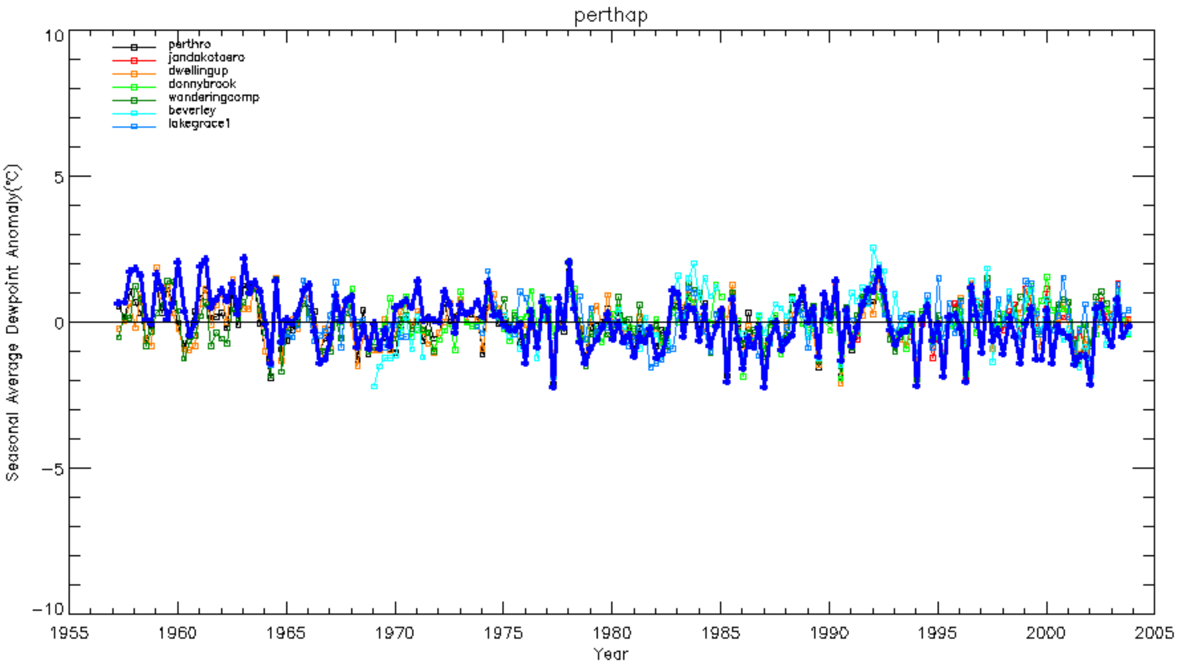


set 1

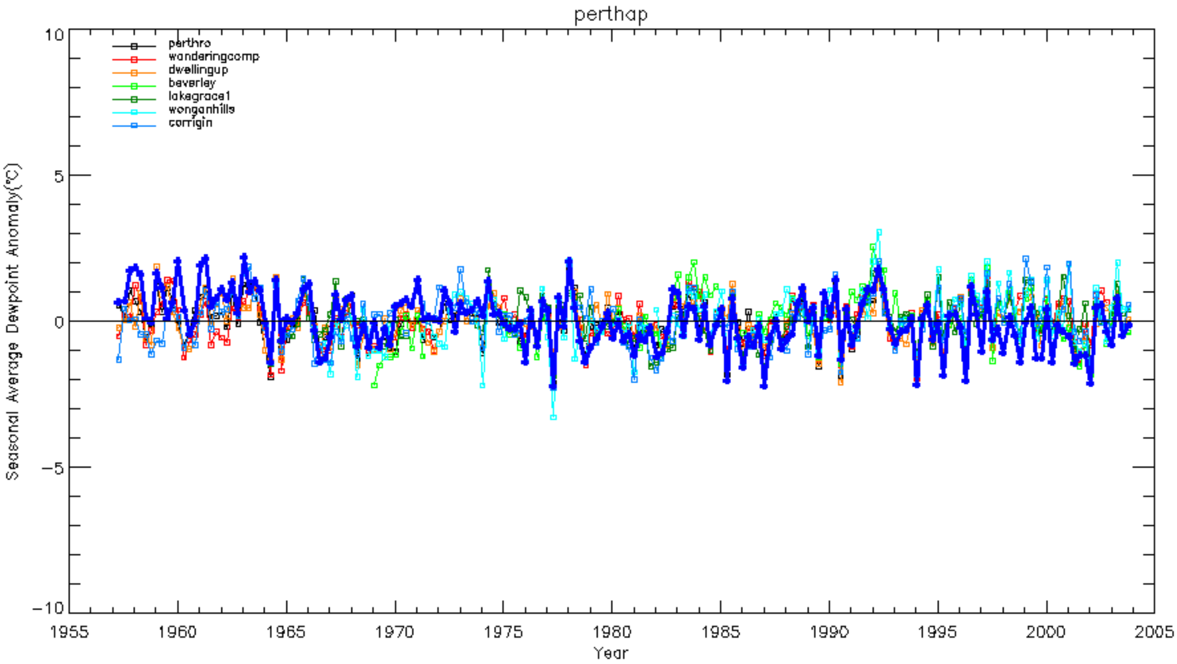


set 2

Fig. 14 *'Candidate minus reference' series for A.) Set 1 and B.) Set 2.*



Set 1



Set 2

Fig. 15 *Seasonal dewpoint anomalies for A.) Set 1 and B.) Set 2.*

In the end, Set 1 is selected as the solution. The smoother data in the 1990s is an important difference, a result of removing 10536 from the set. The more negative series from the late-1990s is also a factor. Careful examination of Fig. 12 shows that the candidate station is among the lowest when looking at the distribution of the anomalies in the 'base set', suggesting that there may be a negative bias. This is consistent with the results in Lucas (2006); a high fraction of the reference stations have mercury thermometers as their humidity instrument. These instruments consistently produce higher dewpoint readings over long time scales. The timing of the breakpoints is also more consistent with the station history, lining up with events known to cause disruptions in climate records. Although this is important, most breakpoints identified at the different stations have no obvious cause in the meta-data.

The makeup of the station set (Fig. 16) is another factor. Set 1 has fewer stations early in the record -- only three available stations before 1964 -- but more generally 5 or 6 reference stations are available. Set 2 has better coverage early in the record, with 4 stations, but as noted above two of the stations (10536 and 8137) are problematic at times. Set 1 replaces these stations with 9172 (Jandakot Aero), a nearby station which continues the record from 9034 (Perth Regional Office), which closed in 1992. Both of these stations have very high correlations with the candidate station record (Table 1). Donnybrook (9534) is the other replacement, a few not-too-serious problems early, but very good after 1970 or so.

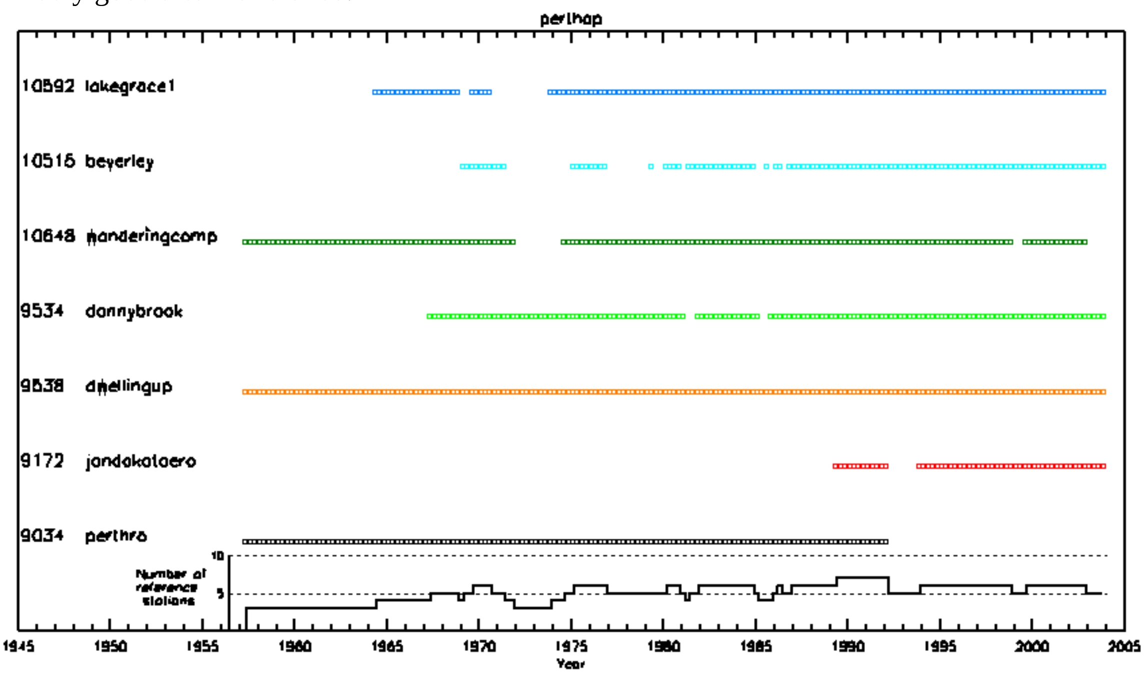


Fig. 16 *Times of valid observations in Set 1, the final set for Perth AP). A time series of the number of available stations is depicted along the bottom.*

10. After selecting the final solution set, it is necessary to calibrate the time series. As noted in step 7, the candidate series and reference series generally do not match up at the end. In many cases, the results suggest that the candidate station is biased low. Along with unavoidable noise in the time series, a likely cause of this consistent low bias is the mischaracterization of the psychrometric coefficient in AWSs equipped with platinum resistance thermometers. A result of this error is that in low-humidity conditions, the dewpoints measured by the AWS will consistently read lower than those measured with the Hg thermometers. In drier climates, this results in a long-term bias[6]. It is also more apparent at candidate stations where the reference series is primarily derived from reference stations using mercury thermometers. For more details, see Lucas (2006).

    To calibrate the series, the weighted-mean seasonal anomaly in the last season of the record (SON03) of the reference stations is set as the bias. This estimated bias amount is set as the initial offset in the final calculation of the homogeneous reference series as mentioned in step 7. Note that this is equivalent to assuming that the reference series

[6] It should be noted that there exists no consensus on which dewpoint reading is the 'most correct'.

has the correct value. The amount of this so-called ‘Last Season Bias Adjustment’ typically has a magnitude of less than 0.5 degrees. However, a few stations in the dry interior of the continent have adjustments of up to 3.6 degrees (Longreach; see Appendix A).

11. The season, year and strength of the final discontinuities are tabulated. Table 2 shows the breakpoints for Perth AP. The table shows the season where the breakpoint was detected, the strength of the shift and any comments required. Generally, only breakpoints significant at the 95% level are kept, although some with slightly lower significance levels are retained to maintain the continuity of the record. These cases are noted in the comments section of the table presented in the appendix. Also, the station history files are examined to determine if a possible cause can be identified in the metadata. Breakpoints that occur within a year of a significant change in the station history are associated with that change. In the majority of cases no apparent cause can be identified.

Table 2 *Identified breakpoints at Perth AP. Shown are the season and year of occurrence, the strength of the breakpoint and the cause as identified in the metadata. Only two of the 6 breakpoints have a readily identifiable cause in the metadata. The remainder are ‘undocumented’.*

Season/Year	Strength	Cause
DJF97	-0.7	site move; AWS epoch
DJF94	-0.3	
MAM88	+0.7	site move
SON82	-0.3	
MAM74	-0.6	
DJF63	-0.5	

12. In the final step, the adjustments are made to the seasonal time series of the candidate station. The first step is to compute the initial offset, the difference from zero between the last breakpoint and the end of the series in SON03. This gives the value of the difference being currently experienced between the composite reference series and the candidate station. To adjust the series, the strength of the breakpoint is added to the complete sub-daily time series for all times at and before the season of the breakpoint. Figure 17 shows a ‘before and after’ comparison of the monthly median dewpoints for Perth.

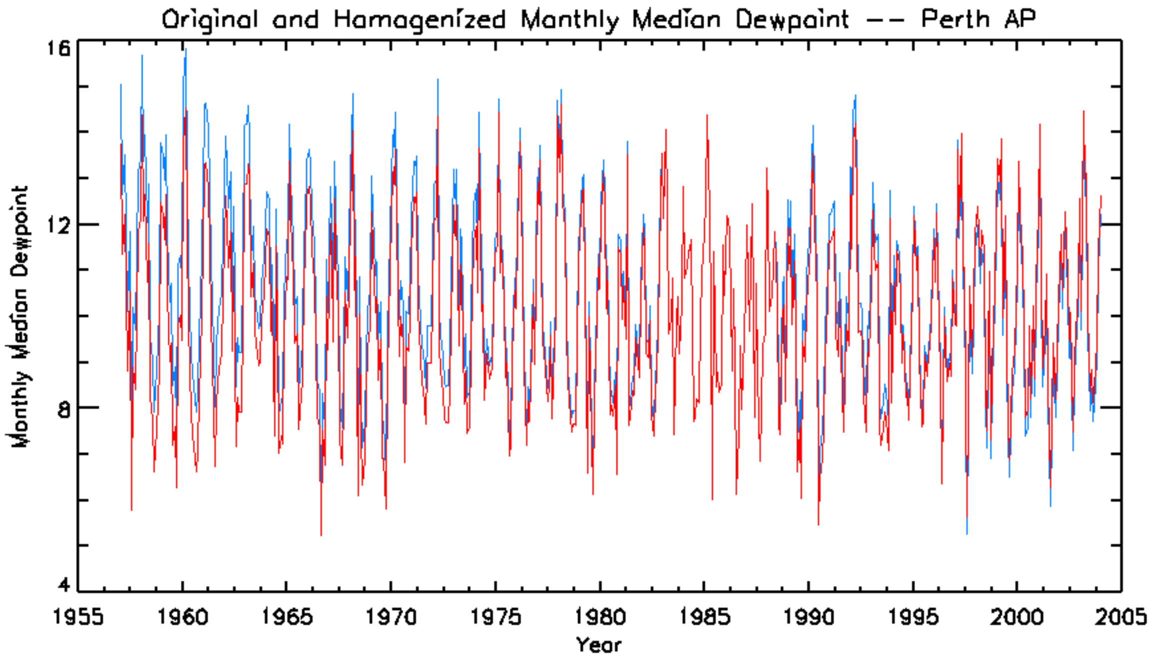


Fig. 17 *Comparison of original (blue) and homogenized (red) monthly median dewpoints at Perth AP.*

6 RESULTS

The homogenization procedure was applied to all 58 candidate stations noted earlier. The details of the outcome for each candidate station, including the graphs and tables described in the previous section, are shown in Appendix A. This section of the document will focus on the 'bigger-picture' generalities of the dataset, including a presentation of the generalized results of the homogenization procedure and a discussion of the validity of the results.

6.1 General comments on homogenization

Unsurprisingly, no candidate station was found to be initially homogeneous. Between 2 and 9 significant breakpoints (or discontinuities) are observed at all the stations. The distribution (Fig. 18) is bimodal; the largest peak is at 5, with a second peak at 8. Over half the stations have 4, 5 or 6 breakpoints. Summing over all stations, 322 breakpoints are observed. The left panel of Fig. 19 shows the absolute value of these changes. The largest peak in the magnitude is between 0.3 and 0.5 degrees, with a significant number of breakpoints having strengths out to 1.5 ^{o}C. A smaller number of breakpoints are as large as 2.5 degrees. The right panel of Fig. 19 shows that there are more negative changes (i.e. dewpoint lower after the breakpoint) than positive. While there are comparatively more negative breakpoints, the deviations in excess of 1^{o}C are more frequent on the positive side.

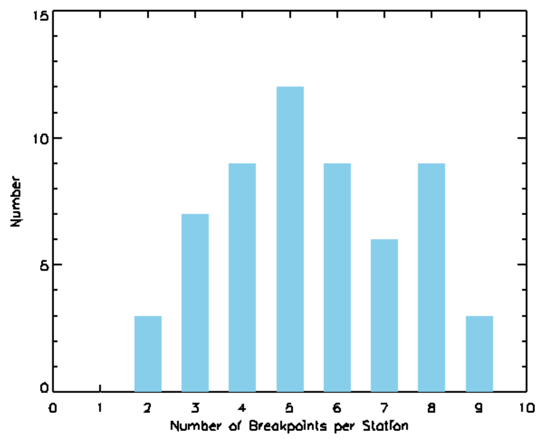


__Fig. 18__ Histogram of the number of breakpoints identified per station.

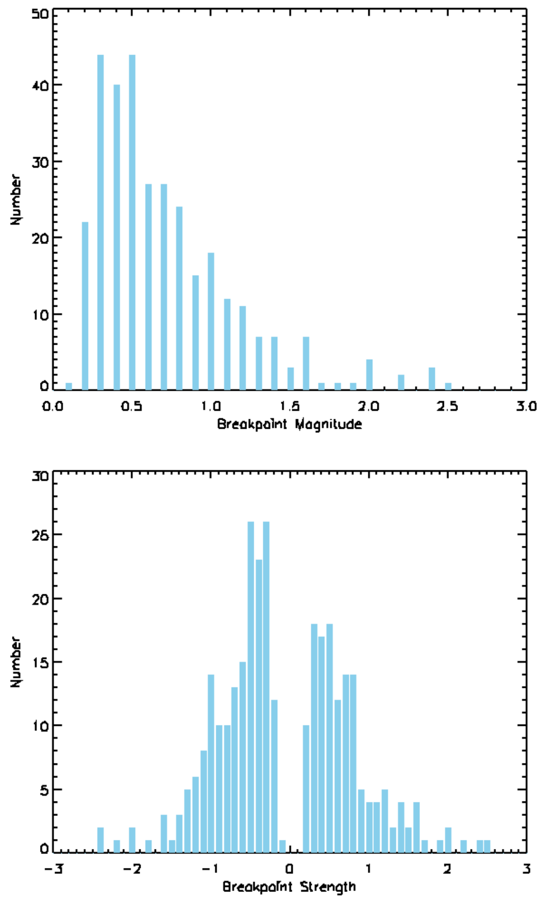


__Fig. 19__ Histogram of breakpoint magnitude (top) and strength.

The annual timing of the breakpoints is shown in Fig. 20. The breakpoint identification methodology dictates that there can be no breakpoints in 1957, 1958, 2003 and the last 3 seasons of 2002 and this is seen in the figure. Generally, there are two broad peaks in the observed series, one in the late-1960s/early-1970s and the other starting in the 1990s.

How meaningful are these peaks? Beyond the limitations noted above, there should be no preference for breakpoint timing; they should be evenly distributed in time. This null hypothesis is examined using a simple χ^2 test (Panofsky and Brier 1968) to examine whether the observed distribution is significantly different from this expectation. To overcome technical limitations of the test, the data are grouped into five-year bins (1960-64, 1964-69, etc.) with the start (1957-59) and end (2000-03) periods placed in their own bins. The theoretical and observed distributions are shown in Table 3, along with the results of the test.

The results clearly indicate that the null hypothesis should be rejected. The observed distribution is not even; the occurrence of the breakpoints is not fully random. Prior to 1974, the breakpoints occur at about the expected rate given the total number observed. The values after 1990 are much higher than expected, while the period from 1975-1990 has breakpoints occurring at a lower-than-expected rate. The numbers of breakpoints during both of these periods are considerably higher than the middle period. One possibility for the pre-1975 period is that this is associated with the '70s Gap' found in many of the candidate and reference stations, although this is not certain. The dropout of reference stations and gaps in the candidate station time series suggests that reliability of the created reference series during this period may not be as high and could result in the spurious detection of breakpoints.

The post-1990 period in particular stands out. This peak is a result of the change of instrumentation associated with the installation of the AWSs. Instruments widely changed from the traditional Hg-thermometers to platinum resistance thermometers which have a different response characteristic, as described in Lucas (2006). The installation of the AWS system represents a major change in the observing system across Australia, with a large impact on the homogeneity of the data. This is the source of the peak in 1996. These changes and other 'metadata' changes are discussed further in the next section. The source of the post-2000 peak is less clear, although some speculation will be presented below.

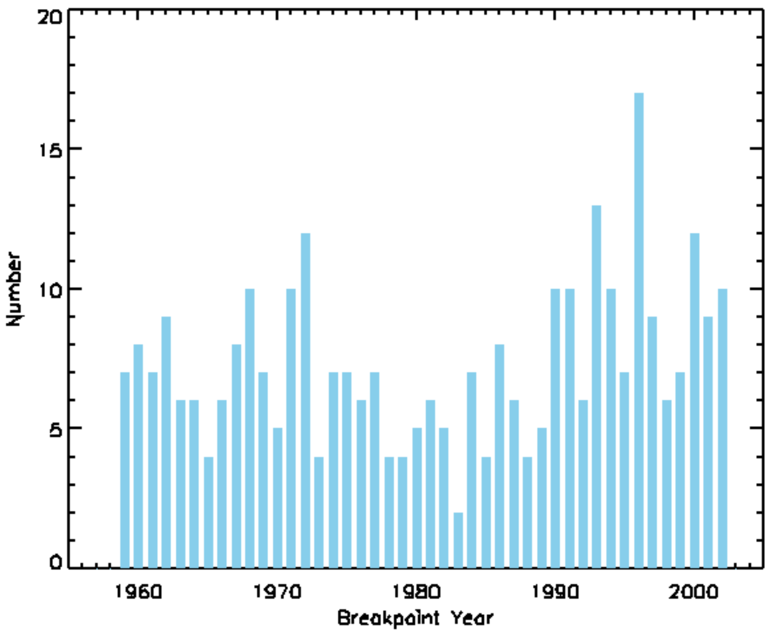


Fig. 20 *Occurrence of breakpoints by year.*

Table 3 *Expected and observed frequencies of breakpoint occurrence by year group into five-year periods. Results from the χ^2 test are also shown.*

	1957-9	1960-4	1965-9	1970-4	1975-9	1980-4	1985-9	1990-4	1995-9	2000-3
Observed	7	36	35	38	28	25	27	49	46	31
Expected	7.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	16.8

χ^2 = 27.2, p-value = 0.001

Figure 21 shows the occurrence of breakpoints by season. In that figure, a peak in the number of breakpoints is observed in the summer (DJF) months, with the lowest number observed in autumn (MAM). Winter (JJA) and spring (SON) show about equal numbers of breakpoints. A χ^2 test similar to that above is applied to examine the null hypothesis of no seasonal preference in breakpoint timing (i.e. a flat distribution). The resulting χ^2 score is 13.9, with a p-value of 0.003, indicating the null hypothesis should be rejected. The number of breakpoints in DJF is significantly higher than expected and autumn has fewer than expected. A closer examination of the timing of the seasonal breakpoints (not shown) does indicate a weak preference for breakpoints to occur in summer, but this number is 'enhanced' by a large peak in DJF02, the last season breakpoints can occur in this methodology. There are 10 breakpoints in this season, more than are found in any of the other 173 possible seasons. Further, some of the strongest negative breakpoints observed occur during this season, with two in excess of 2^{o}C, although overall there are 6 negative and 4 positive. The reason for this concentration of breakpoints is unclear. One possibility is that there is an 'endpoint' effect, caused by the truncation of the data (DeGaetano (2006)). The year 2002 was one of widespread drought and negative dewpoint anomalies (cf. Fig 32) across the country. These conditions, in conjunction with the shortened sample after the breakpoint (only 7 seasons, usually 16), could potentially affect the statistical tests (see step 8) used in identifying the significance of breakpoints. A longer sample (i.e. extending the series further in time) could possibly moderate the low values after this season, and reduce the number of breakpoints identified in this season. The very strong negative breakpoints in the inland areas (e.g. Longreach, Birdsville and Forrest) are a result of the makeup of the reference station network and depend on the characteristics of the instrumentation used at the different stations in the network. The errors in the AWS dewpoint reading which occur as a result of the instrumentation are known to be larger when the relative humidity is low. See Lucas (2006) for a full discussion.

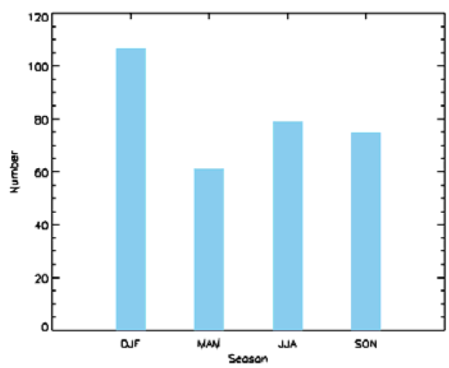


Fig. 21 *Occurrence of breakpoints by season.*

6.2 Comparison with the metadata

While this study has mainly relied on statistical methods, the use of metadata for the identification of inhomogeneities in the data represents a ‘tried and true’ methodology. As noted earlier, the indirect statistical methods should identify all breakpoints regardless of their source. However, a clear signal (overlap) should be seen in the identified breakpoints that coincide with known disruptions in the data. Apparent metadata causes of breakpoints are noted for each station in Appendix A.

The majority of breakpoints do not have an identifiable cause in the metadata. There are several possible reasons for this. First is the incompleteness of the readily available meta-data. The meticulous electronic collection of meta-data began in Australia in 1997. Paper records do exist for times before this, but much of the data has not been propagated into electronic format. That said, there are still many post-97 breakpoints identified that do not have an apparent cause. A second explanation is that the procedure for making humidity measurements is complex. There is a lot of potential for errors, which may not necessarily be random, to occur. For example, systematic differences in observer technique could result in the production of long-term biases. Such factors would often not be identified in the meta-data in any case.

There are several metadata events that are detected in the breakpoint analysis. Particularly significant is the changeover to the AWS as the main observing platform. This switch involves a change in instrumentation, and quite often a site move, up to 10+ km in some (rare) instances. Fifty-three of the 58 candidate stations have switched to an AWS. The rollout of AWSs began in the late 1980s; most (41 of 53) of the stations in this dataset had an AWS installed before 1 November 1996. Of those pre-1996 AWSs, 7 were 'stand-alone' AWSs where that package of instruments became the sole measurement device at that site upon installation. The remainder continued manual observations concurrent with the AWS observations. Internal Bureau documentation[7] indicates that these manual observations remained the primary instruments until late-1996. In effect, the AWS network was 'turned on' on 1 November 1996 at many of the candidate stations.

[7] Observations Instruction 97/5: Primary Instruments. Thanks to B. Trewin for providing this information.

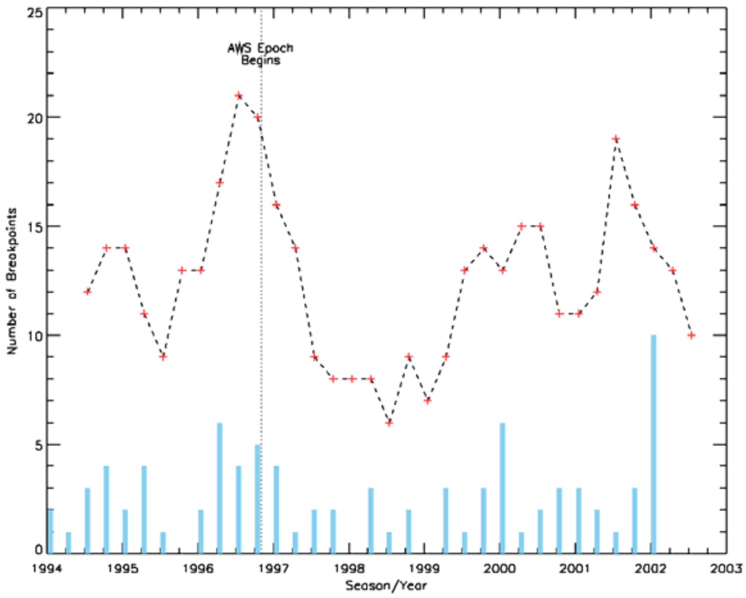


Fig. 22 *Number of breakpoints by season between 1994 and 2003 (blue bar). The dashed line represents the cumulative number of breakpoints over 5 seasons, centred on the time in question. The beginning of the AWS epoch is noted with a dashed vertical line.*

As seen in Fig. 22, the beginning of the AWS epoch is readily apparent as an increase in the number of breakpoints observed by the statistical methodology. Sixteen of the 34 pre-1996 AWS installations with manual observations have a breakpoint identified within one year of this epoch (see Appendix A). Further, 6 of the 7 'stand-alone' AWS show a similar signal at the AWS transition, as do 4 of the 12 post-1996 AWS installations. All told, approximately one-half (26 of 53) of the candidate stations with AWSs show a breakpoint at or near the time of installation. As expected from Lucas (2006), the sign of these changes are overwhelmingly negative and typically have a magnitude in excess of 0.5^{o}C. Only two stations (Alice Springs and Forrest) show a positive change; the magnitudes at both are greater than 1.0^{o}C.

Another likely source of data inhomogeneities that should appear in the metadata are site moves. Quite often these moves occur as a result of the installation of the AWS, particularly those which occur in the 1990s. In some instances, instruments are maintained at the original site for an intercomparison. These intercomparisons, where available, can be used to estimate the impact of the site move.

The stations where useful intercomparisons are available are shown in Table 4. Shown in the table are whether the site move was associated with an instrument change (i.e. AWS installation), the period of the intercomparison and the typical magnitude of the dewpoint difference between the two sites. This is estimated by computing percentile levels over the period in question using only the 0900 LT data. The differences in dewpoint values between the percentile levels are then averaged (weighted appropriately across the distribution) to produce a single value. The details of any breakpoints identified with a site move are also noted.

Hypothetically, the difference in the values of dewpoint at the two stations should be reflected in the strength of any associated breakpoint. Broadly speaking this is the case; stations where the instruments give similar readings have weaker breakpoints (e.g. Adelaide). Those with large differences often have strong breakpoints (e.g. Rabbit Flat). While this general trend holds, there are clearly cases where differences arise.

One source of uncertainty lies in the intercomparison itself. What is the correct length of time over which to perform an intercomparison? When updating the observation network, the Bureau aims for a two-year intercomparison. The values reported in the Table 4 generally occur over this time frame, but exceptions abound. Closer examination of the results clearly indicates (not shown) that the intercomparison values do not remain constant throughout the period of intercomparison. In several cases, this drift is quite large, with values diverging dramatically from those observed early in the period. As an example, at the first Bourke move, the new station consistently reports higher dewpoints than the original for the first few months. As the intercomparison period proceeds, the comparison becomes less favourable and eventually results in the new site being 0.4^{o}C drier. The same tendency is seen (to a somewhat larger degree) at Dubbo and Longreach.

This ‘drift’ likely explains (at least partially) the disparity between the occurrence (or otherwise) of a breakpoint at the time of the move and its identified strength relative to what the intercomparison suggests. The physical reason behind these changing differences is unclear; it is likely that the source lies in the instrumentation and its maintenance (or lack thereof) rather that the microclimatic details of the two sites in question.

Changes in instrumentation are a third source of inhomogeneities which should be visible in the metadata. The biggest instrumentation change in this dataset is associated with the installation of the AWS; the major effects of this change were described earlier in the document. In three instances (Forrest, Canberra and Richmond (NSW)), the humidity instrumentation after the installation of the AWS was switched from the platinum resistance thermometers initially installed to humidity probes (see Appendix A). At Canberra, these changes are clear-cut and identified in the automated breakpoint analysis. A clear breakpoint (of -0.7^{o}C) is seen in DJF96, coincident with the AWS installation. In Oct 2000, the PRT was replaced with a humidity probe and a breakpoint of (+0.5) is observed at that time.

At the other two stations, the changes are less clear in the automated analysis. At Forrest, the PRT is used for two years (during the intercomparison) and then replaced with the HP. One breakpoint is identified during that time, in DJF95. The strength of this breakpoint is +1.4^{o}C, completely at odds with the predicted intercomparison value of -0.8^{o}C. This disparity is a result of the analysis methodology and the switch to the HP. As seen in the candidate –reference plot for Forrest (see Appendix A), the station has a large drop upon installation of the PRT, consistent with the intercomparison. Two years later, when the HP is installed, the series makes a sharp jump upward. The strength of the breakpoint reflects this upward jump. In reality, there should probably be two breakpoints identified here, each associated with the instrumentation change.

At Richmond (NSW), the PRT is installed in Dec 1993 and replaced with the HP in Dec 1999. The (candidate – reference) series here (see Appendix A) shows wildly fluctuating behaviour, broadly consistent with the direction of changes noted at other stations (i.e. PRT has negative change; HP has positive change). While two breakpoints are detected, the timing of these points means they cannot be unambiguously attributed to the instrument changes.

Table 4 *Humidity intercomparisons at stations with a site move. Shown are the site, the dates of the intercomparison, the details of the move, the specifics of any breakpoint associated with the move and the results of the intercomparison.*

Site	Date of comparison	Move Details	Associated Breakpoint	Intercomparison Results
Adelaide	Feb77-Feb79	Site move (~4 km). Joined in Feb 1977	No BP	Original site is ~0.3°C higher. This offset is entirely accounted for by the 'bogus pressure' error.
Albany	Apr65-Jul65	Site move (~11 km inland). Joined in June 1965.	SON66, -1.0°C	Comparison not very useful, few points. A qualitative examination of albany2 suggests that the data are too high during 1965-6, and this is reflected in the delay of the BP by one year.
Bourke	Nov94-Jun96	1st site move, (~6 km). Joined in Jan 1995.	No BP	Original site is 0.4°C higher. There is a bogus pressure issue here, but it only accounts for about 0.1°C of the difference.
Bourke	Dec98-Jan99	2nd site move + AWS install (HP). Joined in Jan 1999.	No BP	Original site is 1.8°C higher during short intercomparison (9/15). A bit less using only 0900 data (~50 points)
Brisbane AP	Apr94-Feb00	Site move (3.8 km) (both have AWS). Joined in Jan 1996.	No BP	New site is higher by 0.3C, a result of bogus pressure
Cobar	Jun62-Oct65	Site move (1.7 km). Join in Jan 1963.	DJF64, -0.6°C	Original site is 1.2°C higher
Dubbo	Feb93-Dec99	Site move (~4 km)+ AWS install (HP). Join in Feb 1993.	MAM93, -0.8°C	Original site is 0.3 C higher.
Forrest	Mar93-Feb95	Site move (~1 km) + AWS install (PRT). Join in Apr 1993.	DJF95, +1.4°C	Original site is 0.8 C higher.
Katanning	Jan99-Mar01	Site move (~5 km) + AWS install (HP). Join in Feb 1999.	MAM99, -0.4°C	Original site is 0.9°C higher
Longreach	Dec67-Mar70	Site move (~3 km). Join in Jan 1968.	No BP	Original site is 0.6°C higher
Miles	Nov97-Jul99	Site move (~500 m) + AWS install (PRT). Join in Nov 1997.	JJA98, -1.1°C	Original site is 0.8°C higher
Moree	Apr64-Nov64	1st site move (~1km). Join in Apr 1964.	DJF64, -0.9°C	Original site is 0.5°C higher
Moree	Jun95-Aug98	2nd site move (~2 km) + AWS install (PRT). Join in Jun 1995.	MAM96, -0.3°C	First site is 0.4°C higher

Normanton	Jun01-Jul01	Site move + AWS install (HP). Join in June 2001.	JJA00, -1.6^{o}C	Original site is 2.3^{o}C higher.
Rabbit Flat	Nov96-Nov98	Site move + AWS install (PRT). Join in Dec 1996.	MAM96, -1.6^{o}C	Original site is 2.5^{o}C higher.
Richmond NSW	Jun94-Oct94	Site move + AWS install (HP). Join in Dec 1993.	SON94, -1.2^{o}C	Original site is 0.3^{o}C higher .
Tennant Creek	Jul69-Jul70	Site move (~2 km). Join in Aug 1969.	No BP	Intercomparison poor
Weipa	Nov92-Feb94	Site move (~7 km) + AWS install (PRT). Join in Dec 1992.	SON92, -0.5^{o}C	Original site is 0.5^{o}C higher.

6.3 Comments on the methodology

The consistent identification of inhomogeneities associated with factors known to cause disruptions, without the explicit use of the metadata, provides confidence that the methodology used is robust and adequate to complete the task at hand. Inhomogeneities associated with site moves, the installation of the AWS and other instrumentation changes are all detected. Despite this, most of the detected breakpoints have no identifiable cause in the metadata (see Appendix A for full details) – the basic routine is designed to detect such undocumented breakpoints. Both the composition of the (presumably) homogenized reference series and the statistical technique to identify breakpoints are considered here.

The assumption made here is that the created reference series are homogeneous and that a shift in the ‘candidate – reference’ series reflects a change in the candidate series. This is a difficult assumption to either refute or verify in terms of any specific breakpoint. Menne and Williams (2005) suggest that reference series formulated by averaging first-difference component series are susceptible to random walks, particularly when the make up of those series is variable in time. These random walks potentially introduce inhomogeneities in the reference series that, if large enough, could create artificial breakpoints in the candidate series. The homogenization exercise here utilizes this methodology, and the makeup of the references series are highly variable in time, with missing data and a changing composition. Indeed, the ‘random walk’ issue noted in Menne and Williams (2005) was observed during the creation of the reference series used here. However, the human oversight and iterative nature of the reference series creation process used here should minimize the occurrence of this. As noted, it was seen on occasion, and in those examples a different selection of reference stations would be chosen to avoid the problem. At one station – Cabramurra – this phenomenon is obvious as a result of the lack of viable reference stations. The associated breakpoint, in the early 1960s, was subsequently ignored in the analysis. In general, this ‘random walk’ phenomenon associated with deficiencies in the reference station data could be responsible for the small increase in breakpoints noted during the ‘70s Gap’, a period with widespread missing observations.

Tests using Monte-Carlo procedures have shown that the two-phase approach used here also has a tendency to produce ‘false alarms’ near both ends of the series (DeGaetano (2006)). The possibility that the peak in breakpoint occurrence in the last three years (see Table 3) and particularly during DJF02 (the last year breakpoints can be detected) is an artefact of the methodology used here cannot be ruled out. An alternate explanation is that this is a real effect caused by known deficiencies in the instrumentation (Lucas 2006). Results shown in the next section (cf. Fig. 32) indicate that 2002-03 was the first widespread dry period after the beginning of the AWS epoch. It would be expected that many of the AWS stations would read low in comparison to the reference station network, often comprised of Hg thermometer reading. As noted earlier, the breakpoints may only reflect a temporary low bias which subsequently returned to a more favourable condition after the dry episode passed. Further studies with extended time series are needed to answer this question authoritatively.

Another potential shortcoming of the methodology is the leeway found in assigning the timing of the breakpoint. This is apparent at both the beginning of the AWS epoch and in looking at the site moves. The actual breakpoint is often not coincident with the known date of the move, but instead occurs within 2-3 seasons. The original EP95 paper also noted a similar tendency, where known discontinuities were detected using the algorithm within a few seasons of their reported time in the metadata. In this study, we have kept the breakpoints at the times identified by the automated technique, rather than using the timing of those known by the metadata. Looking carefully at the results, the breakpoints are often identified with a 'spike' in the (candidate-reference) series, where the two differ for only one season. This generally is not coincident with the change in the metadata are represents an effect that masks the true timing of the breakpoint. This response to spikes also results in the production of spurious breakpoints. In many cases, these false breakpoints show no statistically significant change in dewpoint and are hence rejected from further consideration.

6.4 Validity of the results

There are several steps that can be used to assess the validity of the results. The first (and most powerful?) step is to re-run the homogenization procedure described above on the homogenized series. If many significant breakpoints remain, then the homogenization can only be considered partially successful

For all 58 stations, the first-cut homogenized data was run through the homogenization procedure described above. The same reference stations were used in the second run. Of the 58 stations, 16 were found to contain significant breakpoints that were in need of further examination. Of those 16, three stations were completely re-examined, with a new arrangement of reference stations decided. These three stations (Broome, Camooweal and Meekatharra) are remote stations with issues in the quality of the available reference stations.

Of the remaining 13 stations, nine required the application of the additional breakpoints. In some cases, the same breakpoint appeared in the original analysis, at a lower significance. In others, the new breakpoints occurred within two years (8 seasons) of an original analysis breakpoint and so were excluded by the methodology (see step 8). In general, the new breakpoints were small, requiring adjustments of a magnitude of 0.4^{o}C or less. At the remaining 4 stations, comparison with the reference series suggested that the breakpoints were insignificant.

The tabulation of the times of these breakpoints, along with the original breakpoints, is included in Appendix A.

A second step is to consider the results of the homogenization. Do they provide a more spatially coherent picture than without the data procedure? This is examined by comparing the trends (Table 5) in monthly median dewpoints before and after the homogenization procedure. A more complete discussion of the trends is given in a later section.

Figure 23 shows the trends before the homogenization of the data. The split between positive and negative trends is about even. Strong negative trends are seen in Western Australia; positive trends dominate the east. However, in the east the magnitude of the trends tends to be smaller and negative trends are interspersed throughout. Birdsville is particularly notable, with a positive trend in excess of 1^{o}C/decade.

Figure 24 shows the trends after homogenization. With the application of this procedure, the signs of the trends become mostly positive. The strong negative trends in WA have vanished. The weakly negative trends in VIC have also vanished, replaced with small positive trends. A broad swath of strong increasing trends in dewpoint is seen from the central QLD coast into the centre of the continent. While this is not a conclusive analysis, the trends seem more spatially coherent after the homogenization.

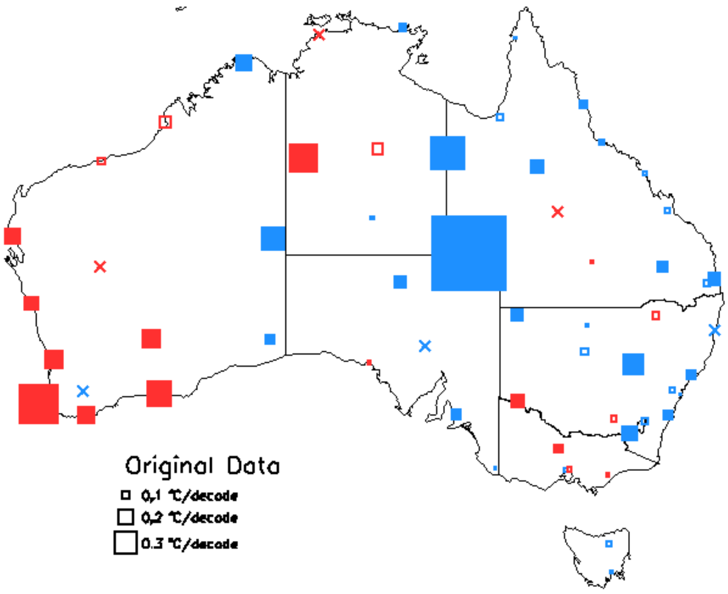


Fig. 23 *Trends in monthly median dewpoint at 0900 between 1957 and 2003 before the homogenization procedure. Blue symbols show increasing dewpoints with time, red decreasing. The magnitude is indicated by the size of the symbol using the reference in the legend. A cross indicates trends with a magnitude of less than 0.02^{o}C/decade.Trends which are statistically significantly different from zero are indicated by the filled symbols.*

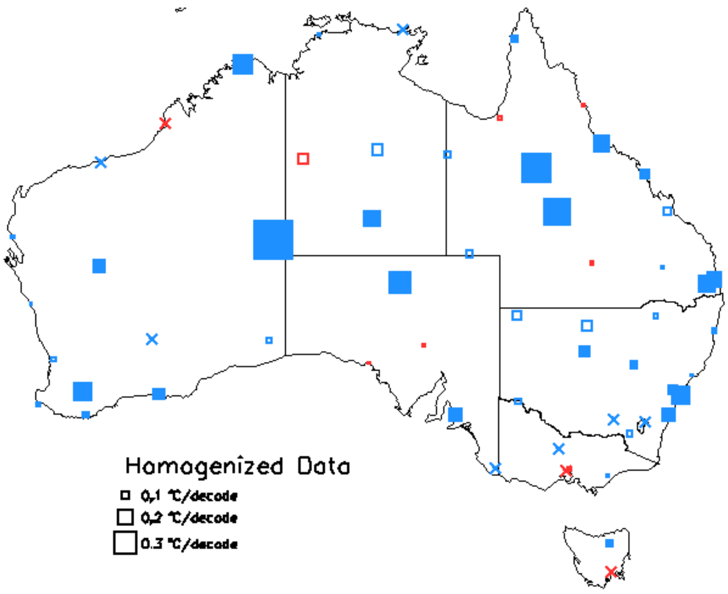


Fig. 24 *As in Fig. 22, except for after the homogenization.*

Figure 25 shows the results from Willett (2007) who performed a global 5ox5o humidity homogenization from 1974 through 2003. This map is extracted from her global picture and only shows the results for Australia. The map in that figure is the trend for specific humidity with units of (g kg-1) per decade. Translating these into dewpoint, the values are generally within the same range as described here, about 0.1 to 0.5 degrees of dewpoint per 10 years. The spatial patterns of the variability are considerably different, though; the signal is quite mixed in Willett but on the balance the trends are negative (i.e. decreasing dewpoints), particularly for southeastern Australia.

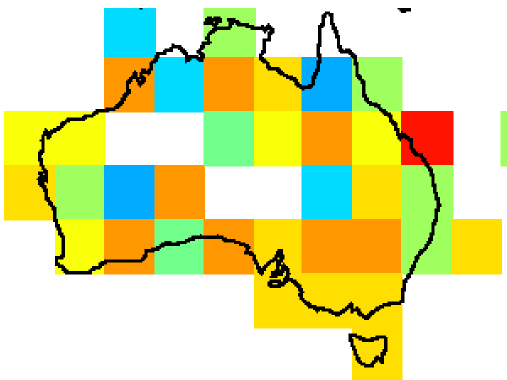


Fig. 25 *Trends in annual specific humidity anomalies from 1974 to 2003 for 5^o x 5^o grid boxes. Green and blue represent positive trends, reds and yellow negative trends. Extracted from Fig 3-34 in Willett (2007).*

Why the disparity between the two studies? A key difference in the trends from this study and Willett's lies in the choice of starting date for the calculation and in the inter-annual (-decadal?) variability of rainfall. The period from 1973-75 was characterized by the strongest La Nina dating back to at least 1950 (judged by the Multivariate ENSO Index; see Fig. 35). Using all-Australia rainfall data from the National Climate Centre, the year 1974 was the wettest year on record (cf. Fig. 33), extending back to the turn of the 20th century and the years 1973-75 were the wettest 3 year period. As will be shown in a subsequent section, dewpoints were also anomalously high during this period over much of the country, particularly the east.

A fairer comparison of the two datasets is made by removing the data from before 1974 in the homogenized data series developed in this project and re-computing the trends. This calculation is shown in map form in Fig. 26 and also tabulated in Table 5. A comparison with Fig 24 shows that both the spatial distribution and the magnitudes of the trends are considerably different in this truncated dataset. In particular, a large area of negative trends is now present in much of QLD, western NSW, VIC and SA. Overall, the spatial patterns of the trends in the truncated series Fig. 26 agree much more favourably with those depicted in Fig. 25, although the match is not exact.

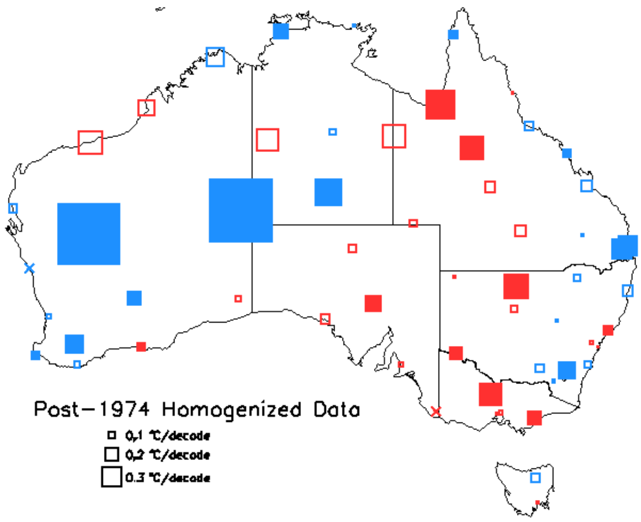


Fig. 26 *As in Fig. 23, except for the post-1974 homogenized data.*

Illustrations of the sources of the discrepancies in trend values are noted in Figs 27 and 28. In Fig. 27, the time series from Longreach indicates that these discrepancies arise because the drier period before 1974 has been eliminated from the calculation. Starting at a high point and eliminating earlier dry points results in a more negative trend, although the negative trend here is not statistically significant. A different situation is encountered at Meekatharra in northwestern Australia (Fig. 28). In this general region, the magnitude of the positive trends has increased greatly. At Meekatharra the positive trend increases by nearly a factor of 5. In this case, the inflation does not result because the 1973-75 period is unusually wet, but rather because an earlier wet period in the late 1950s and early 1960s is eliminated from consideration.

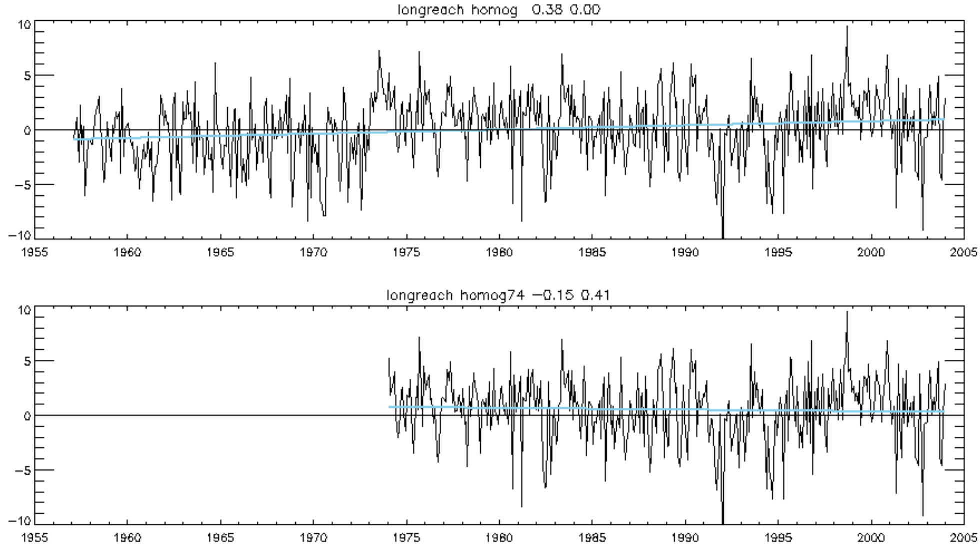


Fig. 27 *Monthly dewpoint anomalies at Longreach, QLD for the entire homogenized dataset (1957-2003) and the truncated set (1974-2003).Trend line is in blue. The magnitude of the trend (left) in degrees per decade and associated p-value are in the title string of each chart.*

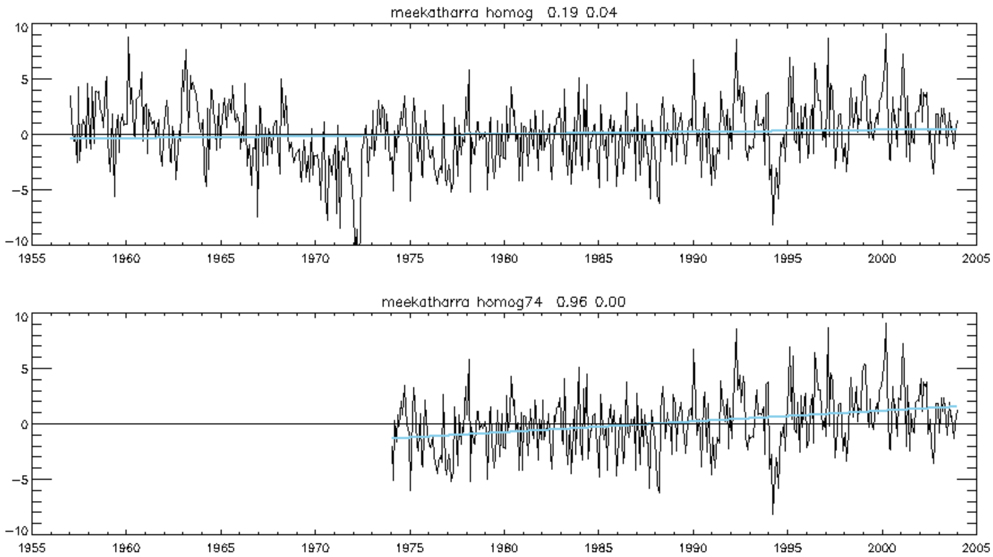


Fig. 28 *As in Fig. 27, except for Meekathara, WA.*

These two examples indicate the care that needs to be taken when interpreting trends in climatological data (see Wunsch 1999). The trends vary considerably depending on the length of the time series. In some areas not only is the value of the trend different, but the sign of the trend is reversed between this study and Willett et al. (2007). The trends from the shorter series aren't 'wrong' or misguided – 30 years, generally considered statistically adequate, are used in the shorter calculation. It is important to remember that weather and climate are constantly changing. In some cases, the time scales of these changes are very long, on the scale of decades or even longer. There is also persistence and a stochastic element involved with in weather and climate, and the effects of these factors can give the illusion of a distinct trend which may not reflect the true behaviour of the climate system. When discussing trends, there is a need to be specific regarding the period over which the trend is computed. More data are always better, but whatever the amount available it may not be enough, particularly when projecting into the future. Finally, one should be cautious about assigning cause and effect, especially if a large portion of the argument rests on the strength of a trend over a particular period. The trends in humidity and their significance are discussed further in the next section.

Table 5 *Trends in the monthly median dewpoint for the original data, the full set of homogenized data and the post-1974 subset of the homogenized data. Units are ^{o}C per decade. The number of points and the p-value of each trend are also shown.*

Station	N	Original DP	p-value	Homog DP	p-value	Post-74 DP	p-value	N (post-74)
Adelaide	564	0.153	0.000	0.205	0.000	-0.062	0.393	360
Albany	564	-0.250	0.000	0.112	0.000	0.087	0.163	360
Alice Springs	553	0.020	0.852	0.240	0.023	0.430	0.047	360
Amberley	564	0.092	0.052	0.245	0.000	0.331	0.000	360
Bendigo	560	-0.147	0.000	0.008	0.854	-0.367	0.000	359
Birdsville	508	1.022	0.000	0.084	0.414	-0.108	0.594	335
Bourke	503	0.023	0.756	0.139	0.060	-0.395	0.007	338
Brisbane AP	563	0.190	0.000	0.225	0.000	0.321	0.000	360
Broome	561	-0.152	0.063	-0.010	0.908	-0.243	0.130	360
Cabramurra	502	0.231	0.000	0.069	0.192	0.040	0.641	359
Cairns	564	0.142	0.000	-0.037	0.256	-0.020	0.747	360
Camooweal	481	0.468	0.000	0.094	0.404	-0.353	0.100	315
Canberra	564	0.073	0.119	0.013	0.786	0.290	0.001	360
Cape Leeuwin	465	-0.551	0.000	0.083	0.020	0.146	0.044	321
Carnarvon	564	-0.236	0.000	0.042	0.474	0.120	0.305	360
Ceduna	564	-0.046	0.273	-0.023	0.580	-0.145	0.069	360
Charleville	562	-0.032	0.707	-0.044	0.594	-0.173	0.293	360
Cobar	564	0.086	0.230	0.177	0.011	-0.090	0.519	360
Coffs Harbour	564	0.006	0.893	0.098	0.031	0.153	0.066	360
Darwin	563	-0.011	0.823	0.045	0.355	0.248	0.010	360
Dubbo	553	0.295	0.000	0.118	0.027	0.025	0.800	352
Esperance	561	-0.361	0.000	0.175	0.000	-0.152	0.025	360
Forrest	562	0.145	0.002	0.070	0.118	-0.084	0.349	358
Galiwinku	475	0.120	0.000	0.018	0.581	0.024	0.638	342
Geraldton	564	-0.212	0.000	0.029	0.555	0.013	0.895	360
Giles	537	0.329	0.001	0.548	0.000	1.006	0.000	343
Hobart	564	0.025	0.517	-0.010	0.799	-0.026	0.707	360
Kalgoorlie	562	-0.273	0.000	0.003	0.944	0.244	0.008	358
Kalumburu	515	0.232	0.003	0.286	0.000	0.278	0.066	347
Katanning	542	0.013	0.716	0.256	0.000	0.311	0.000	351
Launceston AP	564	0.060	0.130	0.116	0.003	0.135	0.065	360
Laverton	564	0.041	0.259	-0.018	0.609	-0.032	0.639	360
Longreach	562	-0.014	0.885	0.384	0.000	-0.154	0.406	360
Mackay	529	0.043	0.334	0.143	0.001	0.159	0.044	360
Meekatharra	562	0.002	0.982	0.193	0.034	0.968	0.000	359
Melbourne	564	-0.065	0.076	-0.047	0.191	-0.066	0.367	360

Mildura	564	-0.202	0.000	0.075	0.121	-0.214	0.025	360
Miles	505	0.170	0.007	0.034	0.585	0.034	0.765	346
Moree	561	-0.086	0.136	0.058	0.306	0.106	0.324	360
Mt Gambier	563	0.021	0.510	0.015	0.649	-0.008	0.895	360
Normanton	563	0.092	0.256	-0.041	0.609	-0.470	0.001	360
Nowra	563	0.152	0.001	0.194	0.000	0.105	0.230	359
Oodnadatta	438	0.186	0.035	0.317	0.000	-0.111	0.491	244
Perth AP	564	-0.264	0.000	0.059	0.150	0.066	0.421	360
Port Hedland	562	-0.089	0.382	0.004	0.969	-0.355	0.087	360
Rabbit Flat	367	-0.395	0.040	-0.131	0.492	-0.341	0.114	343
Richmond (NSW)	558	0.075	0.111	0.160	0.000	-0.048	0.562	355
Richmond (QLD)	546	0.195	0.025	0.414	0.000	-0.389	0.021	348
Rockhampton	564	0.066	0.165	0.091	0.051	0.159	0.074	360
Sale	563	-0.044	0.251	0.032	0.409	-0.242	0.001	360
Sydney	564	0.021	0.641	0.268	0.000	-0.029	0.723	360
Tennant Creek	557	-0.144	0.210	0.141	0.226	0.089	0.699	360
Tibooburra	483	0.187	0.032	0.114	0.178	-0.034	0.847	325
Townsville	564	0.096	0.020	0.242	0.000	0.134	0.100	360
Wagga	564	-0.077	0.140	0.007	0.900	0.131	0.199	360
Weipa	469	0.022	0.463	0.117	0.000	0.157	0.002	356
Williamtown	564	0.148	0.002	0.024	0.597	-0.167	0.044	360
Woomera	563	0.001	0.979	-0.039	0.452	-0.271	0.009	359

6.5 A few words about usage

There are a few considerations necessary when using this data. These are briefly discussed below.

- The homogenization is only valid at 0900 LT. The homogenizations applied here do not work for the 1500 (or other times, presumably…). Applying the homogenization procedure to that data series indicates that serious inhomogeneities remain at that time for nearly all of the candidate stations in this database. This discrepancy arises because there are different factors which influence the dewpoint at that time. An example of such a different process affecting the value of dewpoint in the afternoon would be boundary-layer mixing and the entrainment of free-tropospheric dry air to near the surface. These processes usually lower dewpoint in the afternoon, occasionally quite considerably, but they do not necessarily occur in a spatially coherent way. A separate homogenization (with perhaps different reference stations) is needed to homogenize the afternoon readings.
- The adjustments applied here to the data represent bulk adjustments to the long-term variability of the data. They should not be taken to mean that the individual observations making up the longer series have been 'corrected'. For example, a homogeneity adjustment of say, +0.5 degrees does not mean that every *individual* observation after that should be adjusted by that amount. That homogeneity adjustment applies to the aggregate of the observations. Generally unquantifiable errors still exist in single observations and, with the exception of the identification and quality control measures discussed previously there has been no attempt to adjust any individual measurement in this dataset.

7 A PRELIMINARY HUMIDITY CLIMATOLOGY OF AUSTRALIA

The purpose of this section is to present some features of the spatial and temporal distribution of water vapour (at the surface) in Australia as seen using the quality-controlled, homogenized humidity dataset. A discussion of interannual variability is also presented.

7.1 Monthly Median Maps

Figures 29 and 30 display the spatial variation of median dewpoint at 0900 LT for each month of the year. Each month is shown individually and the traditional seasons (i.e. DJF, etc) are grouped into columns.

Across the country, dewpoints are highest in the summer months and lowest in the winter. At all stations, the peak median dewpoint is observed in February, when it is above 10^{o}C at all stations. The lowest median dewpoints are in August, with dewpoints below 5^{o}C across much of the country.

Spatially, there is a broad meridional gradient in humidity, with higher values typically observed in the tropical latitudes of the north. However, this general pattern is disrupted by the continental boundaries. Dewpoints decrease towards the north from the shores of the Southern Ocean. There is also some departure from the meridional pattern along the eastern and western coasts as well, with higher dewpoints extending down these coasts. This effect is particularly prominent along the east coast, a consequence of the Great Dividing Range. In effect, a pool of drier air is typically found over the arid centre of the continent.

This broad pattern persists throughout the year, with the absolute values of dewpoint modulated by the annual cycle. The typical magnitude of this modulation is about 10^{o}C. In the northern portions of the country, median dewpoints are in excess of 20^{o}C across parts of the region for ten of the twelve months of the year. In February -- the height of the wet season -- median dewpoints above 25^{o}C are noted at two stations, Galiwinku and Normanton. In the southern fringes of the tropics, median dewpoints can drop below 10^{o}C; further north they remain at 15^{o}C or above.

The ‘dry pool’ in the centre of the continent varies considerably with the annual cycle in both spatial extent and magnitude. It is loosely centred on Giles, near the intersection of the NT, WA and SA borders. The dry pool is at its smallest in February, with median dewpoints right at 10^{o}C in WA. By August, the 10^{o}C contour line covers most of the country, and median dewpoints below 0^{o}C are noted in the centre of the country. Some of the asymmetry in the patterns noted earlier is lessened in winter, with drier air extending throughout the eastern and southeastern portions of Australia. As spring begins, the drier air begins to recede and higher dewpoints become more prominent along the east coast.

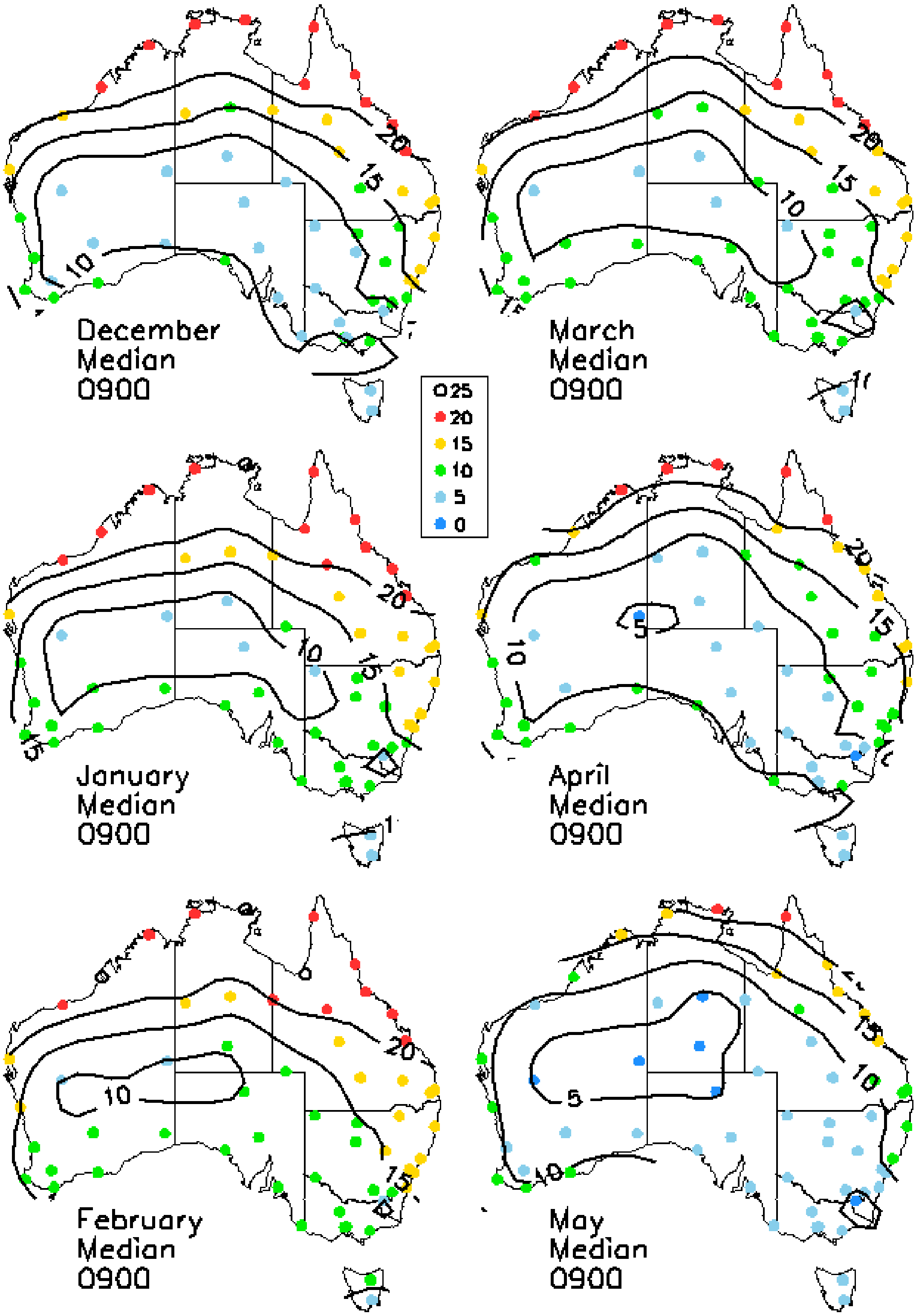


Fig. 29 *Monthly median dewpoint for December through May. Columns are grouped by the traditional seasons. Left column is Summer (DJF) and the right is Autumn (MAM). Contours and colours are shown in 5°C increments.*

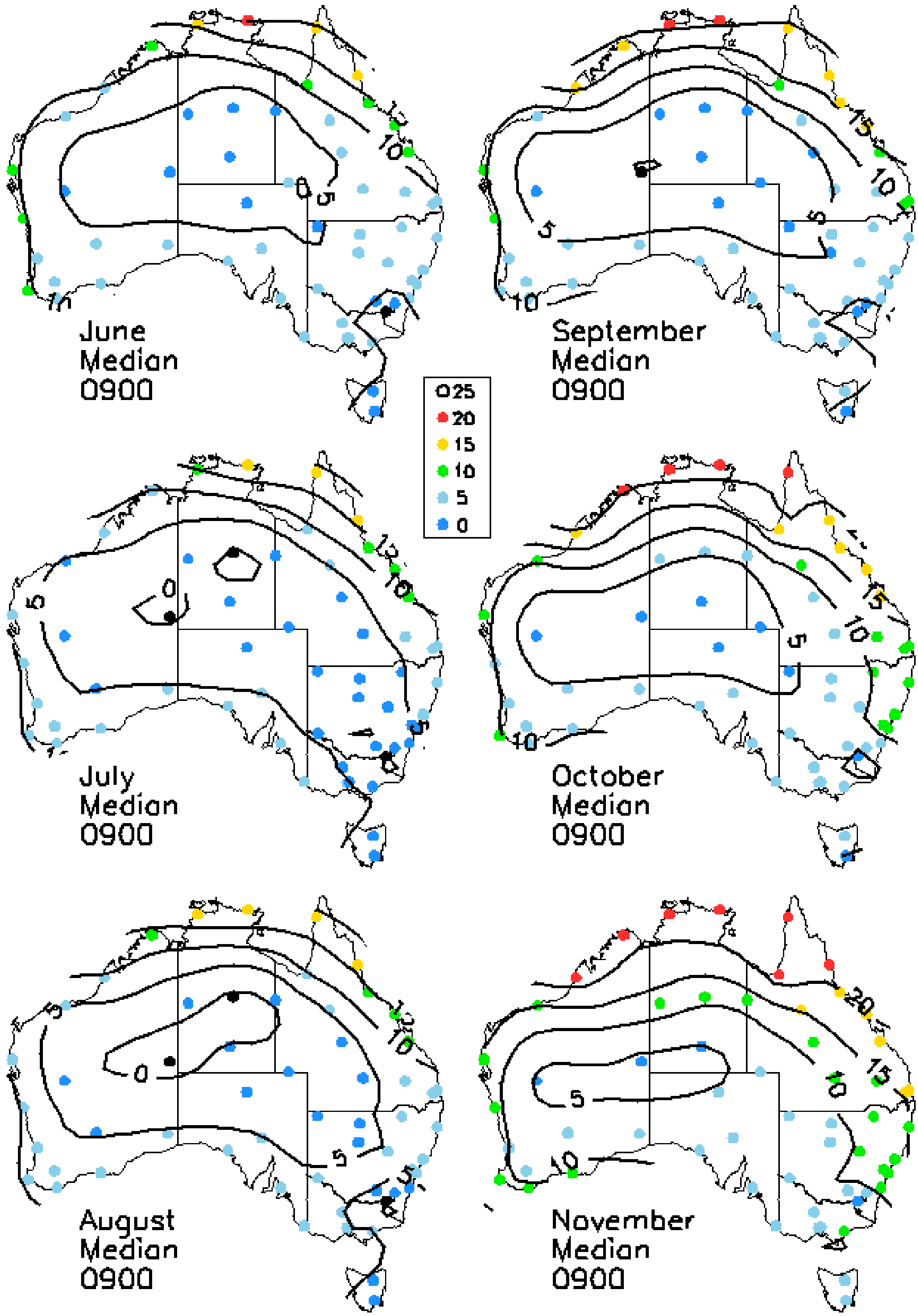


Fig. 30 *As in Fig. 29 except for the months June through November. The columns represent Winter (JJA) and Spring (SON).*

7.2 Graphs of Monthly Dewpoint distributions

Figure 31 shows, for each station in the dataset, the monthly distribution of dewpoint at 0900 LT in the form of box-and-whiskers plots. The total span of the line represents the full range of variability of dewpoint during this month; the blue area of each month represents the range where the observations fall 50% of the time around the median, the so-called ‘inner quartiles’. The more extensive the curve, the greater the range of variability present in dewpoint at the station.

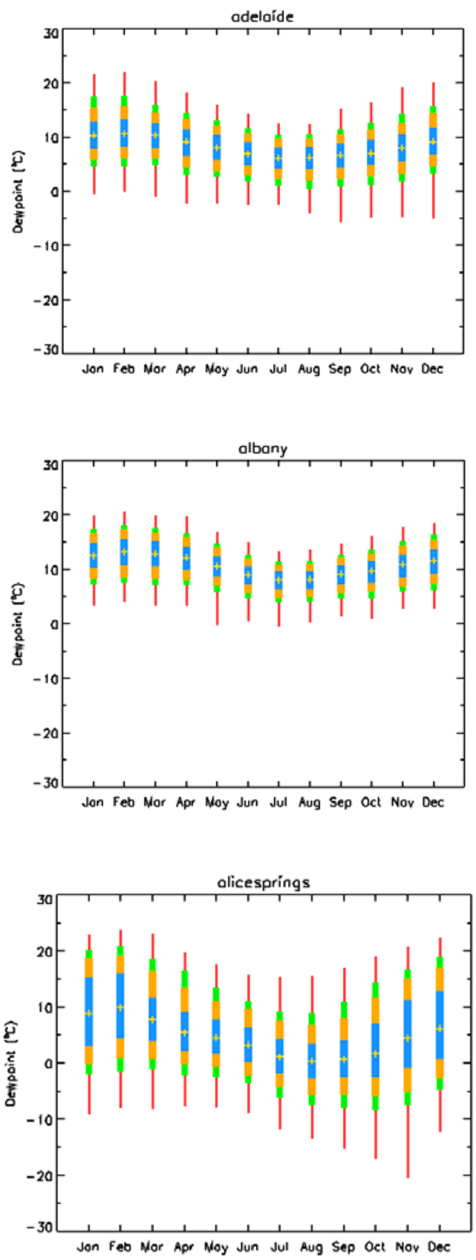


Fig. 31 *Monthly box and whiskers plots showing the distribution of 0900 LT dewpoint for each of the candidate stations. Yellow crosses depict the median, blue are the inner quartiles (25% to 75%), orange the 10-90% range, green the 5% to 95% range and the red lines show the extrema of the entire distribution. All 58 stations are shown, in alphabetical order.*

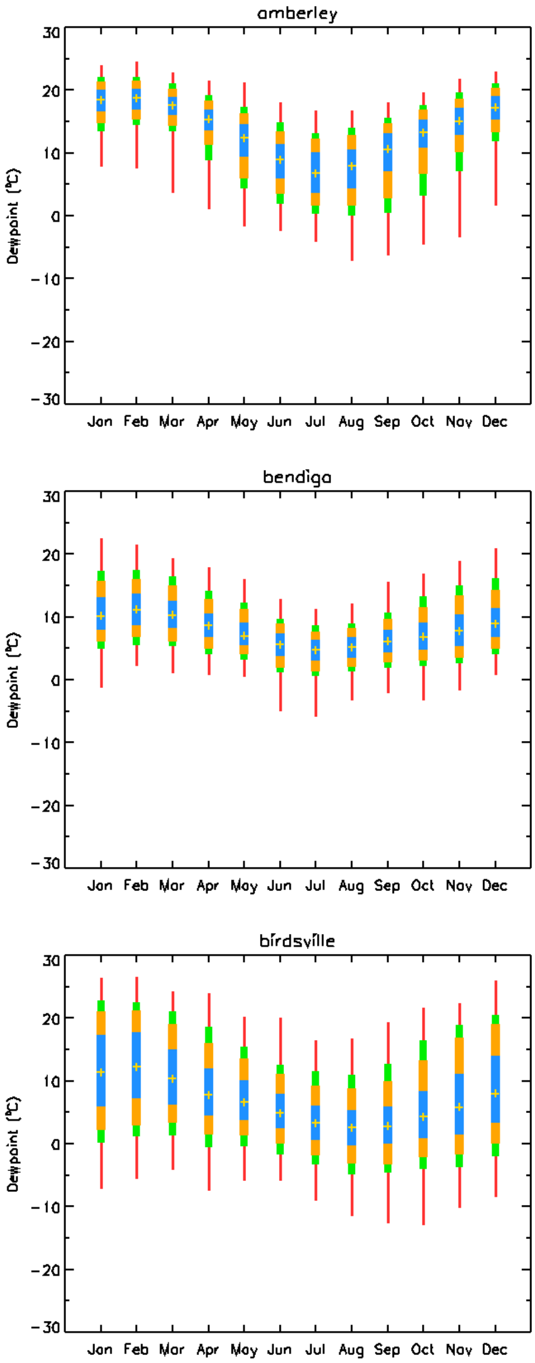


Fig. 31 *(Continued)*

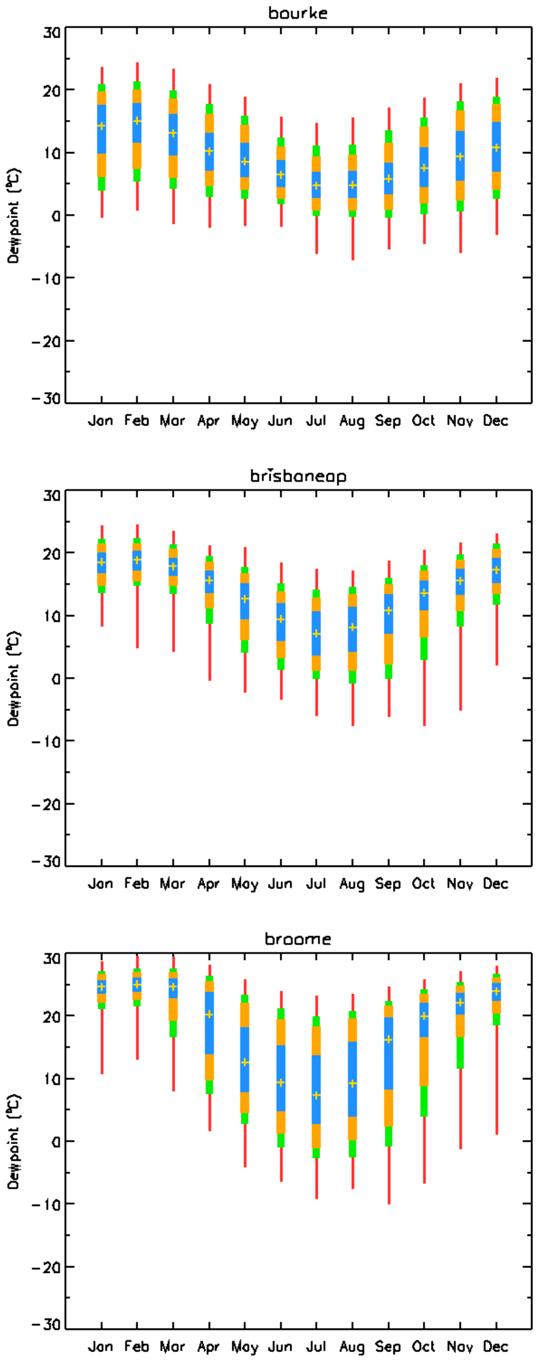


Fig. 31 *(Continued)*

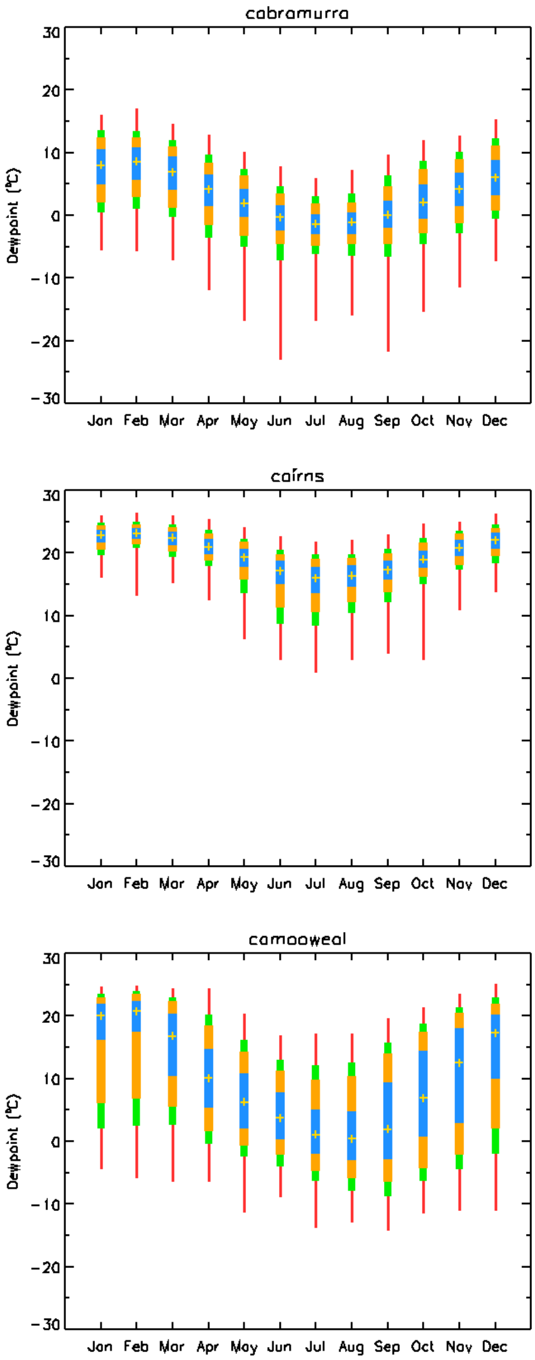


Fig. 31 *(Continued)*

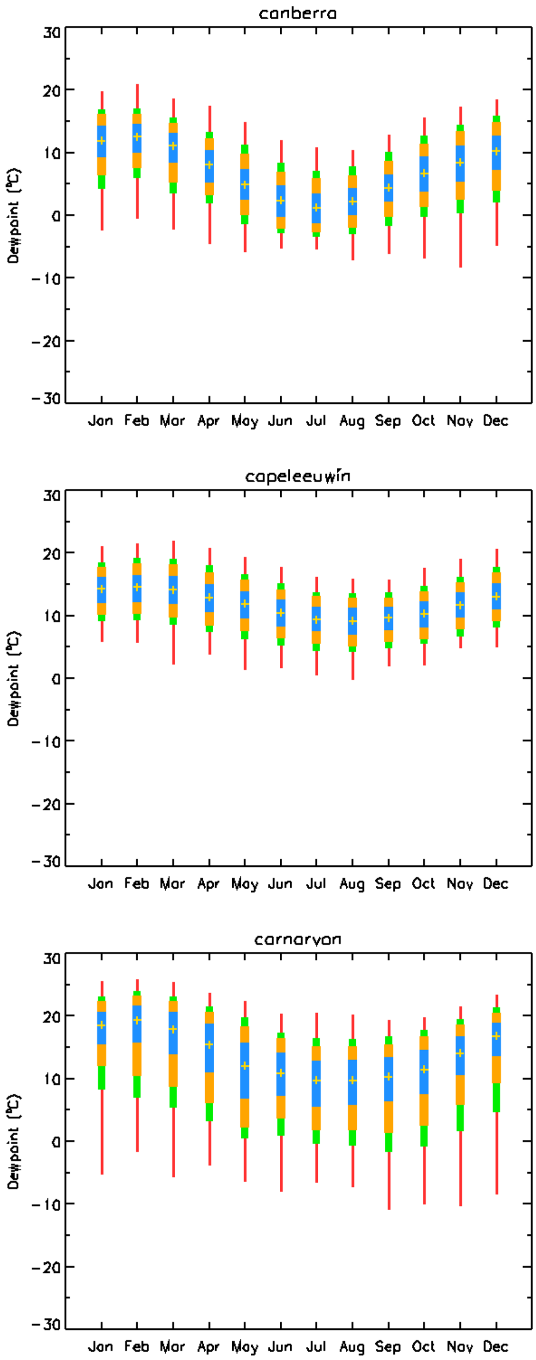


Fig. 31 *(Continued)*

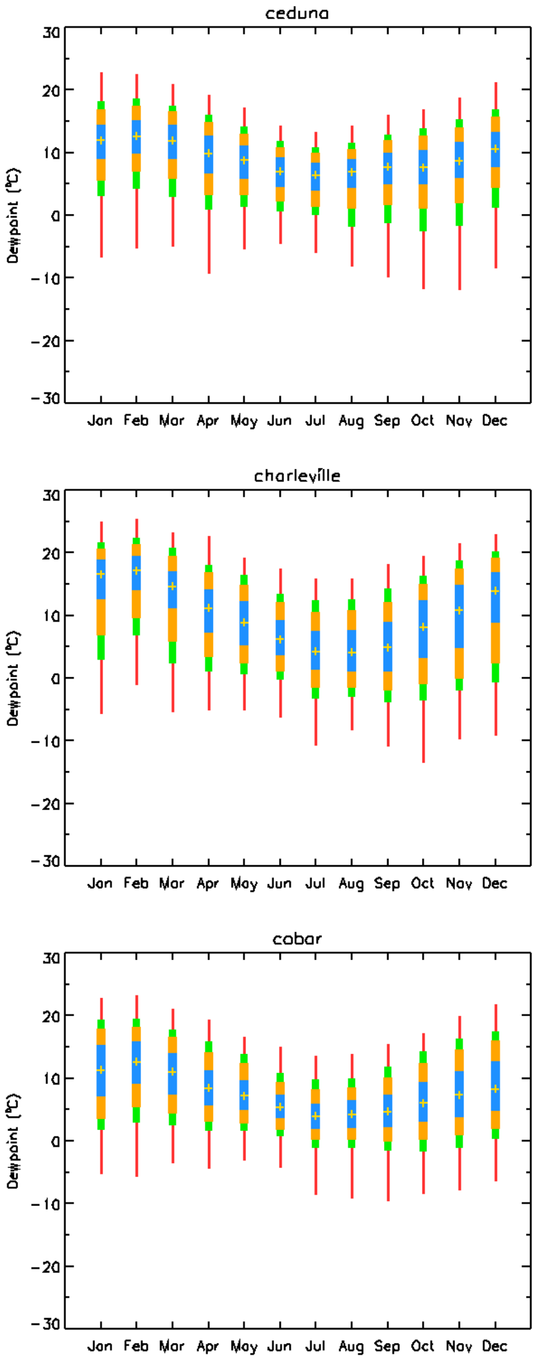
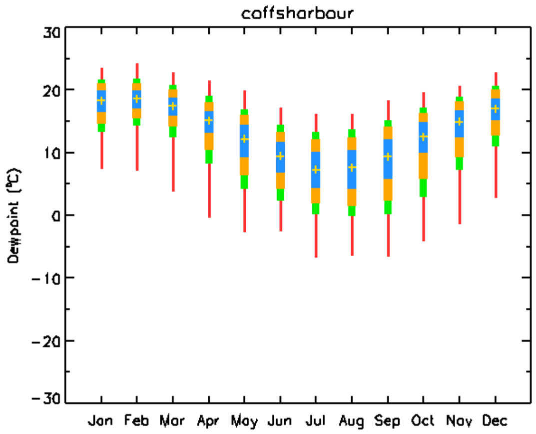
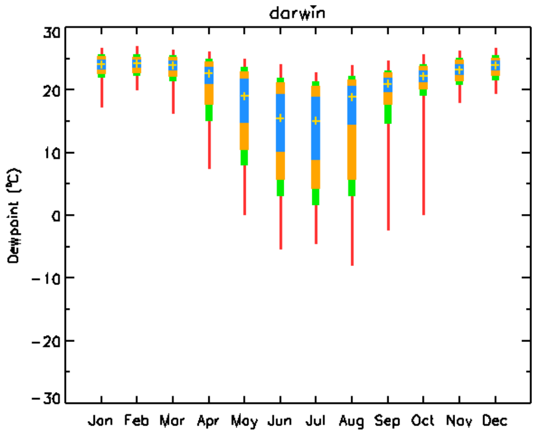


Fig. 31 *(Continued)*





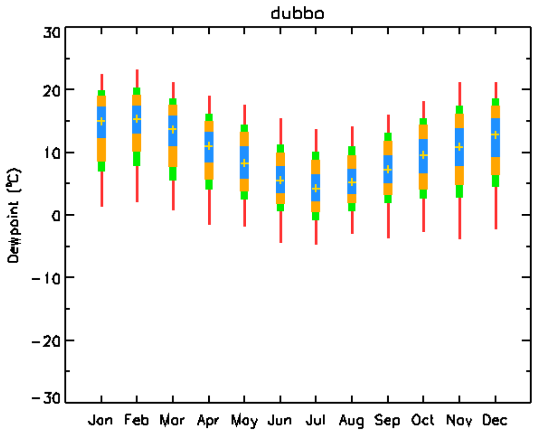


Fig. 31 *(Continued)*

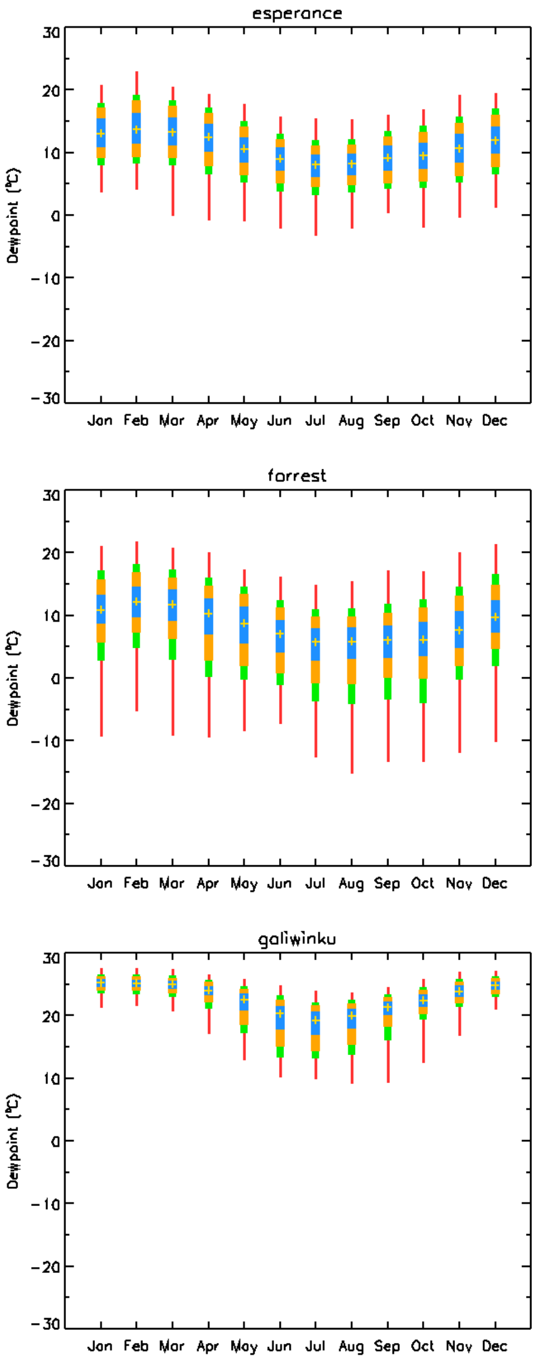


Fig. 31 *(Continued)*

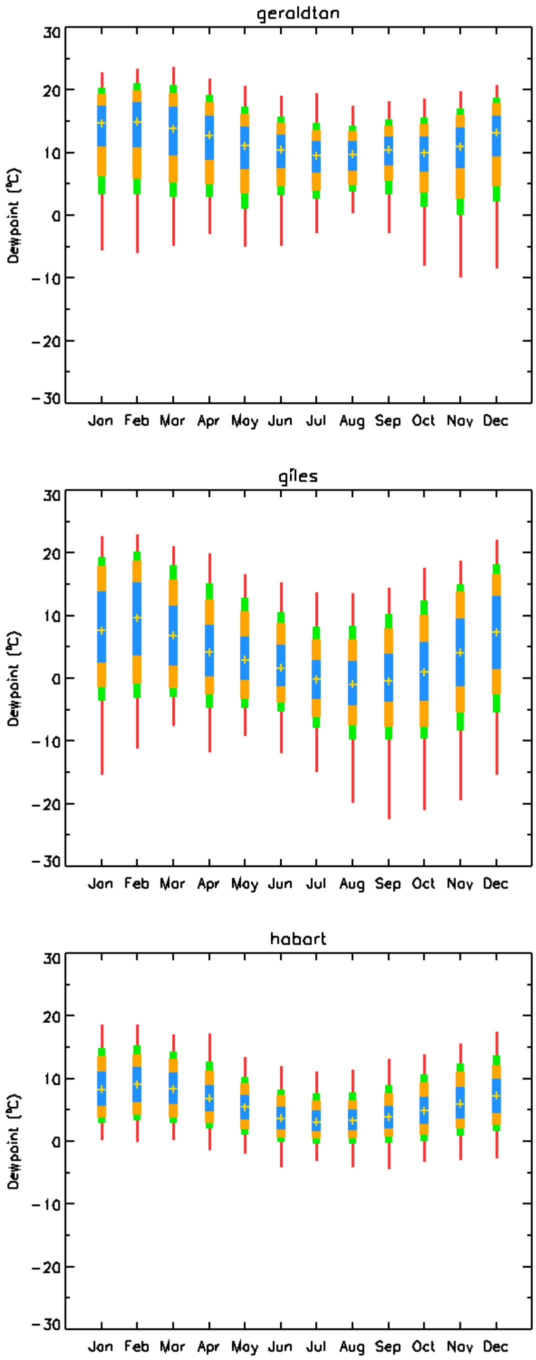


Fig. 31 *(Continued)*

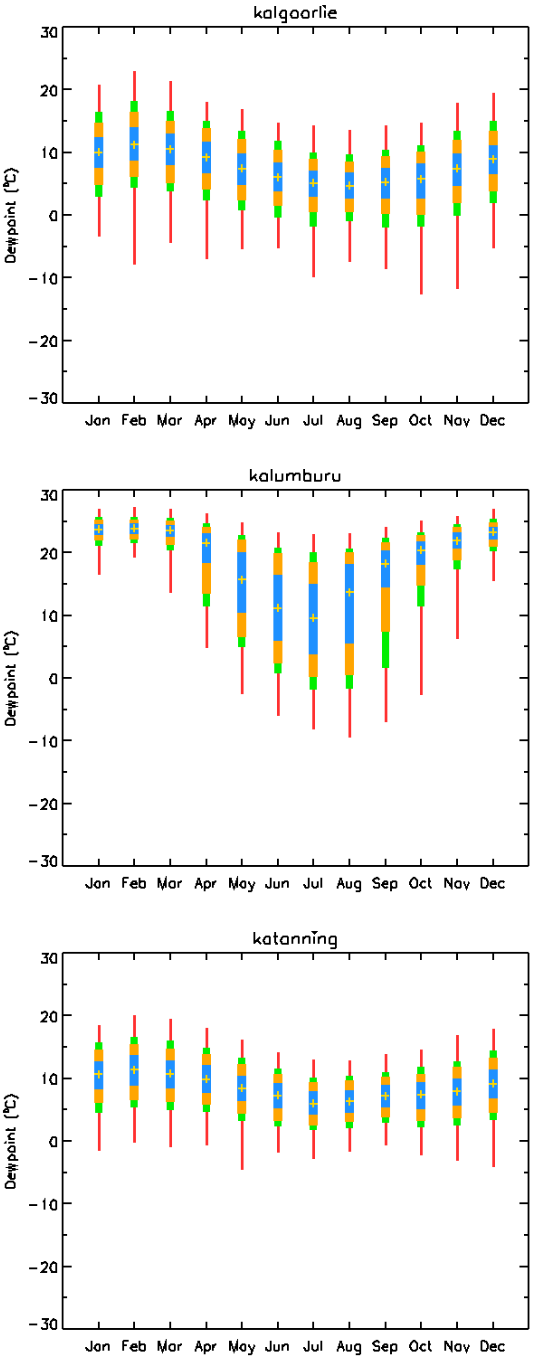


Fig. 31 *(Continued)*

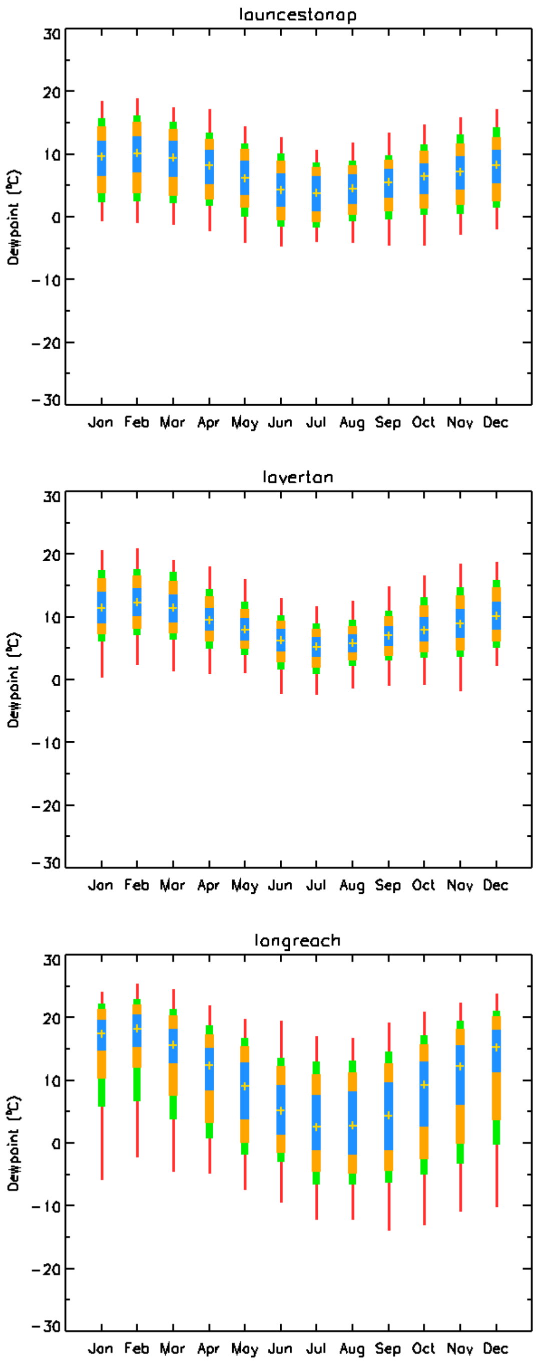


Fig. 31 *(Continued)*

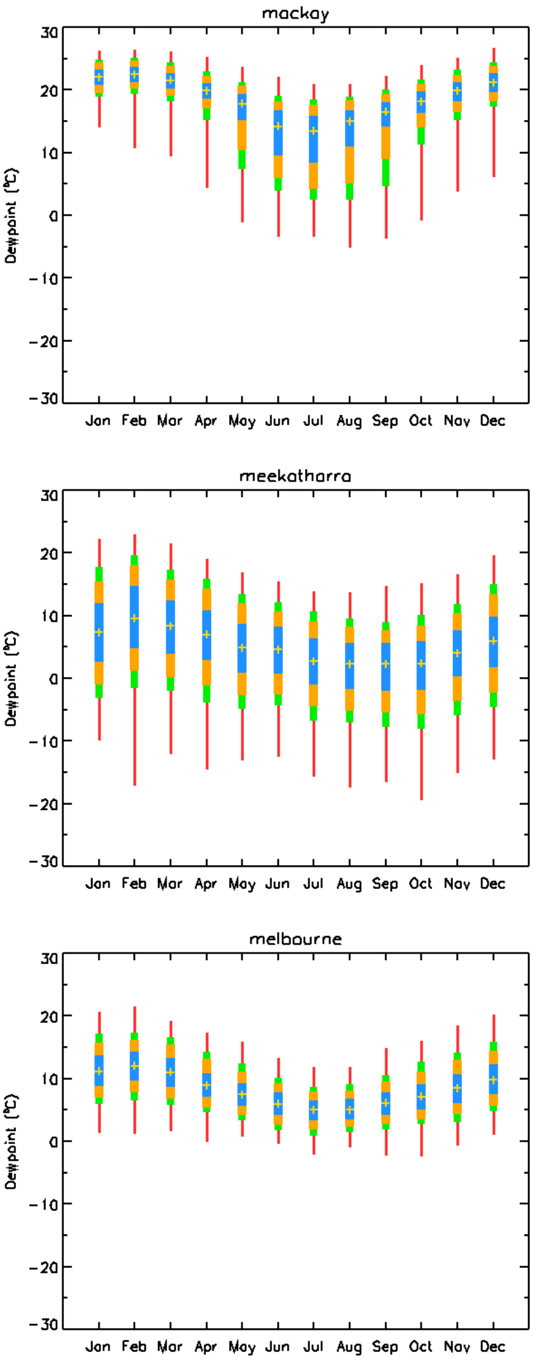


Fig. 31 *(Continued)*

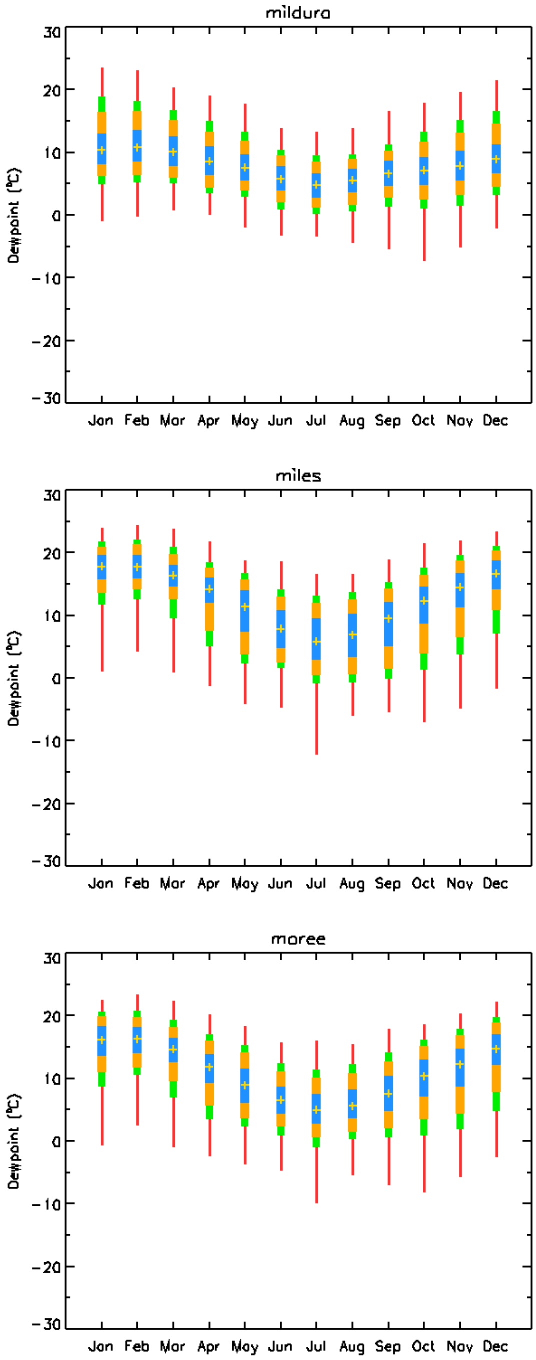


***Fig. 31** (Continued)*

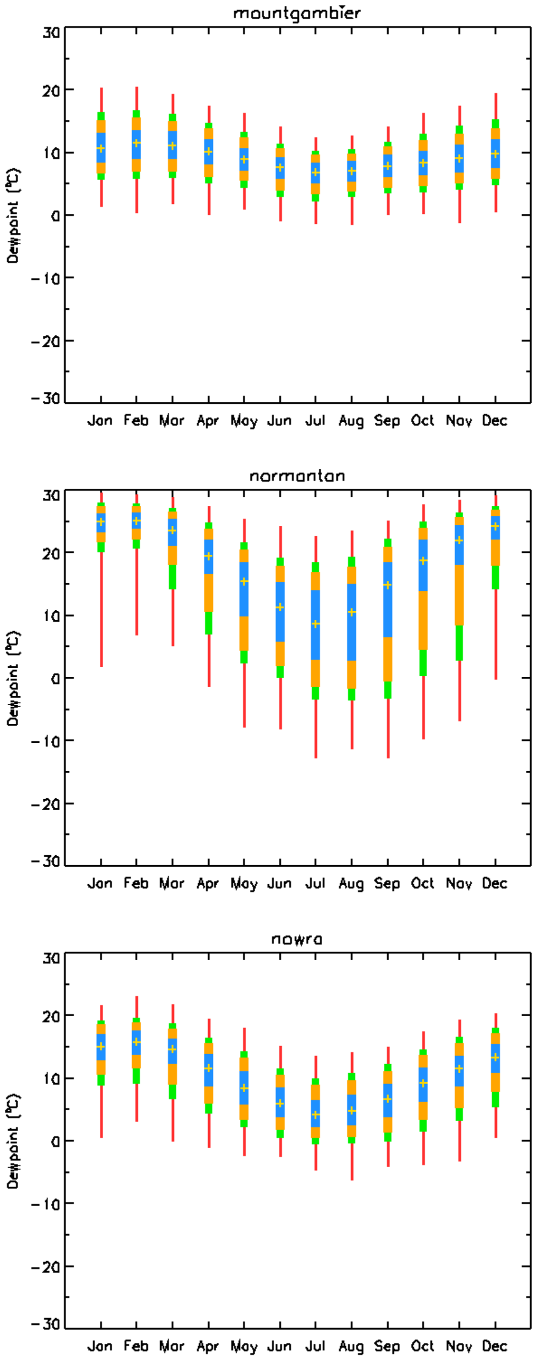


Fig. 31 *(Continued)*

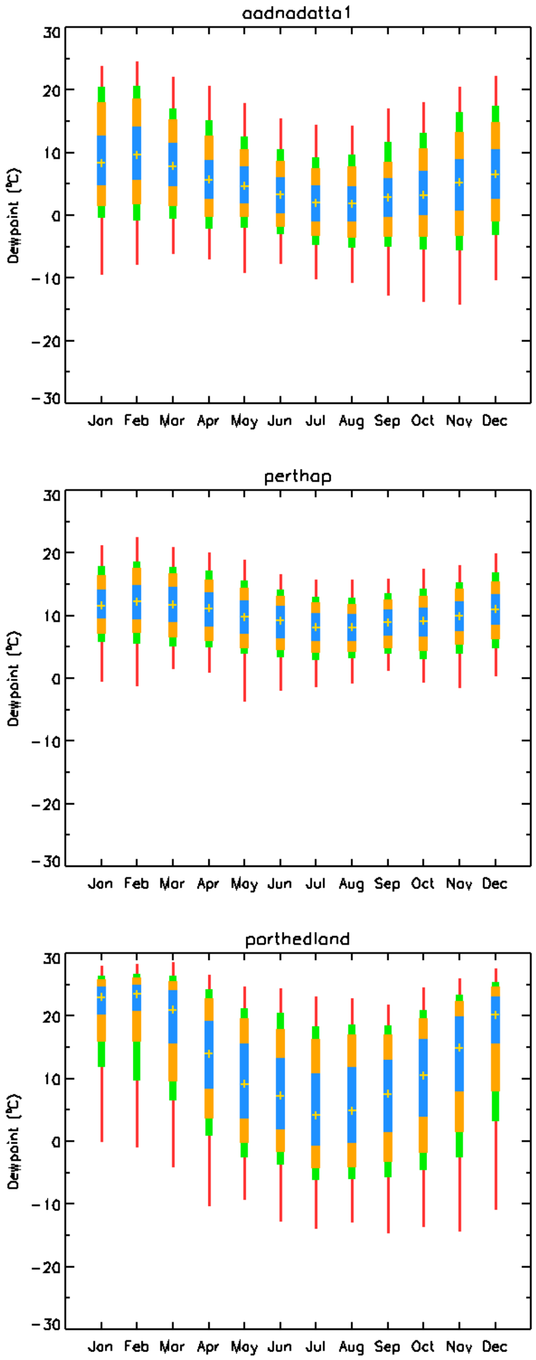


Fig. 31 *(Continued)*

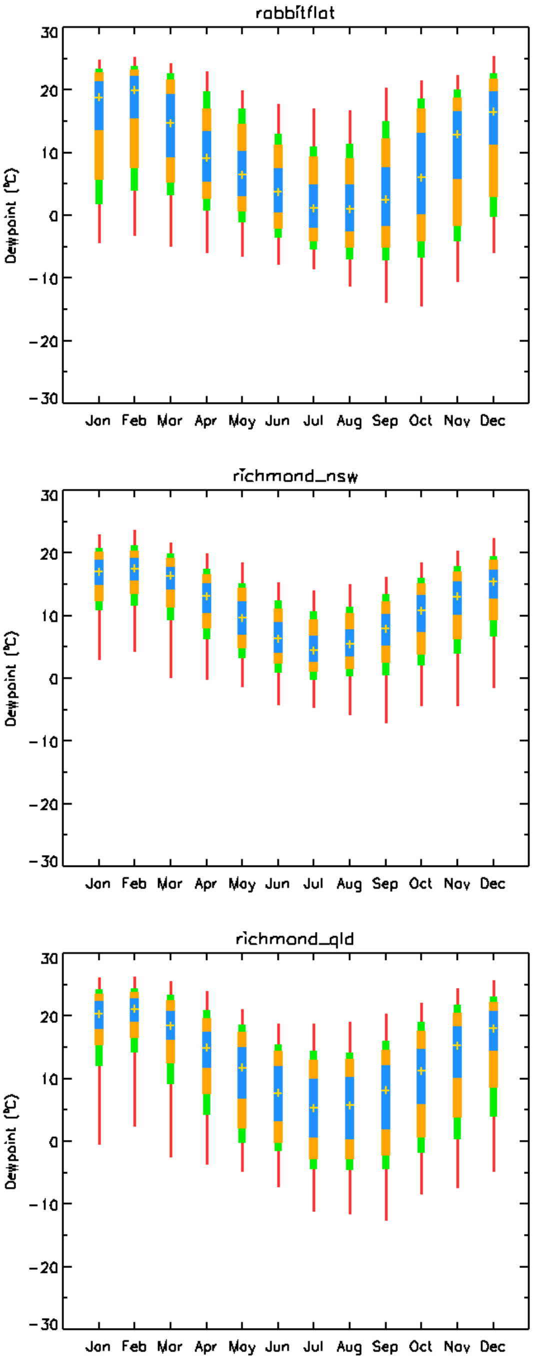


Fig. 31 *(Continued)*

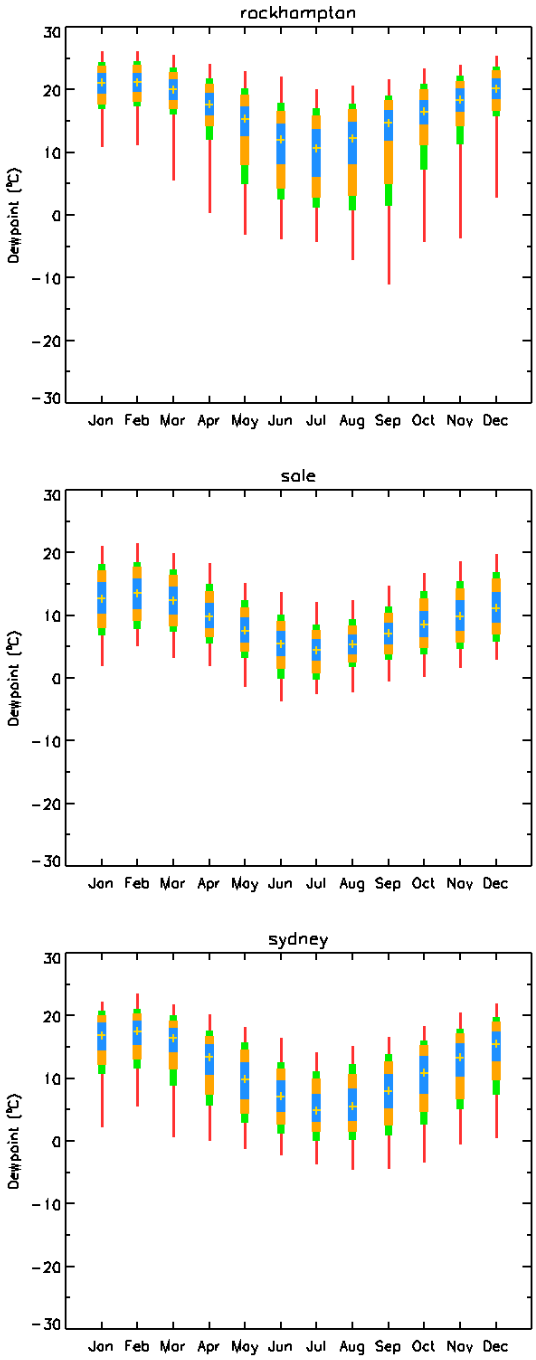


Fig. 31 (Continued)

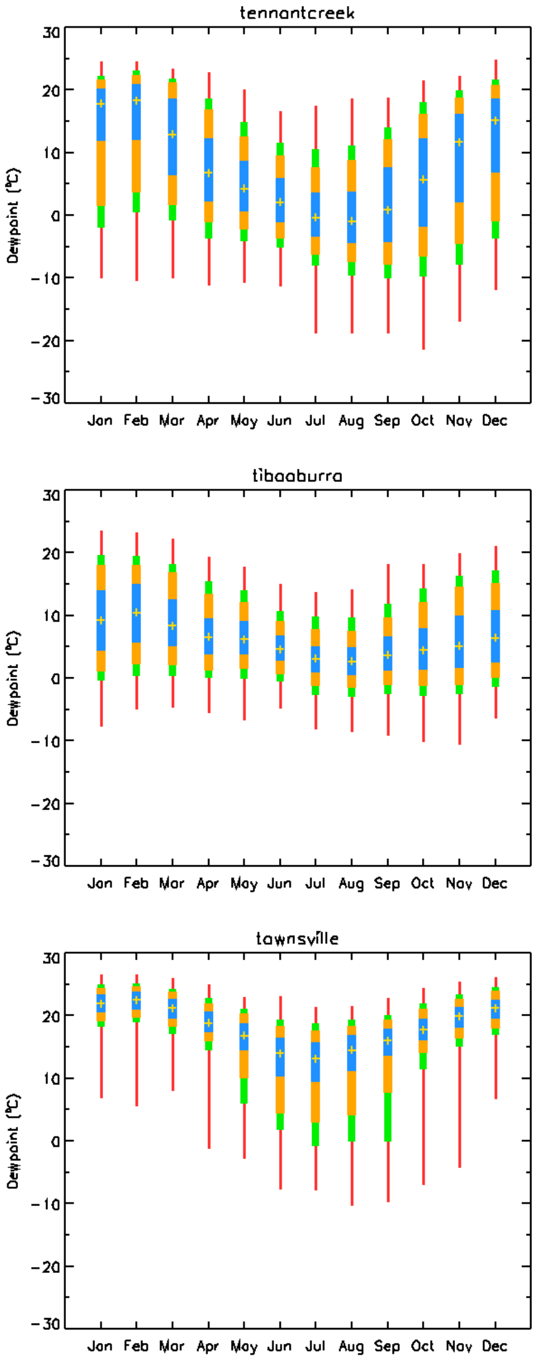
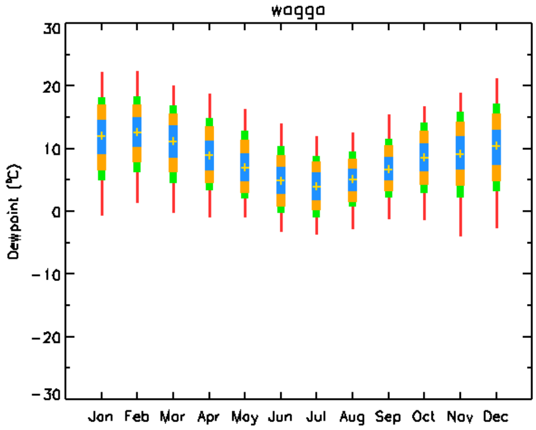


Fig. 31 *(Continued)*



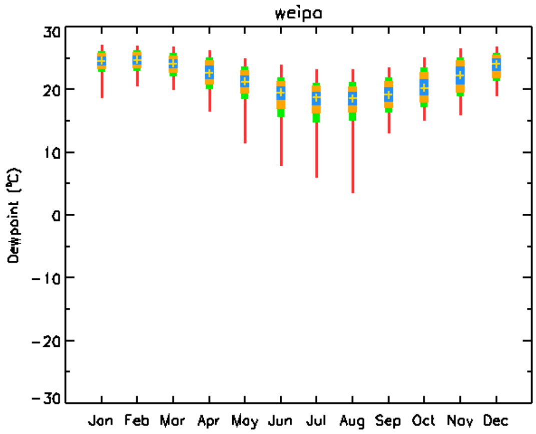


Fig. 31 *(Continued)*

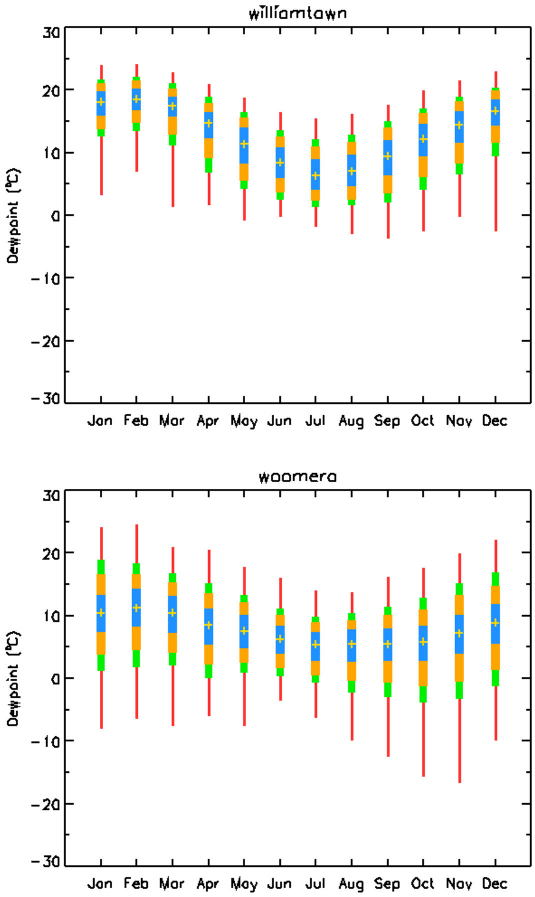


Fig. 31. *Monthly box and whiskers plots showing the distribution of 0900 LT dewpoint for each of the candidate stations. Yellow crosses depict the median, blue are the inner quartiles (25% to 75%), orange the 10-90% range, green the 5% to 95% range and the red lines show the extrema of the entire distribution. All 58 stations are shown, in alphabetical order.*

A perusal of the plots reveals many things. First, the general finding from Fig. 29 and Fig. 30 that dewpoint is, as a rule of thumb, highest in the warmer months and lowest in the cooler months is confirmed here. All stations show a clear annual cycle in the median and many of the other percentile levels.

The magnitude of these annual cycles and the variability within each station are different, though. In the southern parts of the country, the annual cycles are typically smaller and the variability is limited to a relatively narrow range. In the central parts of the country, the range of observations is typically larger and the annual cycle more extreme. Further north, in the deep tropical regions of the nation, the annual cycle is quite pronounced. Variability is typically very low in the wet season, with dewpoints remaining quite high every day. In the drier winter months, median dewpoints drop considerably and the range of observations is large.

The variability is typically skewed towards the low end. More extreme low dewpoints are observed than extreme high dewpoints, in part because dewpoint is bounded above by the dry-bulb temperature. In most cases, the lowest observations of dewpoint typically occur in the late winter and spring. These values, at 0900, are around 0°C in southern areas, and just below -20°C in central and northern parts of the country.

There are a few caveats on these values. First is the time of observations. While not described here, dewpoint undergoes a diurnal cycle, with higher values in the morning and lower values in the afternoon. The strength of this diurnal cycle is quite variable and depends on the details of boundary layer growth and the entrainment of drier free tropospheric air into the near-surface mixed layer. The factors vary with location and the weather conditions. Plots similar to Fig. 31 (not shown) constructed including all observations show considerably lower minimum values, usually observed in the afternoon. The second is the reliability of the numbers at such low values. The relationship between dewpoint and vapour pressure is highly nonlinear, and this non-linearity manifests itself strongly at low values. At these low values, a small change in actual vapour content results in a big change in the dewpoint temperature. The errors are possibly quite large here, and instrument effects like that described in Lucas (2006) come into effect at these humidity levels.

7.3 Interannual variability

The graphs in the previous section highlight the typical values and ranges of dewpoint over Australia. As the climate is not static, the statistical values vary from year to year. This interannual variability is examined in this section.

Figure 32 shows the *normalized* monthly median dewpoint anomaly averaged over all 58 stations in the homogenized dataset. This is not strictly an 'all-Australia' measure, as the station spacing is uneven and no account is made for the area represented by each individual measurement. The values in this plot are computed at each station by dividing the dewpoint anomalies by the standard deviation of those anomalies. The normalization is used because the scale of the anomalies varies greatly from station to station. In the normally dry desert regions of central Australia, the raw anomalies can be quite large, over 10^{o}C in some months, and potentially have a non-representative influence on the true value.

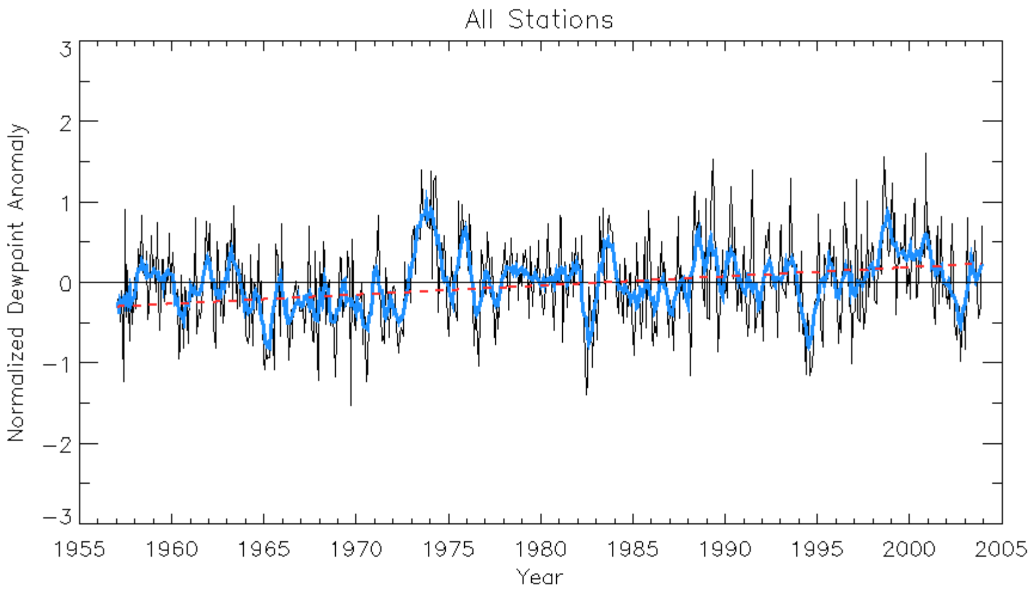


Fig. 32 *Average monthly normalized dewpoint anomaly across all homogenized stations. Blue line is the 7-month smoothed value.*

Typically the average dewpoint anomaly rarely exceeds one-and-a-half standard deviations. In the individual station series (not shown), these excursions can be larger, with anomalies of up to 4 standard deviations being observed at times. In general, negative excursions are typically of a larger magnitude that positive ones (cf Fig. 31).

The time series plot in Fig. 32 clearly indicates wetter and drier periods across the whole of Australia. In some instances these periods can last 5 or more years. The most humid period in the record is centred on 1974, where dewpoint anomalies for the continent as a whole exceeded one standard deviation. Other extended humid periods include the late 1980s and the late-1990s. Some long-lasting dry periods are also evident. One such notable period extends from roughly 1964 to 1972. Short, but intense dry periods are also seen in 1982, 1994 and 2002.

Figure 33 shows the relationship between the monthly anomalies of ‘all-Australia’ rainfall obtained from the National Climate Centre and the normalized monthly median dewpoint anomalies described above. The correspondence between the two curves is very close. Periods of anomalous high rainfall are also periods of higher-than-normal dewpoint; large-scale rainfall deficits are linked to lower-than-normal dewpoints.

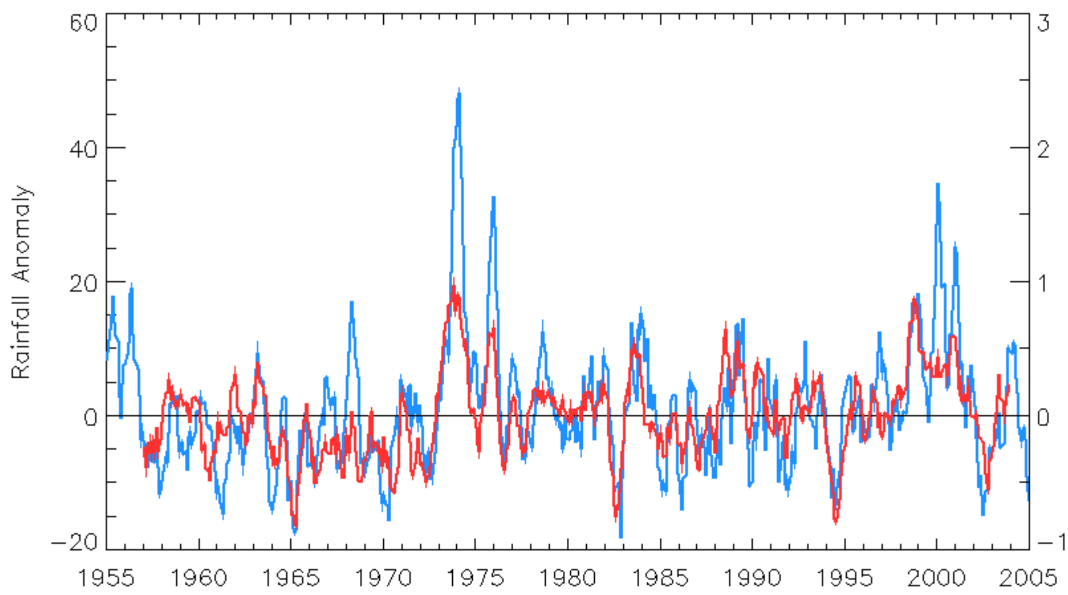


Fig. 33 *Monthly anomalies of ‘All-Australia Rainfall’ (blue, left axis) and nationally-averaged normalized monthly dewpoint anomaly (red, right axis). A seven month running mean has been applied to both time series for clarity.*

Correlating the unsmoothed rainfall and dewpoint anomaly time series at increasing lag intervals (Fig. 34) indicates that the peaks in these two variables occur simultaneously at the monthly time scale. At zero-lag, the correlation coefficient between the two is almost 0.6, highly significant, especially in light of the length of the two time series (564 points).

By lagging the two series relative to each other in time, the idea of causality can be examined. Do enhanced dewpoints prime the atmosphere to produce more rainfall, or does abundant rainfall in turn create higher dewpoints? The highest correlation by far is at zero lag, suggesting that most of any relationship between the two operates on time scales shorter than one month.

Moderate correlations are also seen at both +/- one month lag – likely the result of persistence or the arbitrary discretization of the data by months. Beyond one month, the correlations quickly lose significance for the positive lags (defined here as rainfall leading dewpoint), while weak but statistically significant correlations are noted out to 8 months in the negative lags. Taken at face value, this would imply that there is a tendency for higher dewpoints to precede enhanced rainfall. This apparent effect is relatively small; the correlations are on the order of 0.15. The asymmetrical nature in the correlogram suggests that this is more than just a spurious artefact. However, the physical mechanism by which such a large-scale phenomenon would occur is unknown. Synoptic-scale moisture convergence ahead of storm systems is known to occur with a subsequent enhancement of precipitation and severe weather. However, the time scale of this phenomenon is days rather than months.

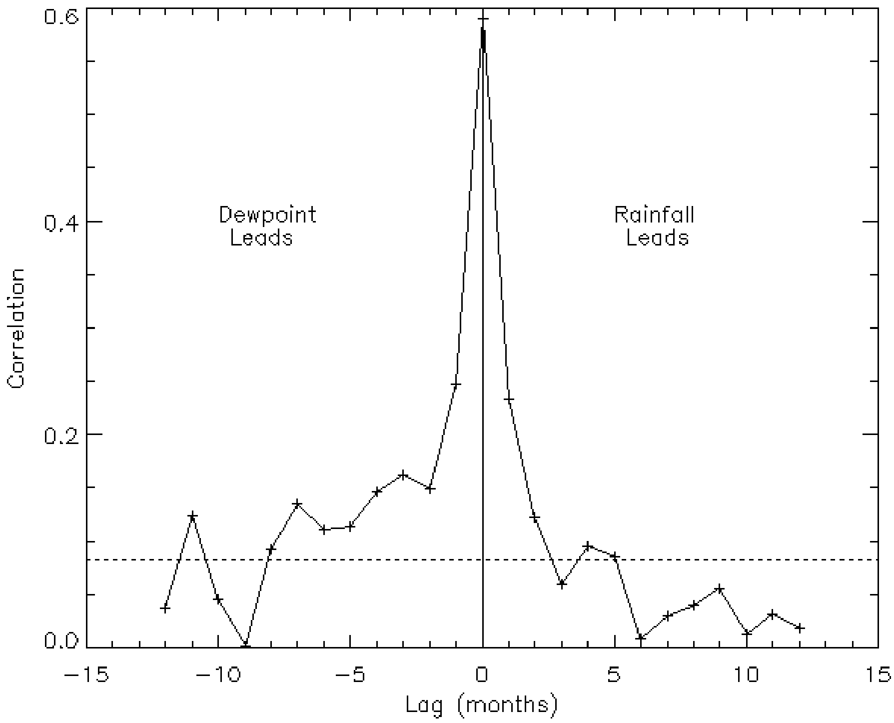


Fig. 34 *Correlogram showing the correlations between monthly dewpoint and rainfall anomalies for the period 1957-2003. Different amounts of lag are considered, defined such that a negative lag means the dewpoint values precede the rainfall. The dotted line represents the 95% significance level for a sample with N=564.*

One well-known source of variability of Australia's climate is the El Niño-Southern Oscillation (ENSO) phenomenon, which modulates rainfall. One of its main effects is that in the warm phase of ENSO (El Niño), drier conditions are observed in Australia. The opposite is true during the cool phase (La Niña). This rainfall effect is primarily observed in the eastern states, particularly QLD and NSW. The relationship between dewpoint anomalies and the Multivariate ENSO Index (MEI; Wolter and Timlin 1998) is shown in Fig. 35. The lines in the chart are 7-month running means; smoothed fields are included for clarity. Positive MEI values in excess of around 0.8 correspond to El Niño periods; negative values of a similar magnitude represent La Niña conditions. A weak relationship can be seen between the two, with correlations between the two (unsmoothed) variables at about -0.12, nominally significant but weak. In the figure, a slight tendency towards higher dewpoints is seen during La Niña periods; the most striking examples of this are the 1973-75 period and the 1998-2000 periods. The opposite tendency is seen during El Niño periods; examples of this include the 1982-83, 1994 and 2002-03 periods. As a whole, the direct ENSO effect on dewpoint seems small and mainly impacts though the rainfall anomalies associated with the circulation.

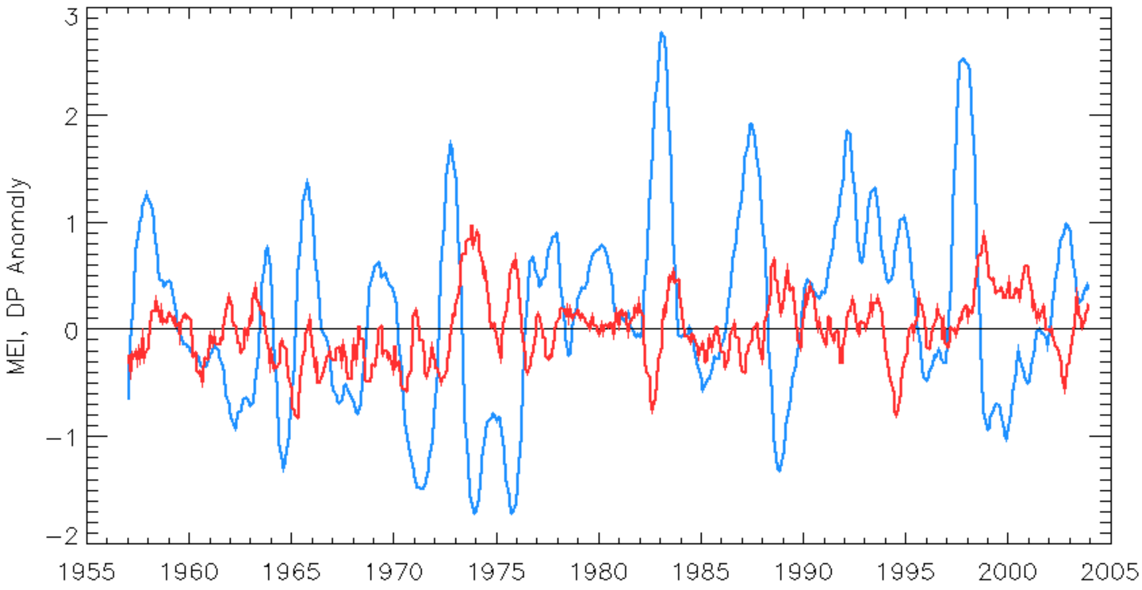


Fig. 35 *Time series of monthly values of the Multivariate ENSO Index (blue) and the all-stations normalized average median dewpoint anomaly (red). A 7-month running mean has been applied to both time series for clarity.*

7.4 Regional Variability

In this section, the variability of dewpoint is examined on a regional basis. Different regions are identified using cluster analysis to group stations based on 1.) the seasonal cycle of dewpoint, i.e. the median dewpoint values over the 4 seasons of the year (i.e. DJF, MAM, etc.); 2.) the variation of dewpoint within each season, measured by the standard deviation within each of the four seasons, and; 3.) the geographic location of the station (latitude-longitude coordinates). These 10 variables are used to create groups of stations with similar humidity climates using the *k*-means clustering algorithm (e.g. Everitt 1993). Using an analysis-of-variance methodology to address the statistical relevance of the clustering, the homogeneous dewpoint stations are classified into seven groups. Figure 36 shows the grouping on the map. Figure 37 graphically displays both the mean properties of the groups and the scatter within the individual clusters. Table 6 summarizes this information.

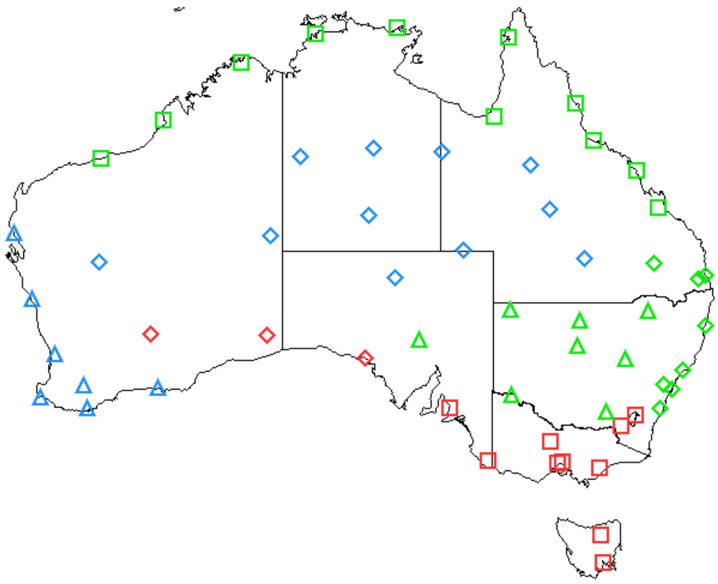


Fig. 36 *Map showing membership of the different clusters as described in Table 5.The clusters are the Tropics (green squares), East Coast (green diamonds), Northern Interior (blue diamonds), Southern Interior (green triangles), South East (red squares), West Coast (blue triangles) and Nullarbor (red diamonds).*

As seen in the figures and tables, the analysis groups the data into broad categories with similar properties. For easier identification, the clusters have been named based on their geographic location. While the clusters are meaningful in a broad sense, there is some variability within the clusters, particularly in those which have more stations.

- The Tropical cluster has 11 members across northern Australia, spanning the whole of the continent. It has a strong seasonal cycle, with high values of dewpoint (>20^{o}C) in the summer. Variability is low in the summer and high in the winter. Within the cluster, there is a fair bit of variability between members. Some stations show quite low dewpoints in the winter; these are mainly the WA members of this cohort.
- The East Coast cluster encompasses coastal NSW and southeast QLD. It has high summer dewpoints which drop considerably in the winter. Variability is small to moderate throughout the year.
- The South East cluster covers the states of VIC and TAS, and also extends into southeastern SA and into Alpine NSW. Dewpoints here have a moderate to strong annual cycle, with the largest variability in the summer. The high mountain station of Cabramurra is the distinct outlier in this group of stations.
- The West Coast cluster covers coastal portions of WA from Carnarvon in the north to Esperance in the south. The seasonal cycle is relatively weak, and the variability during the individual seasons is small.
- The Northern Interior cluster groups stations across the northern part of the country. These stations are inland from the coast. This grouping shows the strongest seasonal cycle as well as the largest intraseasonal variability. Dewpoints are quite low in the winter; this region cluster contains the ‘dry pool’ noted in previous sections. That said, there is a large range of variability between the individual cluster members. The intraseasonal variability is large in all seasons. This finding reflects the ‘all-or-nothing’ nature of the rainfall here; some years are quite wet, most years see little rain.

- The Southern Interior is comprised largely of stations in outback NSW, extending into northern SA and VIC. It has a moderate seasonal cycle and a relatively high intraseasonal variability, particularly in the warmer months.
- The Nullarbor cluster consists of three stations in that geographic region. The seasonal cycle of dewpoint is similar to the Southern Interior cluster, but the variability is lower than the stations included there.

Table 6 *Cluster means and membership. Shown are the name assigned to the cluster and the stations that make it up Also shown are the mean and standard deviation for each cluster, broken down by season.*

Cluster name	Stations	DJF	MAM	JJA	SON
Tropics	Broome, Cairns, Darwin, Galiwinku, Kalumburu, Mackay, Normanton, Pt Hedland, Rockhampton, Townsville	22.9 (0.91)	19.4 (1.41)	12.9 (1.92)	18.1 (1.46)
East Coast	Amberley, Brisbane AP, Coffs Harbour, Miles, Nowra, Richmond (NSW), Sydney, Williamtown	16.6 (1.18)	13.2 (1.42)	6.6 (1.60)	10.8 (1.57)
South East	Adelaide, Bendigo, Cabramurra, Canberra, Hobart, Launceston AP, Laverton, Melbourne, Mt Gambier, East Sale	9.8 (1.43)	8.0 (1.21)	4.4 (0.91)	6.3 (1.16)
West Coast	Albany, Cape Leeuwin, Carnarvon, Esperance, Geraldton, Katanning, Perth AP	13.5 (1.12)	12.0 (1.25)	8.7 (1.01)	9.9 (0.95)
Northern Interior	Alice Springs, Birdsville, Camooweal, Charleville, Giles, Longreach, Meekatharra, Oodnadatta, Rabbit Flat, Richmond (QLD), Tennant Creek	11.8 (3.23)	8.4 (2.98)	2.5 (2.61)	4.6 (2.93)
Southern Interior	Bourke, Cobar, Dubbo, Mildura, Moree, Tibooburra, Wagga, Woomera	10.4 (2.37)	8.6 (2.12)	4.6 (1.57)	6.1 (2.08)
Nullarbor	Ceduna, Forrest, Kalgoorlie	10.2 (1.51)	8.7 (1.72)	4.8 (1.46)	5.8 (1.40)

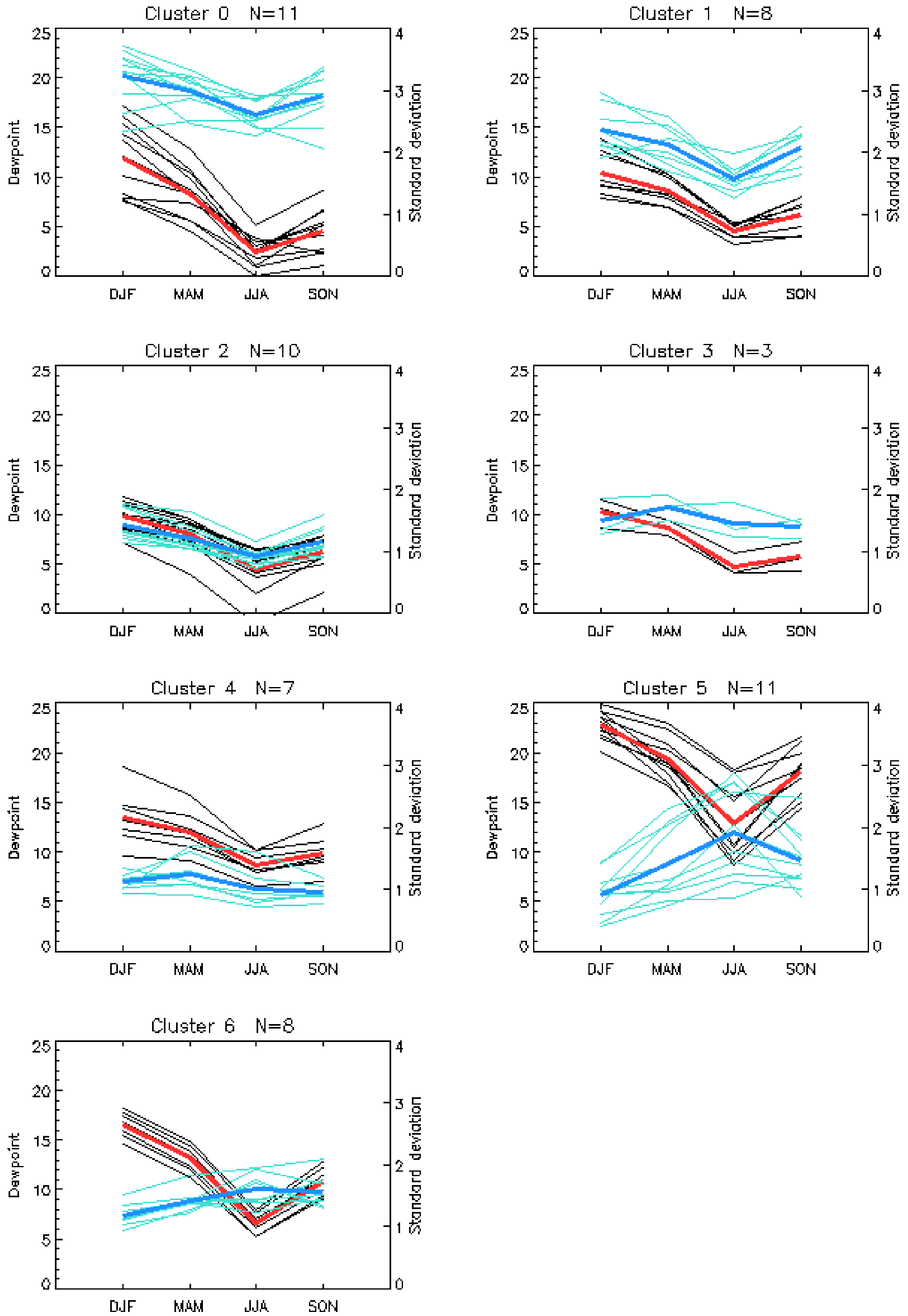


Fig. 37 *Cluster mean values of seasonal dewpoint (thick red line) and standard deviation (thick blue line). Also plotted are the profiles of individual cluster members. The associated cluster names for Clusters 0-6 are, respectively: Northern Interior, Southern Interior, South East, Nullarbor, West Coast, Tropics and East Coast.*

The time series of normalized average median dewpoint for the groups of stations identified by the cluster analysis are shown in Fig. 38. While the time series are broadly similar to the whole country average shown in Fig. 32, there are subtle differences which reflect the spatial variability of humidity over this time. The whole of Australian weather does not march in lockstep.

Many of these regional differences are noted in the severity of the negative anomalies. This is particularly the case for the West Coast group, which overall shows a smaller degree of interannual variability. For example, the dry periods in 1982, 1994 and 2002 are much weaker in the West Coast time series compared to many of the others. Similarly, the wet period in from 1973-75 noted in the other series is quite weak in the west. A qualitative comparison of (station-based) rainfall between the South East and West Coast clusters (not shown) indicates subtle but distinct differences in regional rainfall amounts between the two areas. The 1960s saw more rainfall in the west. In the southeast, the 1973-75 period typically experienced more rainfall and the 1982-3 period showed less rainfall over a longer period. The differences are subtle, but the regional rainfall differences are generally in the same sense as the dewpoint anomalies. One speculation as to the source of these differences in rainfall is related to ENSO. El Niño is known to have a smaller effect on rainfall in the west. It should also be noted that this analysis is indicative but not conclusive, as an average of spatially incoherent rainfall data from a handful of stations will not necessarily give the same signal as seen in the broader-scale regional dewpoint data.

7.5 Long-term Trends in Dewpoint

One use of homogenized series such as the one created here is in the computation of long-term trends. Homogenized data allow for a greater degree of confidence in the final calculation as artificial effects – present in most long-term weather-related time series data – have been removed. These effects often mask the true value of the trend.

Globally, an upward trend in observed near-surface humidity has been noted (e.g. Trenberth et al. 2007), although as a general rule the datasets upon which this calculation rests have not been homogenized. The magnitude of this reported trend (in specific humidity) is quite small, around 0.06 to 0.07 g kg^{-1}/decade. This value is more robust over the ocean. As noted earlier, Willett et al. (2007) confirmed this global trend with homogenized data, but their results indicated that the humidity trend in Australia was negative over many areas, the opposite of the reported global trend which was computed from 1974 (see Fig. 25).

This tendency in Australia was noted in earlier discussions. The findings from this analysis show generally spatially coherent, positive trends over the period from 1957-2003.

In this section, numerical values of the trends are computed. To create the final time series over which the trend is computed, the normalized time series of the individual stations are averaged. An average normalization factor is computed; simply the mean of the standard deviations of the dewpoint anomalies at the individual stations. An ordinary least-squares analysis is used to estimate the trend values. Monthly measurement errors equal to the standard deviation of all the values in a given month are assigned to compute the confidence interval. The confidence intervals of the trend are further altered to take into account the autocorrelation (coefficient of ~0.32 nationally at 1-month lag) in the time series (Santer et al. 2000).

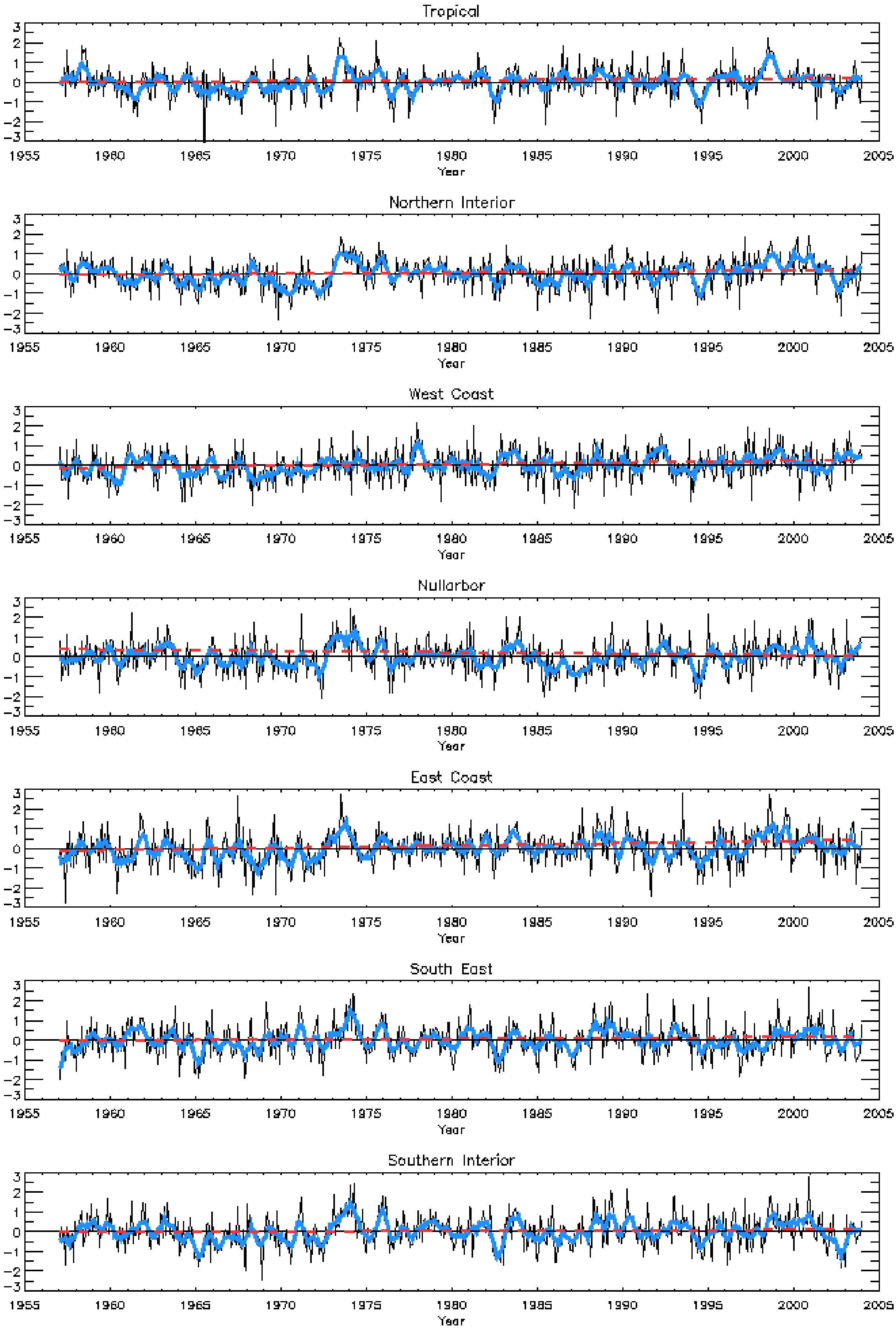


Fig. 38 *Time series of normalized monthly median dewpoint anomalies averaged over the different clusters.*

This amount of autocorrelation results in an increase of the confidence intervals (reported as 2-sigma ranges) by about a factor of 1.4. The normalized trends and confidence intervals are converted back into ‘real units’ through multiplication by the average normalization factor.

Table 7 shows the trends for the average median anomaly and associated confidence intervals, both nationally (‘all stations’) and for the regional subsets. The trends are reported in degrees of dewpoint per decade, different (but equivalent) units from the other studies in the literature. The conversion between units is not entirely straightforward as the value of the trend in specific humidity terms depends on the underlying dewpoint. The relationship between dewpoint and specific humidity is non-linear, and the mean monthly specific humidity cannot be obtained by applying a simple formula to values of the mean monthly dewpoint. For a comparison of magnitudes, a trend in dewpoint with a value of 0.1^{o}C/decade is equivalent to a trend in specific humidity of 0.052 g kg^{-1}/decade, 0.071 g kg^{-1}/decade and 0.094 g kg^{-1}/decade when the dewpoint is 10^{o}C, 15^{o}C and 20^{o}C, respectively.

Table 7 *Trends in average median dewpoint anomalies from 1957 to 2003.*

Set	Trend (^{o}C/decade)
All Stations	0.117 ± 0.130
Tropics	0.077 ± 0.083
Northern Interior	0.169 ± 0.162
West Coast	0.117 ± 0.061
Nullarbor	-0.101 ± 0.037
East Coast	0.179 ± 0.060
South East	0.057 ± 0.061
Southern Interior	0.058 ± 0.085

Nationally, the overall trend in surface dewpoint is positive at just over 0.1°C per decade. This value exceeds the confidence interval, suggesting that the sign of the trend is definitely positive. Further, the trend is roughly the same magnitude as those identified globally. Considerable regional variation is noted, although all values are nominally positive. The largest trends are found in the Northern Interior region, over twice the value of the national average. The lowest trends are found across southern Australia, particularly in the Nullarbor (where the trend is negative) and South East regions. The confidence intervals are large, in many cases larger than the values of the trends themselves. In those cases the trends are indistinguishable from zero given the confidence interval. Regionally, definitive positive trends are seen in the Northern Interior, West Coast and East Coast clusters

As suggested earlier, the final value of this small trend is highly dependent on the start and end times chosen. Willett et al. (2007) showed negative trends for much of Australia; however, this was likely because of the choice of the starting time of the trend. The period from 1973-75 was characterized by a strong La Nina and positive rainfall anomalies across most of the country, with a corresponding increase in the dewpoint (cf. Fig. 35). This is the source of their apparent negative trend.

The sensitivity of the trend values to the starting point is highlighted in Fig. 39, which estimates the 30-year trend of the monthly all-stations dewpoint anomaly using different starting points – 1 January for every year between 1957 and 1973. The figure shows the distribution of these computed trend values. Thirty-year trend values over this period range from -0.05^{o}C/decade (1973) to ~0.19^{o}C/decade (1960). Fifteen of 17 are positive, with a magnitude of over 0.05^{o}C/decade. Of the other two nominally negative trends, one is effectively zero (-

0.003°C/decade, 1972). The mean trend value over this period is 0.104°C/decade with a standard deviation of 0.06°C/decade. This provides more confidence in the value of the trend computed above. The wide confidence intervals computed earlier are mainly the result of two observations corresponding with anomalously high rainfall across Australia.

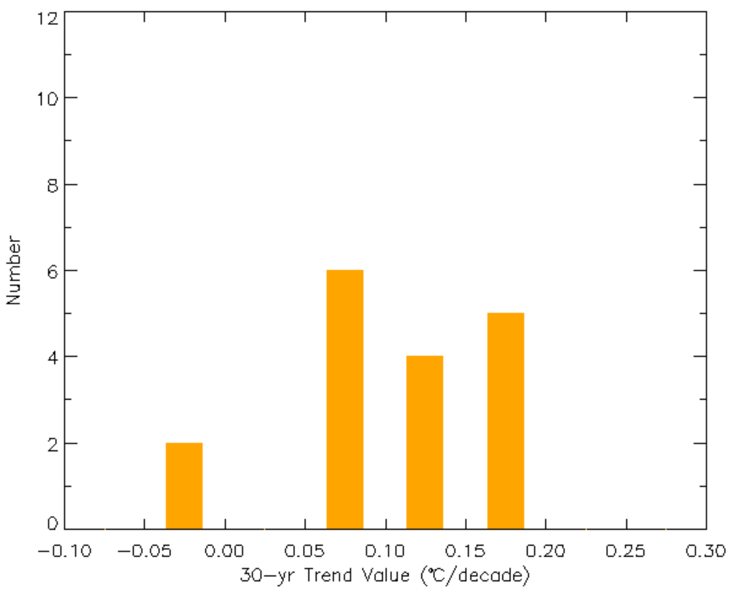


Fig. 39 *Histogram of 30-year trends in monthly median dewpoint anomalies with different starting dates. Thirty-year trends are computed starting on 1 January for every year between 1957 and 1973.*

The findings in this section suggest that the estimate of the general humidity trend in Australia is broadly consistent with the global trend identified in other studies. It seems unlikely that the general overall trend for Australia is negative, as reported in Willett et al. (2007); that finding is likely a result of the unfortunate choice of starting the calculation during one of the wettest periods in recent Australian history. There are also variations in the regional values of the trends. The largest trends are noted in northern parts of Australia, away from the immediate coast. In the southern reaches of the country, the trends are smaller, and the confidence intervals here include the possibility of negative trends. The true trend value remains uncertain; the confidence intervals are quite large.

Globally, Willett et al. attributed an indirect anthropogenic source to the increasing humidity. Climate simulations hypothesize that water-vapour feedback processes act to keep relative humidity approximately constant around the globe (e.g. Pierrehumbert et al. 2006). Rising temperatures increase the saturation vapour pressure of the atmosphere. As a result, the actual amount of water vapour must also increase to maintain constant RH. Evidence suggests this is true in the real world throughout the troposphere as well as in the models (Santer et al. 2007; Dessler et al. 2008). An increase in mean temperatures has been observed over much of Australia since the middle of the 20th century (Nicholls 2006), suggesting that a corresponding increase should also be seen in surface humidity.

It is difficult to conclusively state at this juncture whether the observed increase in dewpoint observed in this study is due to anthropogenic sources. One factor confounding this observation is the observed strong relationship between anomalies of dewpoint and rainfall (Fig. 34). Over roughly half of Australia, annual rainfall totals have been increasing, particularly in the northwestern part of the country. In the eastern and southwest portions of the country, rainfall totals have been declining (Nicholls 2006). However, the dewpoint trends from individual stations (Fig. 24; Table 5) do not replicate the rainfall pattern. The highest humidity trends are observed in western QLD and central Australia, regions where the trends in rainfall are weak or even negative. Many stations on the east coast are showing strong positive trends despite a strong negative trend in rainfall. In southern Australia where the lowest trends in humidity are observed, declining rainfall could be acting to moderate global trends driven by anthropogenic warming.

8 SUMMARY AND CONCLUSIONS

This study describes the procedures used creation of a high-quality, historical surface humidity dataset for Australia. The time period of the dataset extends from 1957 through 2003; 58 individual stations across Australia are used. The data have been homogenized; that is, artificial non-meteorological changes in the characteristics of the data have been identified and removed. This procedure provides a better basis for estimating the long-term changes in humidity across Australia. The dataset, consisting of monthly quantities, will be available through the National Climate Centre of the Bureau.

In the first step of this homogenization procedure, the data are subjected to extensive quality control procedures, both automated and manual. The procedures identify periods of poor quality measurements in the form of spikes and tracking errors in the data, which are subsequently removed from further analysis.

The homogenization proceeds by comparing the data at the candidate station with a homogeneous reference series representative of the area. As a rule, such series do not exist naturally; they must be created from a composite of nearby stations. To create these series, data from nearby reference stations are meticulously compared and combined to produce the final reference series. Typically, between four and nine stations are used in any one reference series. In total, data from over 250 stations were used directly to create the reference series; many other stations were considered but not used in the solutions.

Departures of the candidate station from this reference series are statistically evaluated to identify ‘breakpoints’ – points in time where an artificial change has occurred in the time series. The magnitude of the change is determined and a correction is applied. There are known causes to some of these breakpoints, but in the majority of cases no cause can be identified. Typically, about five breakpoints are identified in each series. Homogenisation changes applied to the dewpoint are on the order of 0.5 degrees, with a slight preference towards negative changes. A peak in the timing of breakpoints is seen in the mid-1990s; much of this peak corresponds the beginning of the AWS Epoch, when data from these instruments became the official measurements.

The refined dataset is used to make a preliminary investigation of the climatology of surface humidity in Australia. The spatial patterns and typical ranges of variability at a given location are presented. Several different patterns of behaviour in dewpoint were identified, each corresponding to a broad geographical region.

The interannual variability of dewpoint is also examined. Nationally averaged, the highest dewpoints were observed in the mid-1970s. Extended periods of positive anomalies were also observed in the late-1980s and late-1990s. Extended periods of low-dewpoint were observed in the 1960s, with several shorter dry periods seen since that time. For the country as a whole, monthly median dewpoint anomalies are shown to correlate quite strongly with anomalies in rainfall with zero lag. Interestingly, dewpoint anomalies for several months ahead of a rainfall anomaly show a weak, but significant positive correlation as well. The physical reason for such a correlation is unknown.

The longer-term trends in humidity are also examined. As a national average, a trend of 0.117 ± 0.130^{o}C/decade in dewpoint is observed. This value, when converted to appropriate (but equivalent) units, agrees well with global trends in humidity identified in Dai (2006) and Willett et al. (2007). The trends do vary spatially, with the highest trends being observed in the northern interior of the continent. The lowest trends, although still nominally positive, were in the southern part of the country. No attribution of the source of the trend is given at this time, although the value is broadly consistent with that expected from simulations of the climate.

This dataset is important in that it allows a confident look at the long term behaviour in dewpoint across the country. Future work could be done to expand upon this project. There are more stations that could be added and the stations that are included will periodically need to be extended forward in time. An attempt could be made to extend the homogenization to times other than 0900; an afternoon time (say 1500) would be a useful addition. Higher temporal precision in making the adjustments to the time series by incorporating the metadata information more explicitly would subtly affect the results, but would be a useful addition. This could result in the addition (or subtraction) of more breakpoints. Finally, more work could be done to expand our understanding of the observed climatology and the physical drivers behind it.

9 REFERENCES

Alduchov, O.A. and Eskridge, R.E. 1996: Improved Magnus form approximation of saturation vapor pressure. *J. Appl. Meteor.*, **35**, 601-9.

Bryson, R.A. 1997. The paradigm of climatology: An essay. *Bull. Am. Meteor. Soc.*, **78**, 449-55.

CIMO 1996: “Measurement of Humidity” in Guide to Meteorological Instruments and Methods of observations, WMO No 8, World Meteorological Organisation, Ch 4., 25 pp.

Dai, A. 2006: Recent climatology, variability and trends in global surface humidity. *J. Climate,* **19**, 3589-606. doi: 10.1175/JCLI3816.1.

DeGaetano, A.T. 2006: Attributes of several methods for detecting discontinuities in mean temperature series. *J. Climate*, **19**, 838-53.

Dessler, A.E., Zhang, Z. and Yang, P. 2008: Water-vapor climate feedback inferred from climate fluctuations, 2003–2008, *Geophys. Res. Lett.*, **35**, L20704, doi:10.1029/2008GL035333.

Easterling, D.R. and Peterson, T.C. 1995: A new method for detecting undocumented discontinuities in climatological time series. *J. Int. Climatol*., **15**, 269-377.

Everitt, B.S. 1993: *Cluster Analysis*. Halsted Press, New York.

Gaffen, D.J. and Ross, R.J. 1999: Climatology and trends of U.S. surface humidity and temperature. *J. Climate*, **12**, 1648-61.

Jovanovic, B., Jones, D.A. Collins, D. 2007: A high-quality monthly pan-evaporation dataset for Australia. *Climatic Change*, doi:10.1007/s10584-007-9324-6.

Lucas, C. 2006: An examination of dewpoint biases introduced by different instrumentation. . *BMRC Res. Lett*., **4**, Available from http://www.bom.gov.au/bmrc/pubs/researchletter/reslett_04/reslett_04.pdf.

MacGregor, G. R. 2006: Climatology: Its scientific nature and scope. *Int. J. Climatol.*, **25**, 1-5.

Menne, M.J. and Williams Jr, C.N. 2005: Detection of undocumented changepoints using multiple test statistics and composite reference series. *J. Climate*, **18**, 4271-86.

Nicholls, N. 2006: Detecting and attributing Australian climate change: a review. *Aust. Meteor. Mag*., **55**, 199-211.

Nicholls, N., Collins, D., Trewin, B. and Hope, P. 2006: Historical instrumental climate data for Australia – quality and utility for paleoclimatic studies. *J. Quarternary Sci.*, **21**, 681-8.

Panofsky, H.A. and Brier, G.W. 1968: *Some Applications of Statistics to Meteorology.* The Pennsylvania State University, 224 pp.

Peterson, T.C. and Easterling, D.R. 1994: Creation of homogeneous composite climatological reference series. *Int. J. Climatol*., **14**, 671-9.

Peterson, T.C., Easterling, D.R., Karl T.R. and others, 1998: Homogeneity adjustments of in situ atmospheric climate data: A review. *Int. J. Climatol.*, **18**, 1493-517.

Pierrehumbert, R.T., Brogniez, H. and Roca, R. 2006: On the relative humidity of the Earth's atmosphere, in *The Global Circulation of the Atmosphere*, Princeton Univ. Press, Princeton, N. J.

Robinson, P.J. 1998: Monthly variations in the dew point temperature in the coterminous United States. *Int. J. Climatol*., **18**, 1539-56.

Robinson, P.J. 2000: Temporal trends in United States dew point temperatures. *Int. J. Climatol*., **20**, 985-1002.

Santer, B.D. and others. 2000: Interpreting differential temperature trends at the surface and in the lower troposphere. *Science*, **287**, 1227-32.

Santer, B.D. and others. 2007: Identification of human-induced changes in atmospheric moisture content. *Proceedings of the National Academy of Sciences*, **104**, 15248-52.

Strangeways, I. 2003: *Measuring the Natural Environment, 2nd Edition*. Cambridge University Press, 534 pp.

Trenberth, K.E., Jones, P.D., Ambenje, P., Bojariu, R., Easterling, D., Klein Tank, A., Parker, D., Rahimzadeh, F., Renwick, J.A., Rusticucci, M., Soden B. and Zhai, P. 2007: Observations: Surface and Atmospheric Climate Change. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor M. and. Miller H.L (eds.)). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Trewin, B. 2001 Extreme temperature events in Australia. PhD thesis, Melbourne Uni.

Wang, J.X.L. and Gaffen, D.J. 2001: Late twentieth century climatology and trends of surface humidity and temperature in China. *J. Climate*, **14**, 2833-45.

Willett, K.M., Gillett, N.P., Jones P.D. and Thorne, P.W. 2007: Attribution of observed surface humidity changes to human influence. *Nature*, **449**, 710-3. doi:10.1038/nature06207.

Willet, K. M. 2007: Creation and analysis of HADCRUH: A new global surface humidity data set. Ph D. thesis, 198 pp.

Wolter, K., and M. S. Timlin. 1998: Measuring the strength of ENSO events - how does 1997/98 rank? *Weather*, **53**, 315-24.

Wunsch, C. 1999: The interpretation of short climate records, with comments on the North Atlantic and Southern Oscillations. *Bull. Am. Meteor.Soc*., **80**, 245-55.

10 APPENDIX A. HOMOGENIZATION DETAILS BY STATION

This section provides details and notes for each candidate station included in the homogenization. For each locale there is a short paragraph highlighting the physical details of the station and the locations of reference stations. An overall subjective judgment of the quality and reliability of the different aspects of homogenization is also provided.

Next is a list of the reference stations used in the homogenization (station numbers; refer to Appendix B for names and locations) and the amount of bias identified in the last season (SON 2003) used to calibrate the series as noted in step 10. Also shown are the geographic coordinates of the station(s) and the instrumentation used to measure humidity at the end of the record.

The ‘candidate minus reference’ time series is presented in the figure. The details of this graph are identical to those presented in Fig. 11 in the main text. The chart graphically shows the strength, timing and statistical significance of the identified breakpoints. Similar information is tabulated below. Additionally, the table also identifies the likely cause of a given breakpoint if such information is available (it generally isn’t…). Alternatively, breakpoints which aren’t statistically significant but included anyway are also noted in this column. If only one of the tests returns a statistically significant result, this is noted as well. Often on these marginal breakpoints, the p-value of the statistical test is also given

Also noted in the table are the additional breakpoints identified in the ‘second pass’ of the homogenization. Nine stations were identified to have additional breakpoints in this analysis. In general, these breakpoints will not be visible on the ‘candidate-reference’ graph. On the individual station tables, they are noted in the comments.

Finally, the amount of adjustment required between the final breakpoint and the end of the series is also noted. At a few sites, the significance level (‘plev’) used in the initial identification of breakpoints was changed. This is indicated here as well.

10.1 Adelaide

This site is a composite. The original observations extended until February1977, when the new station moved to the other side of the CBD, further away from the coast. Between 4 and 8 reference stations are present at all times. Reference stations are nearby, with the furthest being 106 km away. A relatively high number of breakpoints at the station, with few obvious sources indicated in the metadata. Quality: **Good.**

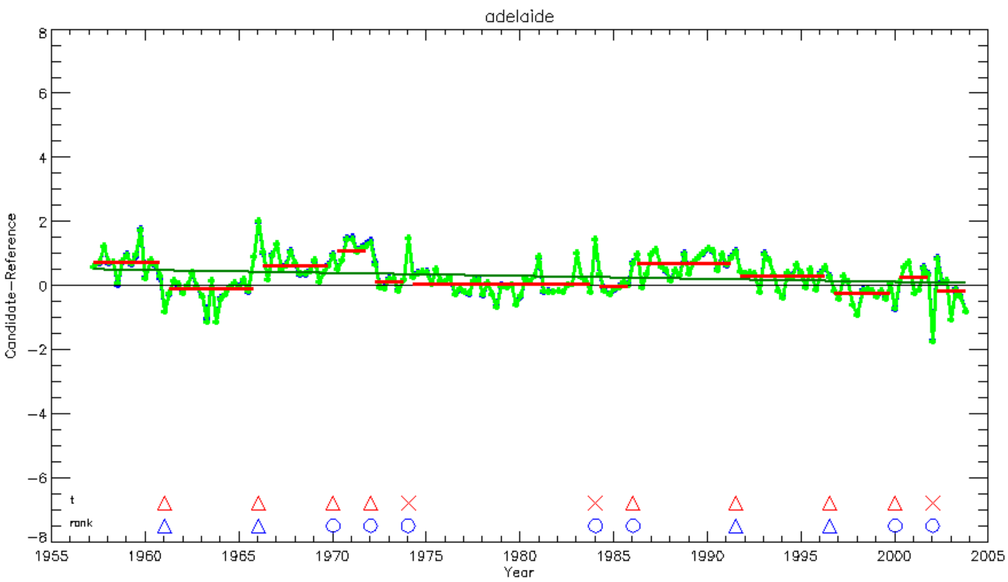
Location: -34.9330 138.5833 (original site: -34.9254 138.5869)

Station numbers: 23000, 23090 (current)

2003 Instrumentation: PRT

Reference stations: 23034, 24521, 23083, 23733, 22008, 23321, 23057, 23031

Last Season Bias Adjustment: -0.8



Season/Year	Strength	Cause
DJF02	-0.5	
DJF00	+0.5	
JJA96	-0.5	AWS epoch
JJA91	-0.4	
DJF86	+0.7	
DJF72	-1.0	
DJF70	+0.5	
DJF66	+0.7	
DJF61	-0.9	

Initial Adjustment: -0.2

10.2 Albany

This station is a composite site. The original observations (up until 1965) were made in Albany Town, right on the coast. The airport observations were made a significant distance inland (~11 km). The sites were joined in June 1965. There is some evidence that the dewpoint data at the new station are biased high in 1965 and 1966, but they are retained unchanged in the analysis. A distinct difference in the dewpoint climate is apparent between the two stations. Full observations at the original site have subsequently been re-started in 2002, but are not used here. An adjustment is made at the time of the change, but the results may be a bit uncertain. There are between 4 and 7 reference stations throughout. Reference stations range from 125-300 km distant. Quality: **Fair.**

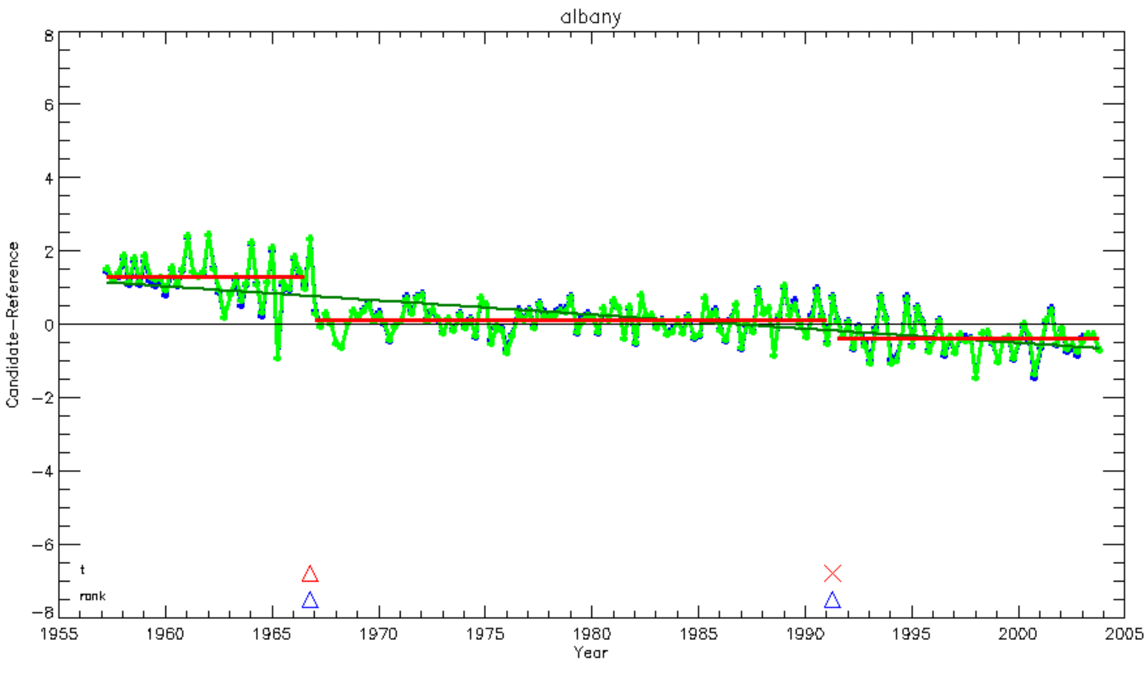
Location: -34.9414 117.8022 (original site: -35.0289 117.8808)

Station Numbers: 9500,9741 (current)

2003 Instrumentation: PRT

Reference Stations: 9573, 9538, 10622, 9592, 10648, 10592, 9534

Last Season Bias Adjustment: -0.7



Season/Year	Strength	Cause
MAM91	-0.4	AWS begin
SON66	-1.0	site change (1 yr before)
DJF62	-0.4	2nd pass, although visible when plev=0.05

Initial Adjustment: -0.4

10.3 Alice Springs

This station has continuous high-resolution observations throughout its record. SitesDB suggests a minor site move in 1974. The record shows a large amount of variability and several high-magnitude breakpoints. The difference plot is noisy. Five to eight reference stations through most of period, although only 3 before mid-60s. A total of 9 stations used in composite. Reference stations are generally quite far away, with stations from 230-580 km distant. Quality: **Good**

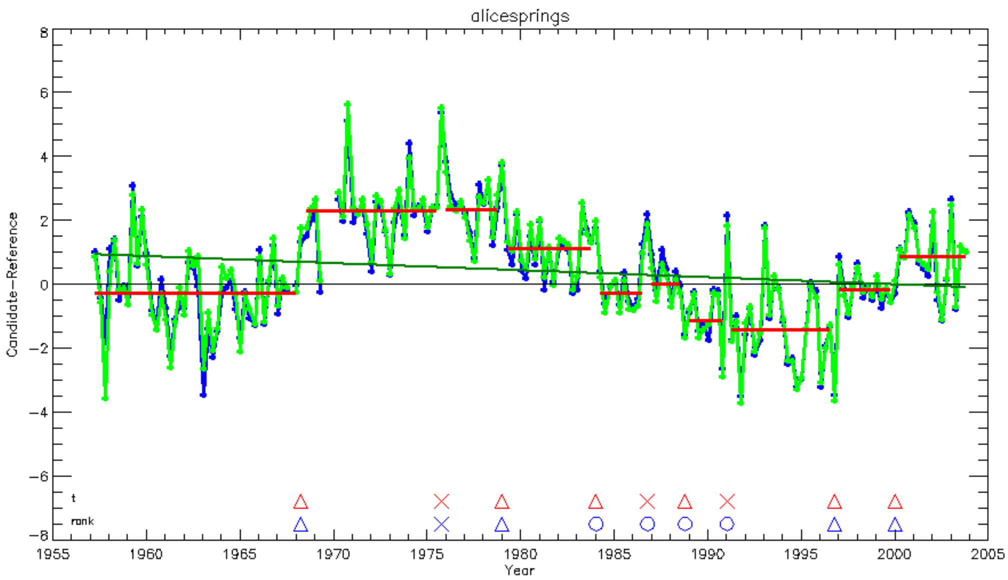
Location: -23.7951 133.8890

Station Numbers: 15590

2003 Instrumentation: PRT

Reference Stations: 15511, 15528, 15602, 15603, 17043, 13017, 15526, 16085, 15635

Last Season Bias Adjustment: 1.0



Season/Year	Strength	Cause
DJF00	+1.0	
SON96	+1.2	AWS epoch
DJF91	-0.3	not significant
SON88	-1.1	
SON86	+0.3	not significant
DJF84	-1.4	
DJF79	-1.2	
MAM68	+2.5	

Initial Adjustment: 0.8

10.4 Amberley

A station that has good time resolution aside from a 6-year period in late-80s/early-90s when only 2 observations a day were available. There are typically between 4 and 7 reference stations. There is a period of a few seasons with only 3 reference stations. Quality: **Good**

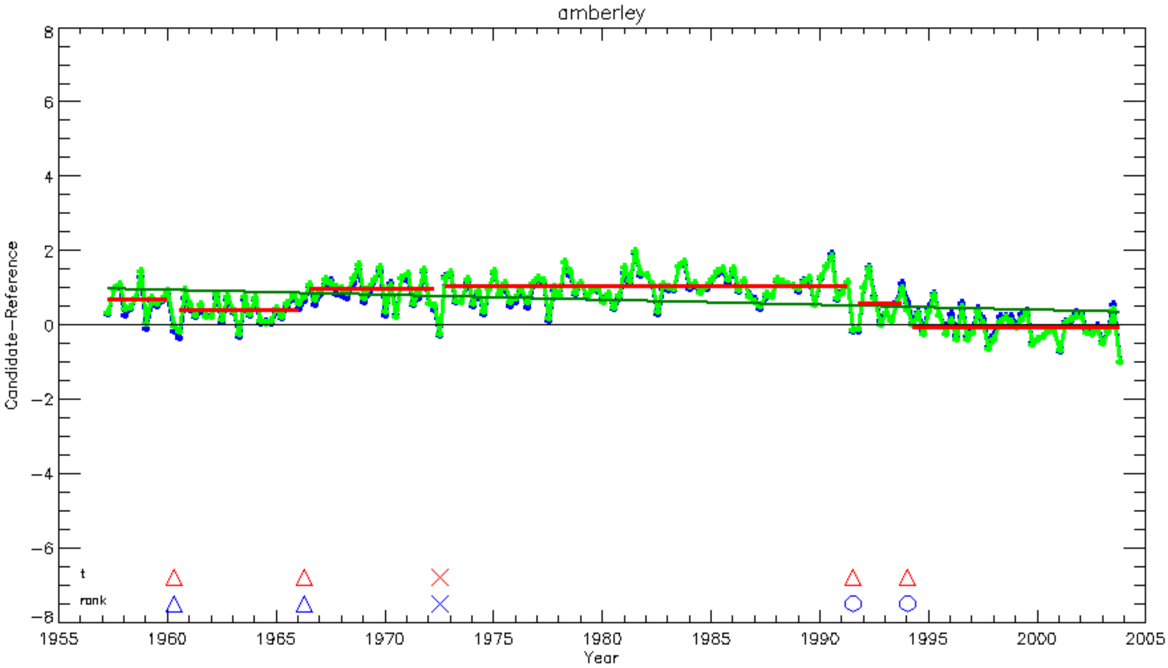
Location: -27.6297 152.7111

Station Number: 40004

2003 Instrumentation: PRT

Reference Stations: 40211, 40223, 40842, 40214, 58158, 58012, 40264, 58130, 58131

Last Season Bias Adjustment: -1.0



Season/Year	Strength	Cause
DJF94	-0.6	
JJA91	-0.5	
MAM66	+0.6	
MAM60	-0.3	

Initial Adjustment: -0.1

10.5 Bendigo

This is a composite station, with the move coming in October 1991. Initially, the observations were made at Bendigo Prison, later transferring to the airport. The AWS reading become official in 1993. There are between 4 and 10 reference stations throughout the record. All are relatively close, within 200 km. Quality: **Good**

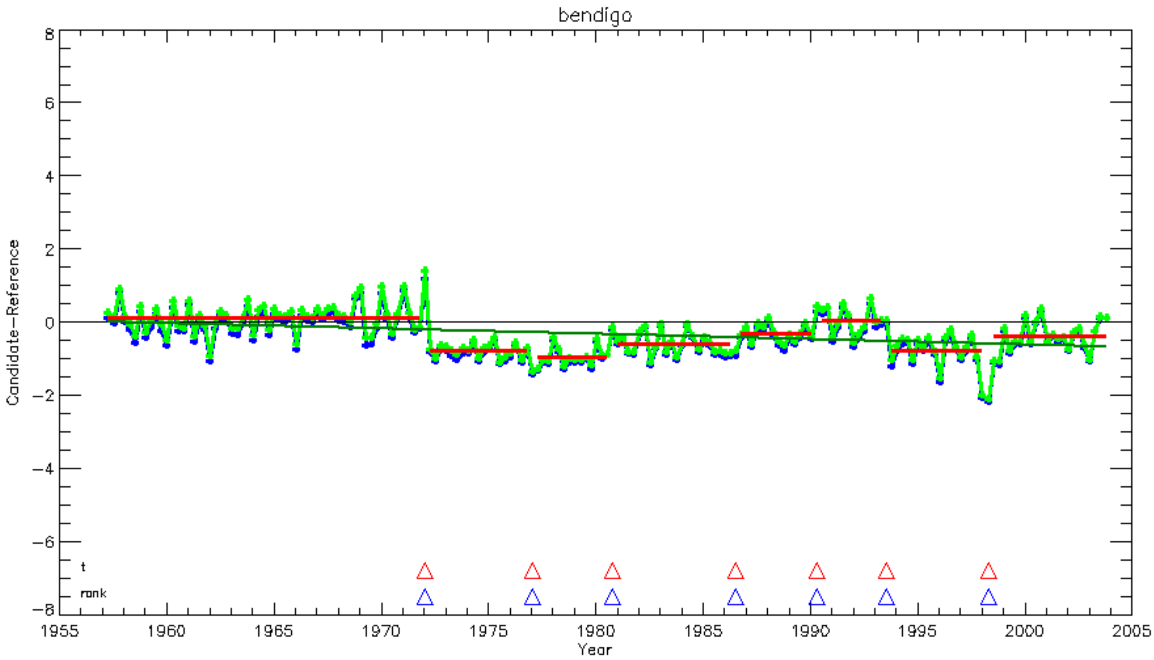
Location: -36.7394 144.3267 (current), -36.7533 144.2825

Station Numbers: 81003, 81123 (current)

2003 Instrumentation: PRT

Reference Stations: 80015, 82042, 88110, 82002, 74128, 88109, 77042, 89085, 79040, 89002

Last Season Bias Adjustment: 0.1



Season/Year	Strength	Cause
MAM98	0.3	
JJA93	-0.8	AWS install may93
MAM90	+0.4	
JJA86	+0.3	
SON80	+0.4	
DJF77	-0.2	
DJF72	-1.0	

Initial Adjustment: -0.4

10.6 Birdsville

This station has poor resolution through most of the record, and the quality of some of the observations is probably doubtful, too. This is particularly true in the early periods of the record. The paper metadata suggests observer changes in 1965 and 1968, which line up with some changes in the candidate-reference series (although not identified in the breakpoints). Reference stations are far away (260 km to closest!) and the plots are very noisy. A total of 9 stations used, although only 3 are available early on. A nearby AWS also exists, but is not included in the record here. Quality: **Fair**

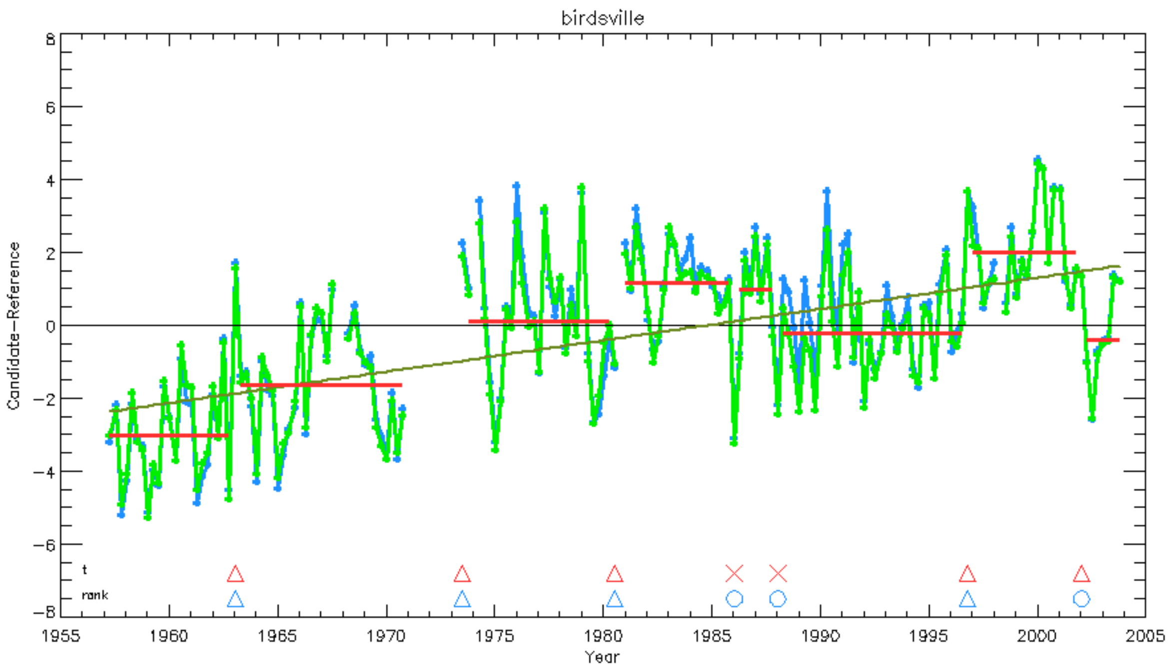
Location: -25.9003 139.3486

Station Numbers: 38002

2003 Instrumentation: Hg

Reference Stations: 16065, 17043, 17005, 17110, 15603, 16001, 19017, 16085, 17096

Last Season Bias Adjustment: 1.2



Season/Year	Strength	Cause
DJF02	-2.4	
SON96	+2.4	
DJF88	-1.2	not significant
JJA80	+1.0	
JJA73	+1.7	
DJF63	+1.3	

Initial Adjustment: -0.4; plev=0.05

10.7 Bourke

This station is a composite station, with two site moves. The first was in 1994 and the second in 1998. This station has poor data resolution prior to 1987, but the quality appears reasonable. There is a significant period of missing data in the early 1970s, both in the candidate series and at the reference stations, where only two are briefly available at one point. Quality: **Good with some shortcomings.**

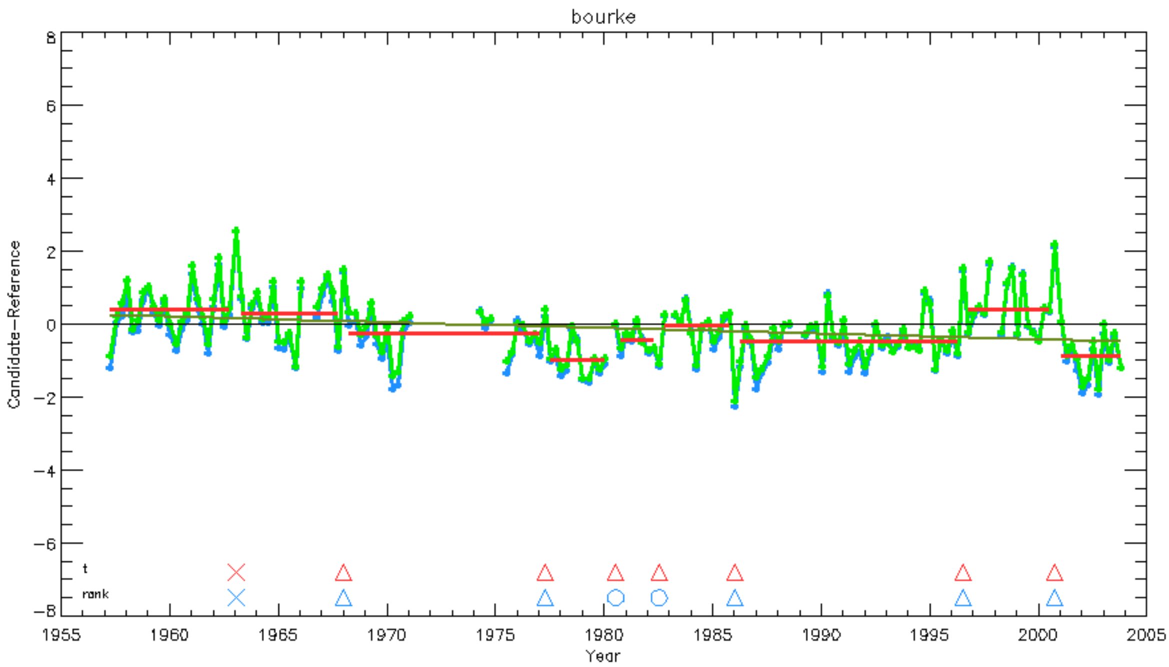
Location: -30.0362 145.9521 (current), -30.0917 145.9358, -30.0423 145.9520

Station Numbers: 48013,48239,48245 (current)

2003 Instrumentation: HP

Reference Stations: 48030, 48027, 51039, 46043, 64008, 49019, 65012, 50052

Last Season Bias Adjustment: -1.2



Season/Year	Strength	Cause
SON00	-1.3	
JJA96	+0.8	
DJF86	-0.4	
JJA82	+0.4	
JJA 80	+0.5	
MAM77	-0.6	
DJF68	-0.5	

Initial Adjustment:-0.9; plev=0.05

10.8 Brisbane AP

This site is a composite station, with the join occurring in 1995 in this study. This is a high-quality station with good data resolution throughout. Four to seven nearby reference stations are available at all times. The second pass breakpoints look to be associated with a few seasons of poor observations at the site, rather than a long-term problem. Quality: **Good**

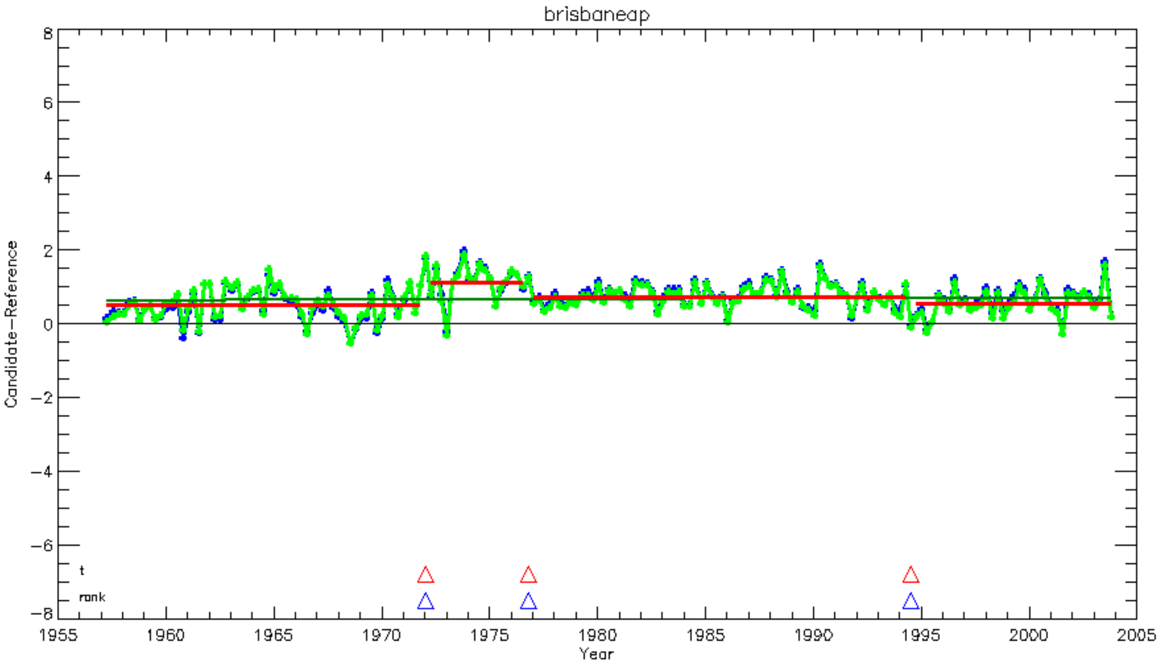
Location: -27.3917 153.1292 (current), -27.4178 153.24

Station Numbers: 40223, 40842 (current)

2003 Instrumentation: PRT

Reference Stations: 40211, 58158, 40264, 40004, 40214, 58131, 58012, 40126

Last Season Bias Adjustment: 0.2



Season/Year	Strength	Cause
MAM95	0.4	2nd pass
JJA94	-0.3	
DJF93	-0.4	2nd pass
SON76	-0.5	
DJF72	+0.7	

Initial Adjustment: 0.5

10.9 Broome

Reference stations are a bit dodgy and hard to come by in this part of Australia. This makes the homogenization a bit more uncertain. This is done to help relieve problems with the station spatial distribution. The data quality and time resolution at Broome itself is good. Broome has the highest believable dewpoints observed in Australia, realistically in excess of 28 C quite often. Quality: **Good**

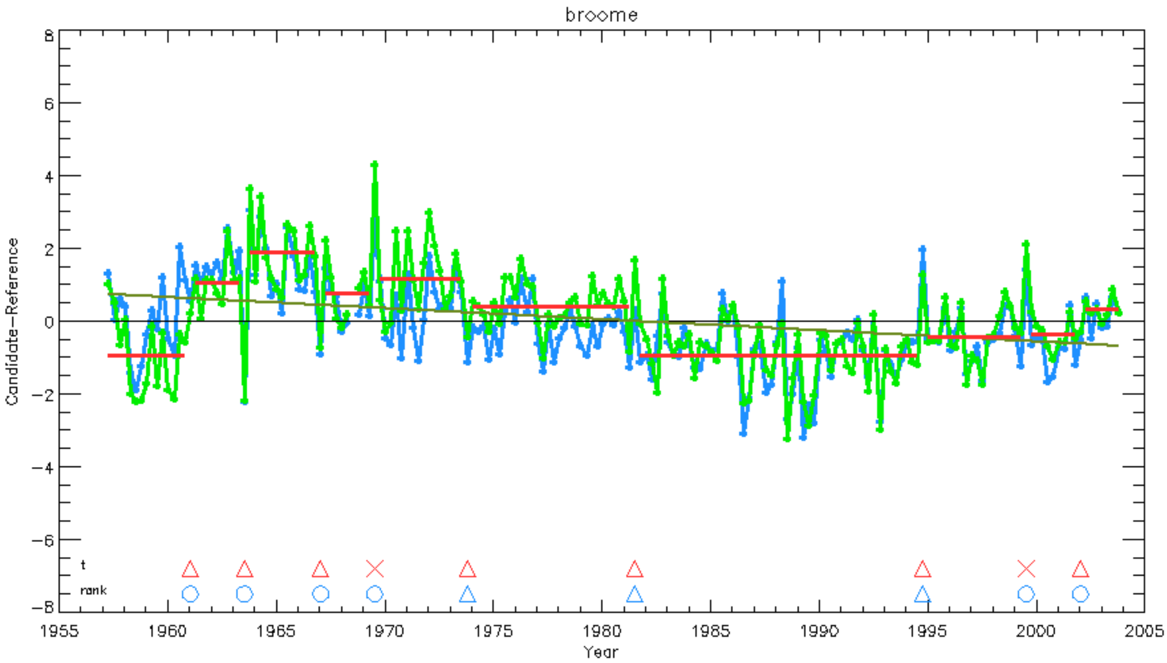
Location: -17.9492 122.2336

Station Number: 3003

2003 Instrumentation: PRT

Reference Stations: 3030, 1005, 1013, 1012, 3080, 1021, 3032, 3007, 4032

Last Season bias adjustment: 0.2



Season/Year	Strength	Cause
DJF02	+0.7	
SON94	+0.6	
JJA81	-0.8	
SON73	-0.8	
JJA69	0.4	
DJF67	-1.1	
JJA63	0.8	
DJF61	2.0	

Initial adjustment: 0.3

10.10 Cabramurra

This is a relatively poor station, with only one observation a day through very much of record. SitesDB suggests that humidity observations were perhaps not always up to standard during the pre-AWS days. It is also a composite station, with the join occurring in March 1997. There are only 3 reference stations early in the record. The apparent breakpoint at SON69 has not been included in the data. This looks like an artefact of the analysis, and not a real breakpoint (i.e. the 'random walk' noted in the main text. It has been ignored. Quality: **Fair**.

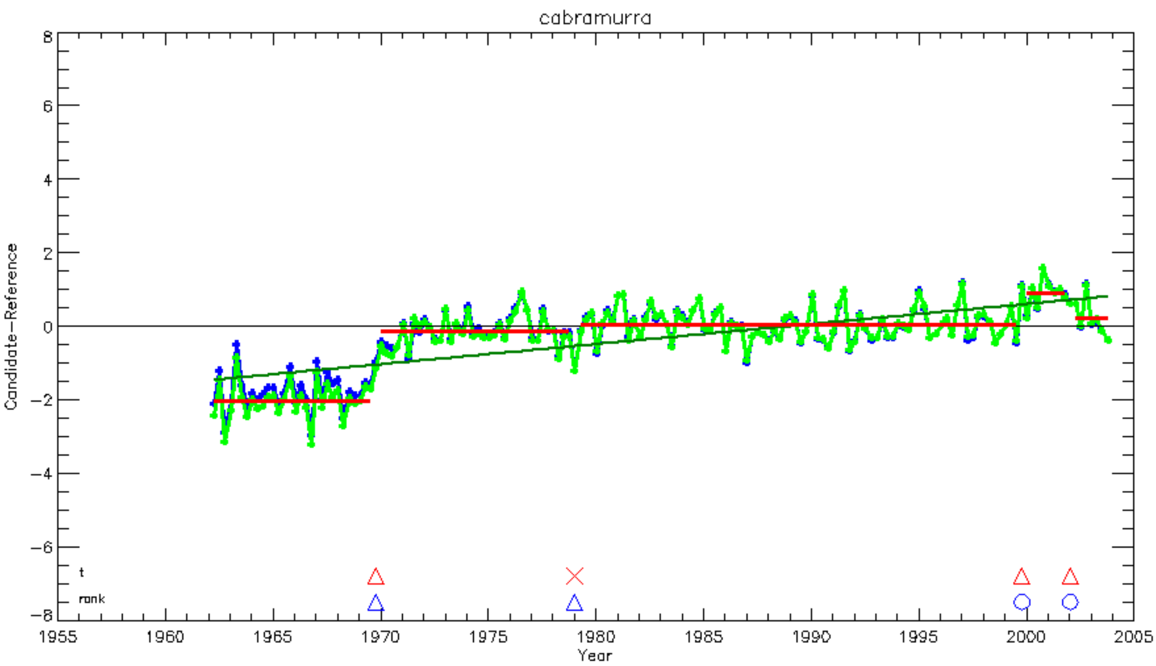
Location: -35.9371 148.3779 (current), -35.9383 148.3842

Station Numbers: 72091, 72161 (current)

2003 Instrumentation: HP

Reference Stations: 72043, 82011, 73007, 72023, 83025, 70263, 82002, 70014, 68102

Last Season Bias Adjustment:-0.4



Season/Year	Strength	Cause
DJF02	-0.7	
SON99	+0.8	
DJF79	+0.3	

Initial adjustment: 0.2

10.11 Cairns

This station has good temporal resolution and between 4 and 9 reference stations at all times. Metadata indicates a small movement of the instruments in July 1999. Reference stations are generally close by. Quality: **Good**

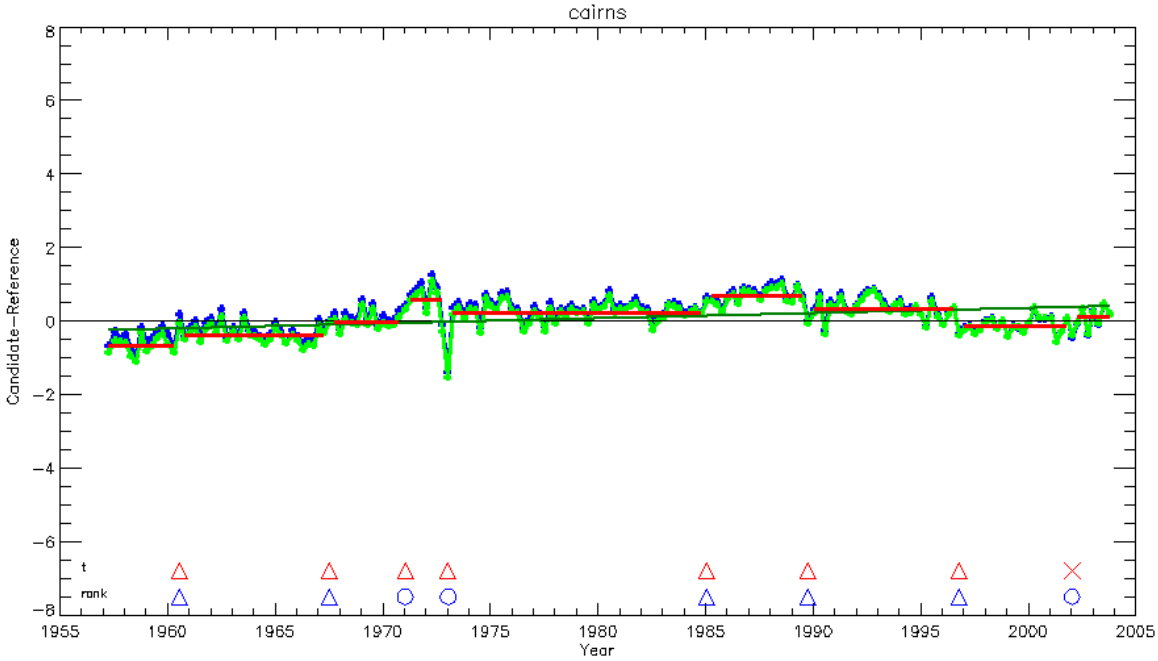
Location: -16.8736 145.7458

Station Number: 31011

2003 Instrumentation: PRT

Reference Stations: 31037, 32037, 31034, 31084, 31029, 31108, 32025, 32040, 28004

Last Season Bias Adjustment: 0.2



Season/Year	Strength	Cause
DJF02	+0.2	not significant
SON96	-0.4	AWS epoch
SON89	-0.3	
DJF85	+0.4	
DJF73	-0.3	
DJF71	+0.6	
JJA67	+0.4	
JJA60	+0.3	

Initial Adjustment: 0.1

10.12 Camooweal

Several periods of missing data and obviously incorrect observations (in the 1995-96 time period). Good temporal availability of reference stations, but closest is 165 km away. Most are much further away. Quality: **Fair**

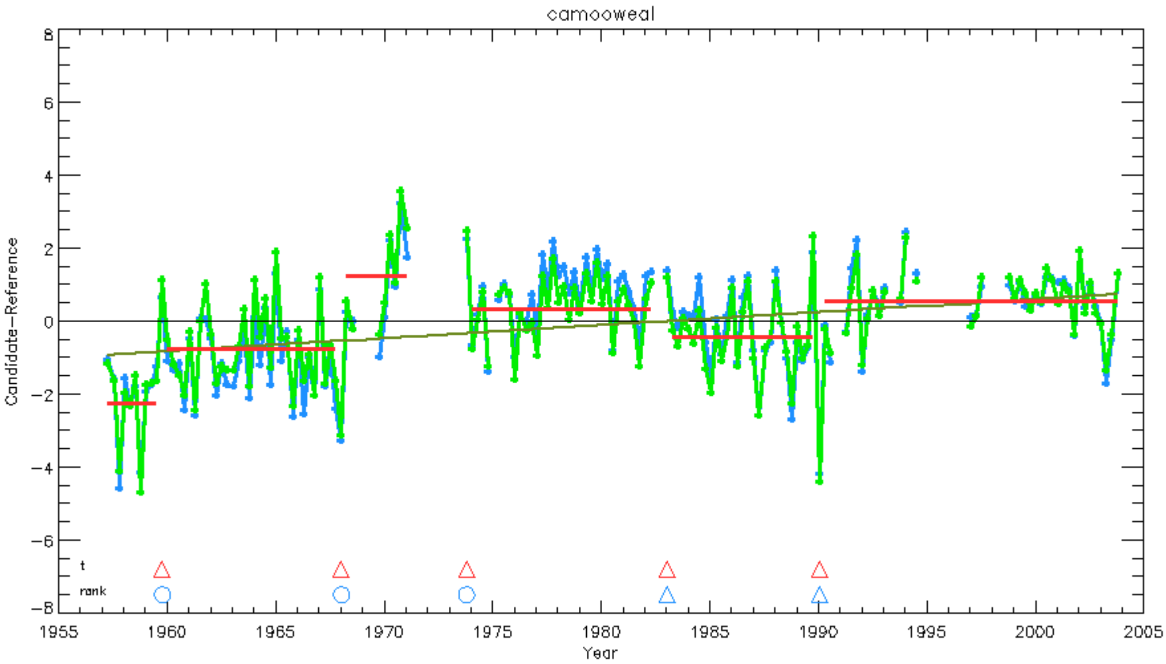
Location: -19.9225 138.1214

Station Number: 37010

2003 Instrumentation: HP

Reference Stations: 29127, 37043, 29025, 15085, 15135, 30045, 37051, 15087, 15034, 29141, 38003

Last Season Bias Adjustment: 1.3



Season/Year	Strength	Cause
DJF90	+1.0	
DJF83	-0.8	
SON73	-0.9	
DJF68	+2.0	
SON59	+1.5	

Initial Adjustment: 0.5

10.13 Canberra

This is a good quality station with high resolution data. An adequate number of nearby reference stations is available, although only three are present early in the record. The second pass breakpoints appear when plev=0.06. After the AWS is installed, this station uses a PRT to measurure humidity before later switching to a humidity probe. The AWS appears to start before the official epoch at this station, with the breakpoint in DJF95. Quality: **Good.**

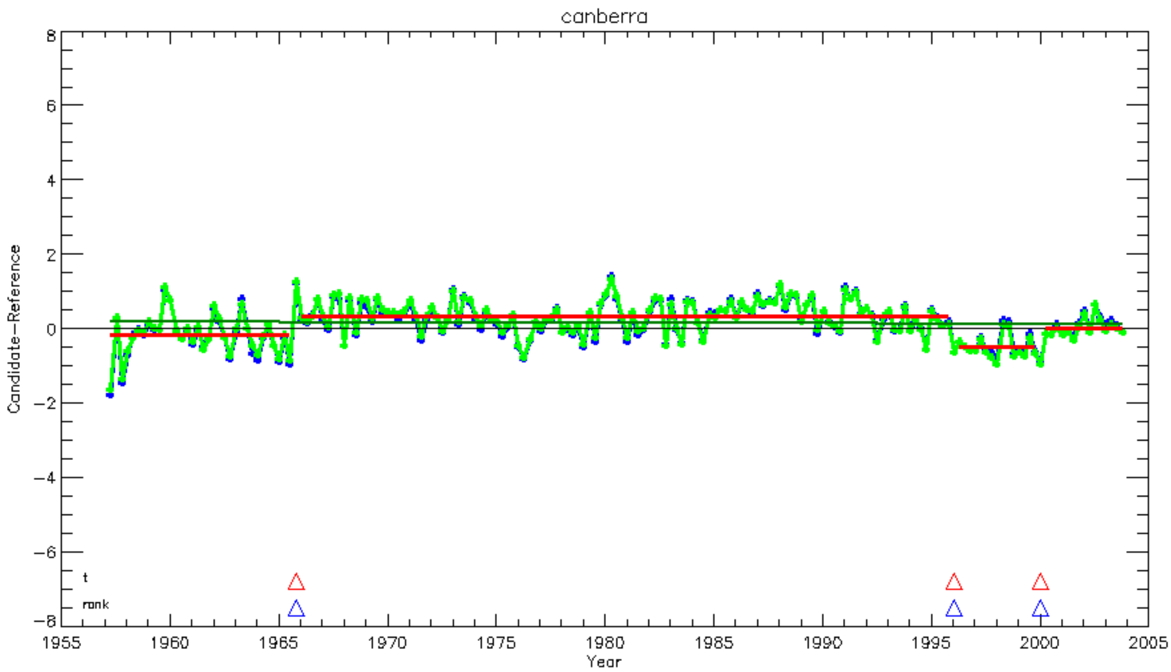
Location: -35.3049 149.2014

Station Number: 70014

2003 Instrumentation: HP

Reference Stations: 73009, 72150, 83025, 68102, 65091, 69049, 72023

Last Season Bias Adjustment: -0.1



Season/Year	Strength	Cause
DJF00	+0.5	humidity probe installed feb00
DJF96	-0.7	AWS install dec95
JJA92	-0.4	2nd pass
JJA84	+0.3	2nd pass
SON65	+0.7	

Initial Adjustment: 0.0

10.14 Cape Leeuwin

This station has relatively poor time resolution, only 2 observations per day over much of the record. There is also a significant gap during the late-1960s and early 1970s. This station is literally right on the coast, and probably not particularly representative of the regional conditions at large. The AWS becomes the only reading upon installation in 1993. Quality: **Fair**

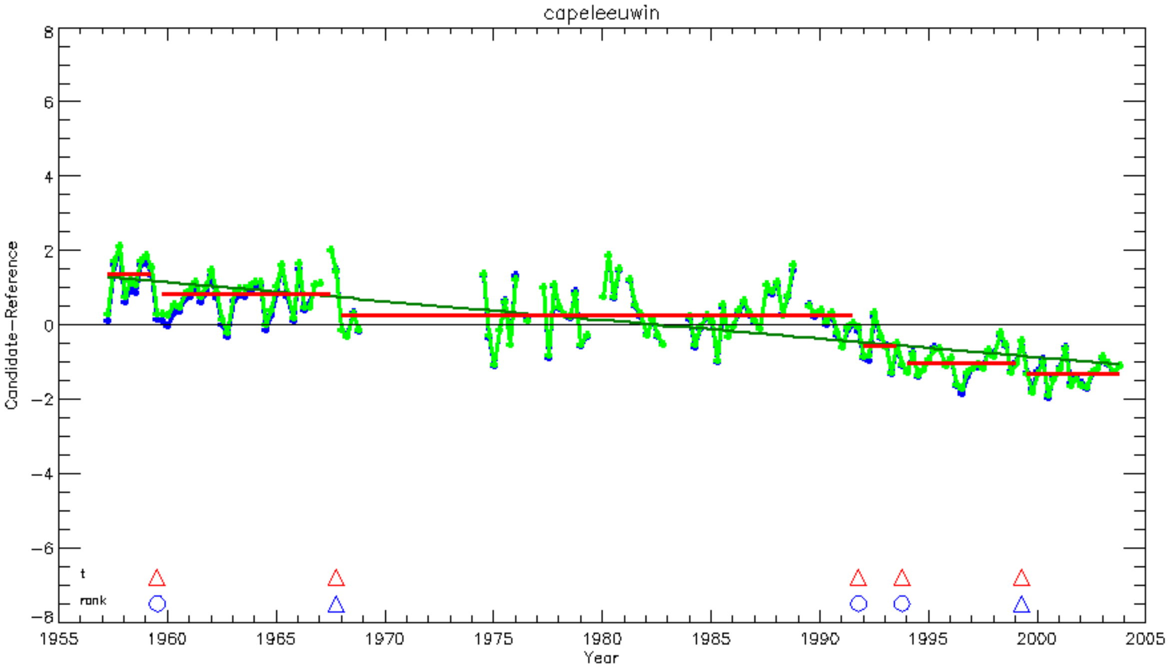
Location: -34.3728 115.1358

Station Number: 9518

2003 Instrumentation: PRT

Reference Stations: 9592, 9573, 9538, 9515, 9534, 9021, 9741, 9500, 9519

Last Season Bias Adjustment: -1.1



Season/Year	Strength	Cause
MAM99	-0.3	
SON93	-0.5	AWS install feb93
SON91	-1.0	
SON67	-0.8	
JJA59	-0.6	

Initial Adjustment: -1.3

10.15 Carnarvon

This station has a good time resolution, but the reference stations range from 115-730 km away. This large distance is required to get adequate reference station coverage. The time resolution at the station is good. Quality: **Good**

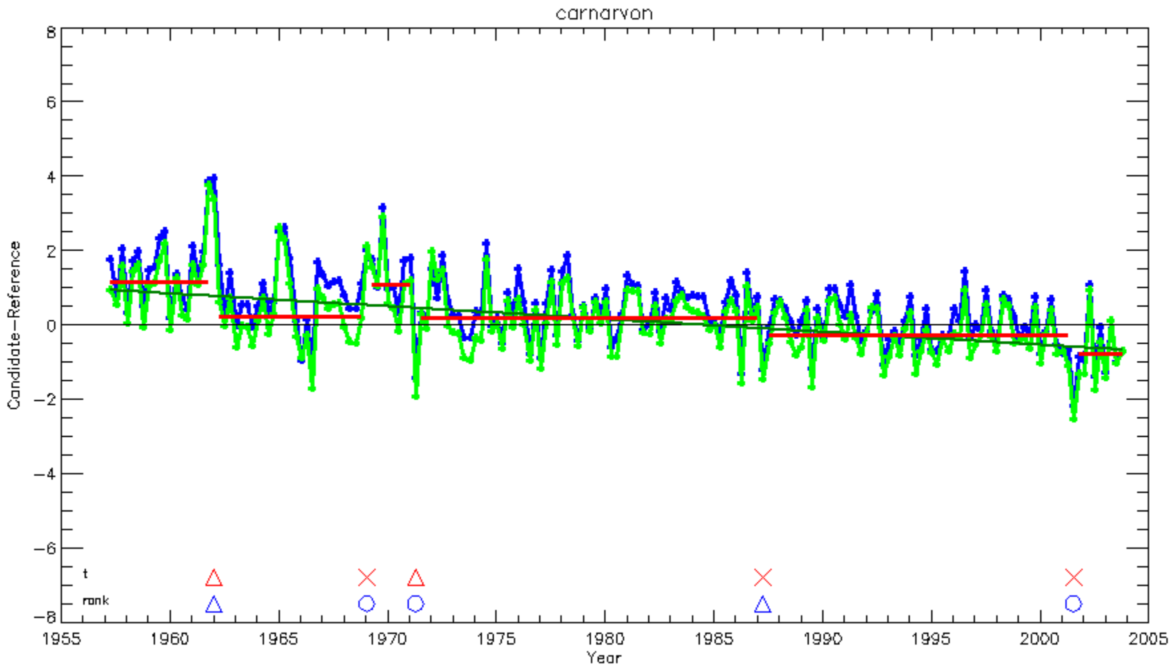
Location: -24.8878 113.6700

Station Number: 6011

2003 Instrumentation: PRT

Reference Stations: 5007, 8251, 5016, 8093, 8025, 8051, 6025, 6044, 8137, 7057

Last Season Bias Adjustment: -0.7



Season/Year	Strength	Cause
JJA01	-0.5	not significant
MAM87	-0.3	
MAM71	-0.9	
DJF69	+0.8	not significant
DJF62	-0.9	

Initial Adjustment: -0.7

10.16 Ceduna

This station has good time resolution throughout the record. The reference stations are suitably close (within ~300 km). The station history suggests a local site move in 1969. Quality: **Good**.

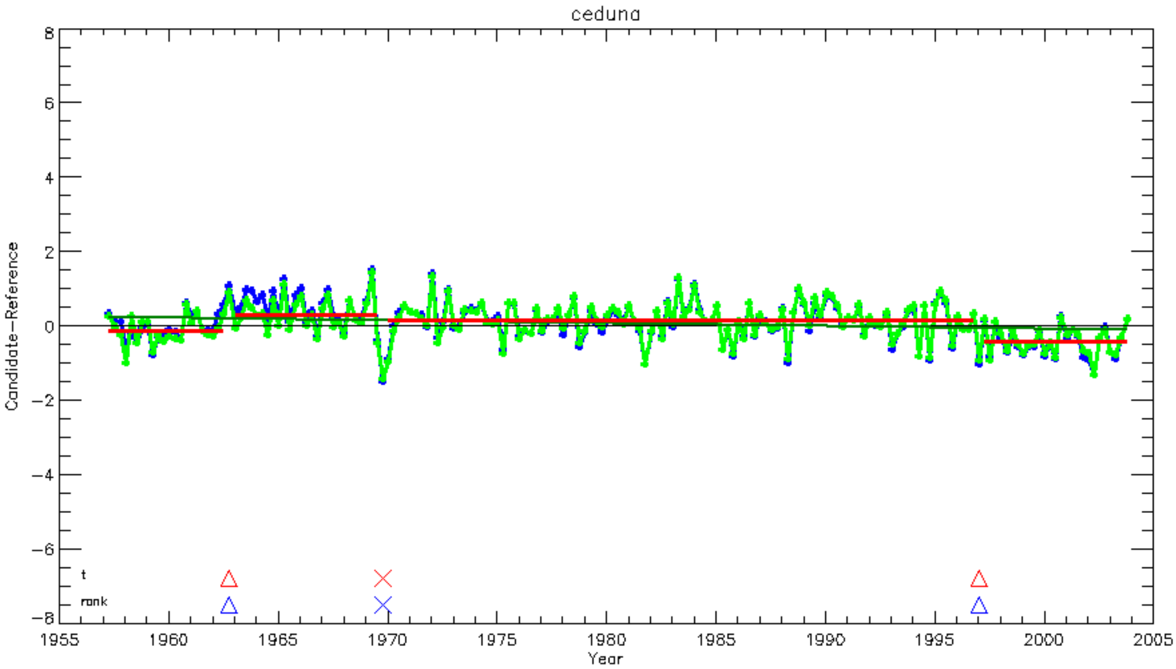
Location: -32.1297 133.6976

Station Numbers: 18012

2003 Instrumentation: PRT

Reference Stations: 18079, 18069, 18044, 18139, 16032, 18040, 16001

Last Season Bias Adjustment: +0.2



Season/Year	Strength	Cause
DJF97	-0.5	AWS epoch
SON62	+0.4	

Initial Adjustment: -0.4

10.17 Charleville

Good time and space resolution throughout. Quality: **Good**.

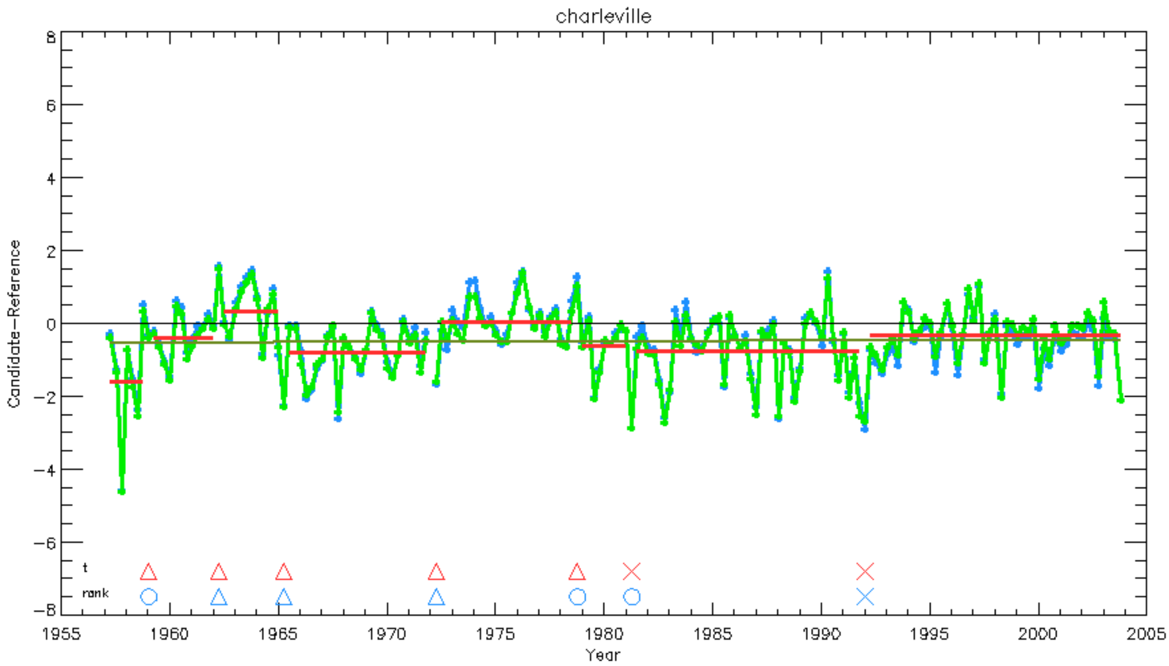
Location: -26.4156 146.2452

Station Number: 44021

2003 Instrumentation: PRT

Reference Stations: 35069, 36031, 48015, 53048, 41038, 43030, 36030, 45015, 36143, 43034, 43109

Last Season Bias Adjustment:-2.1



Season/Year	Strength	Cause
SON93	+0.8	2nd Pass
DJF92	+0.5	
MAM90	-1.0	2nd pass
SON78	-0.7	
MAM72	+0.9	
MAM65	-1.1	
MAM62	+0.7	
DJF59	+1.2	

Initial Adjustment: -0.3

10.18 Cobar

This station is a composite station, with the join occurring in this analysis in January 1963. Station has generally good time resolution throughout the period, as well as an adequate number of nearby reference stations. The number of available stations lowers to two or three in the early-1970s. Quality: **Good**.

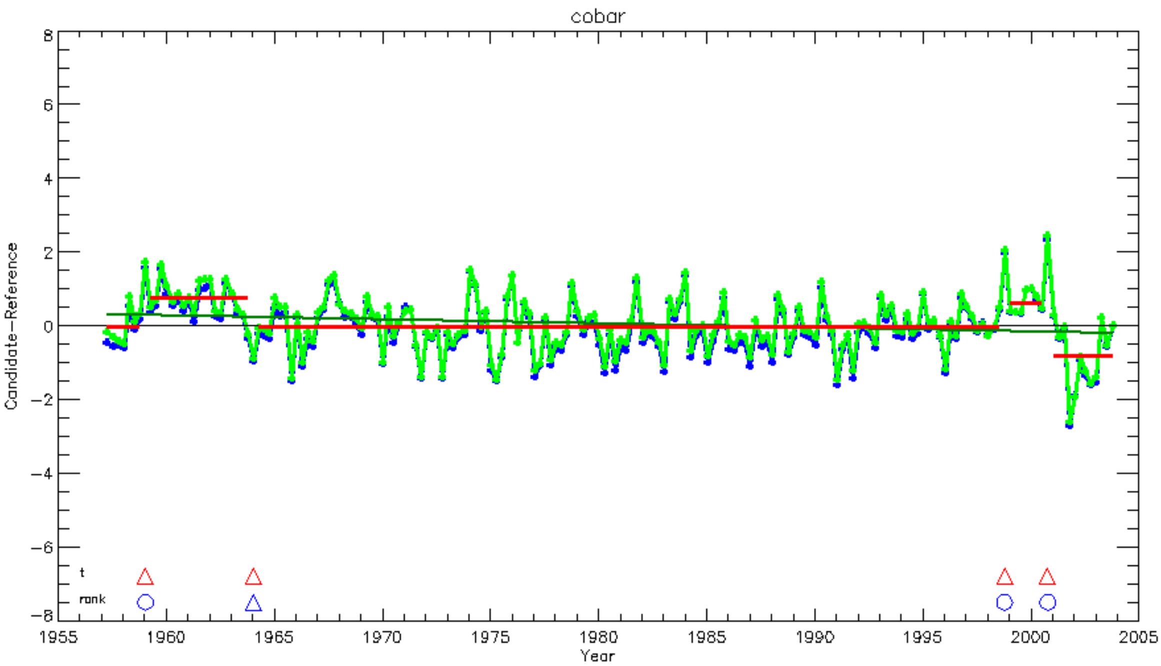
Location: -31.4853 145.8292 (current), -31.5, 145.8

Station Numbers: 48030, 48027 (current)

2003 Instrumentation: PRT

Reference Stations: 48013, 50052, 51039, 75032, 46043, 75039, 65026, 65012

Last Season Bias Adjustment: 0.0



Season/Year	Strength	Cause
SON00	-1.5	
SON98	+0.6	
DJF64	-0.6	composite join at jan63
DJF59	+0.9	

Initial Adjustment: -0.8

10.19 Coffs Harbour

There are five to eight reference stations throughout record. All are within 200 km. Time resolution of data is high. A new Met Office was built in 1967 (suggesting a site move, but it is not clear) and the instruments were moved 200 m in 1989. Quality: **Good.**

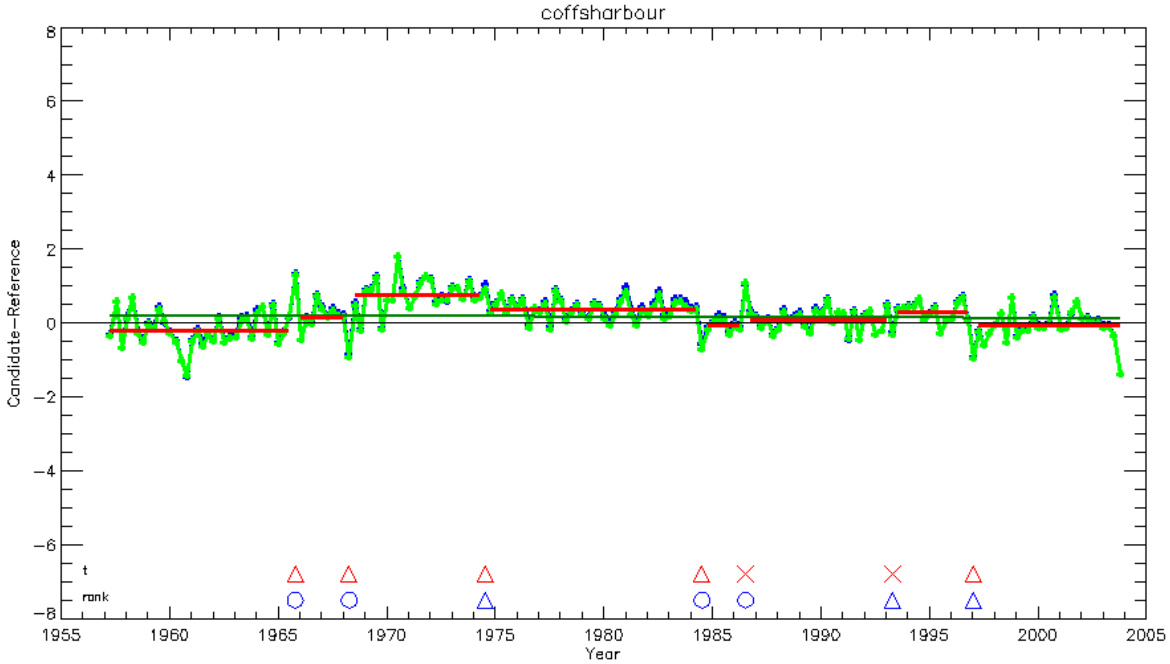
Location: -30.3107 153.1187

Station Number: 59040

2003 Instrumentation: PRT

Reference Stations: 58037, 58012, 58130, 59017, 60026, 59030, 57095, 59001

Last Season Bias Adjustment: -1.4



Season/Year	Strength	Cause
DJF97	-0.4	AWS epoch
MAM93	+0.2	
JJA84	-0.4	
JJA74	-0.5	
MAM68	+0.6	New building?
SON65	+0.3	

Initial Adjustment: -0.1

10.20 Darwin

The time resolution and quality of the Darwin data are quite good. The number of available reference stations varies by quite a bit, as low as two in the mid-1970s up to seven at other times. This does add a bit of uncertainty earlier in the record. Quality: **Good**.

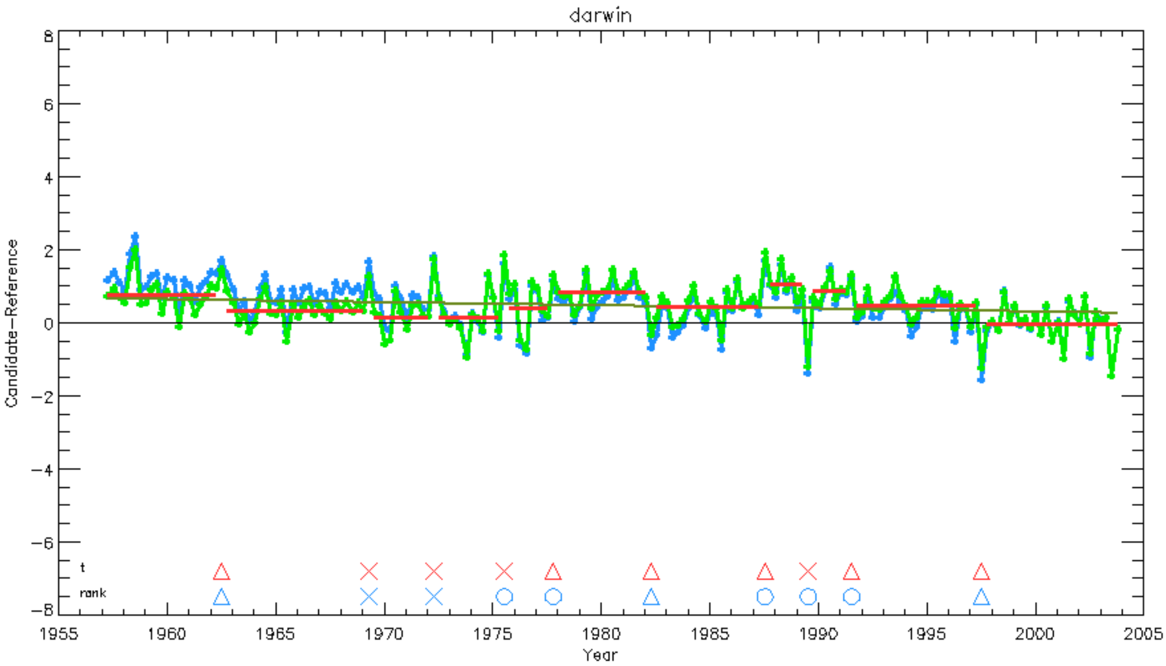
Location: -12.4242 130.8925

Station Number: 14015

2003 Instrumentation: PRT

Reference Stations: 14401, 14042, 14008, 14400, 14090, 14213, 14161, 14198

Last Season Bias Adjustment: -0.2



Season/Year	Strength	Cause
JJA97	-0.5	AWS epoch?
JJA91	-0.3	
JJA89	-0.2	not sig
JJA87	+0.6	
MAM82	-0.5	
SON77	+0.5	
JJA75	+0.3	not sig
MAM69	-0.2	not sig
JJA62	-0.5	

Initial Adjustment: 0.0, plev=0.05

10.21 Dubbo

This station has poor time resolution until the AWS installation in late-1992. The station is a composite site with the join occurring in this dataset in February 1993. The station also had a significant site move in October 1986. The reference station proximity and availability is very good. The AWS becomes the official reading upon installation. Quality: **Fair**.

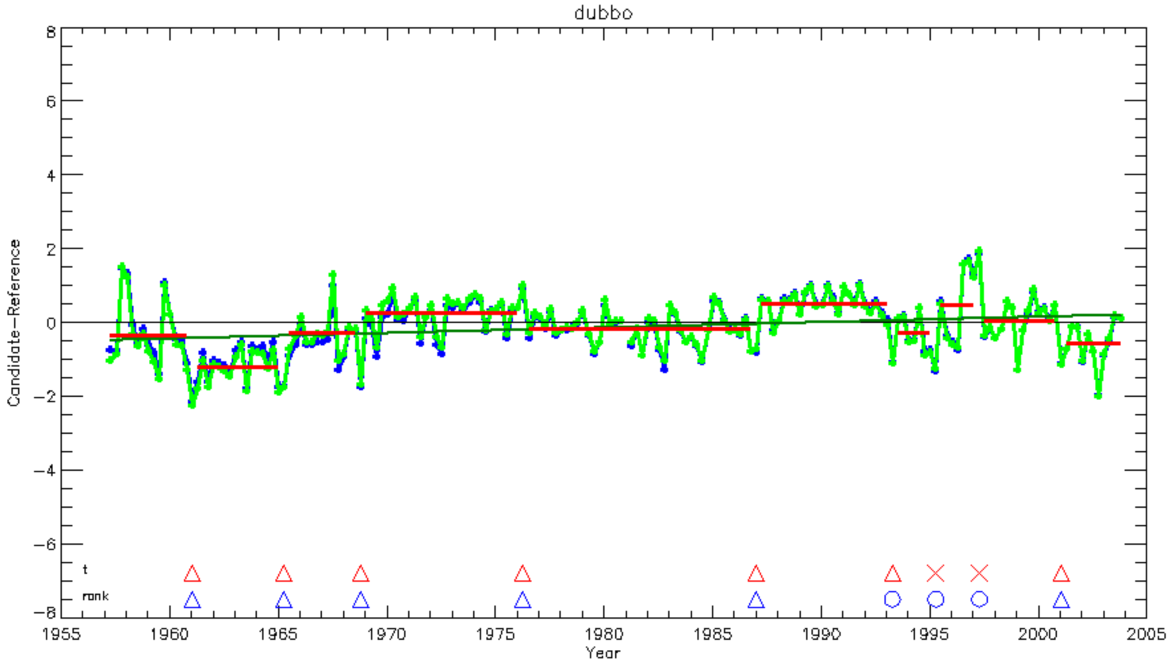
Location: -32.2206 148.5753 (current), -32.2385 148.6089

Station Numbers: 65012, 65070 (current)

2003 Instrumentation: HP

Reference Stations: 64008, 55024, 65026, 65034, 67033, 64009, 61086, 62013, 50031

Last Season Bias Adjustment: +0.1



Season/Year	Strength	Cause
DJF01	-0.6	
MAM97	-0.4	
MAM95	+0.8	
MAM93	-0.8	AWS install; site join
DJF87	+0.8	Site move
MAM76	-0.4	
SON68	+0.5	
MAM65	+0.9	
DJF61	-0.9	

Initial Adjustment:-0.6

10.22 Esperance

This is a composite station, with the join occurring in July 1969. The join coincided with a site move of 4 km. High temporal resolution after join, only 0900 and 1500 before. A reasonable number of reference stations, but most are 300-400 km distant. Quality: **Good.**

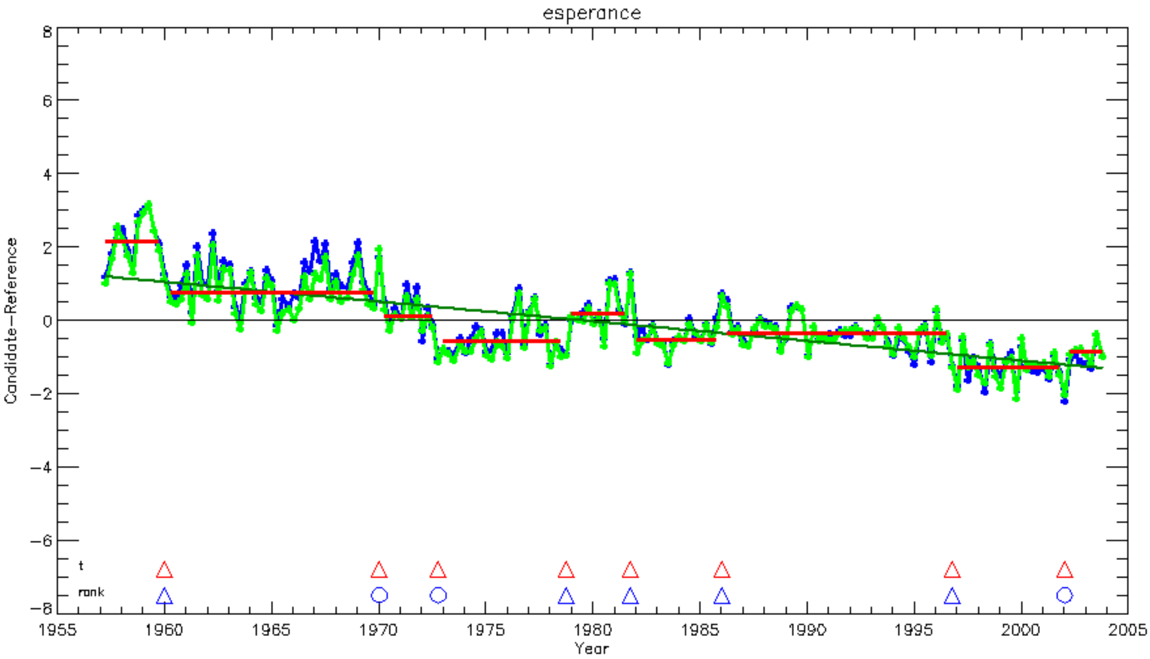
Location: -33.8300 121.8925 (current), -33.85 121.8833

Station Numbers: 9541, 9789 (current)

2003 Instrumentation: PRT

Reference Stations: 9542, 9631, 9500, 9741, 9581, 10633, 10592, 10579, 11019, 10536, 12065

Last Season Bias Adjustment: -1.0



Season/Year	Strength	Cause
DJF02	+0.4	
SON96	-0.8	AWS epoch
DJF86	+0.3	
SON81	-0.7	
SON78	+0.6	
SON72	-0.7	
DJF70	-0.7	site join?
DJF60	-1.3	

Initial Adjustment: -0.9

10.23 Forrest

A composite station joined in April 1993 in this analysis. Good time resolution throughout most of record. Station is in a relatively data sparse area, so only 3-4 reference stations before 1980. All stations are 230–615 km distant. Upon installation, the AWS becomes the official measurement. Initially, the AWS used a PRT. After two years, this was switched to a humidity probe. These changes in instrumentation are only represented by one breakpoint, likely because of the brevity of the PRT record. Quality: **Good**.

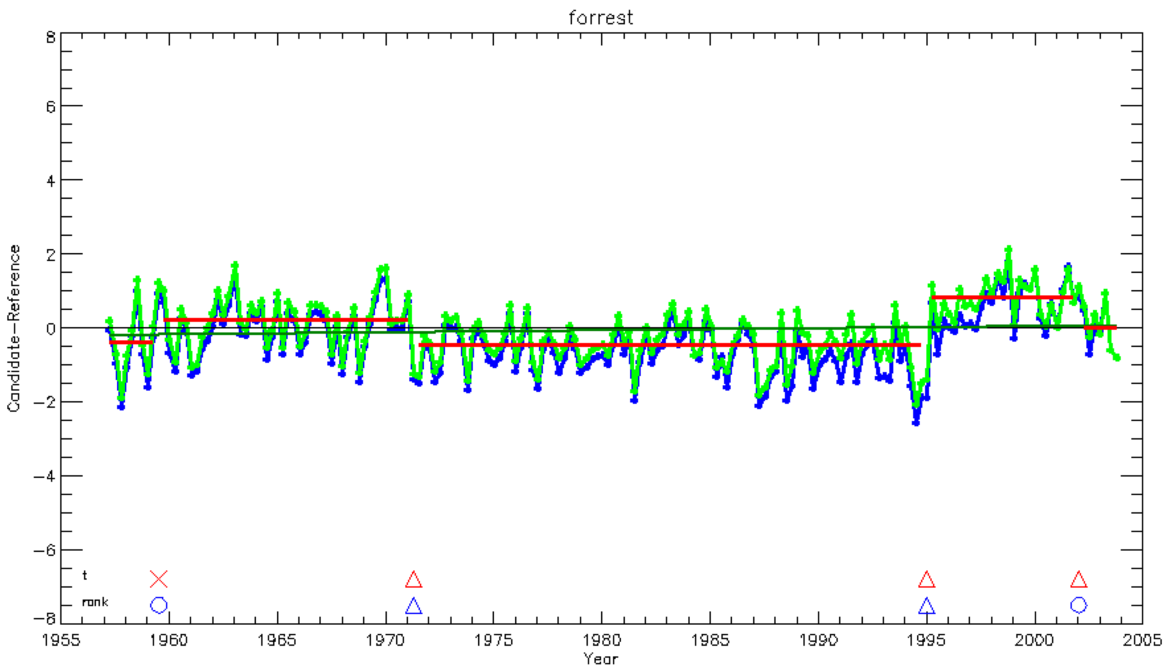
Location: -30.8453 128.1092 (current), -30.8389 128.1139

Station Numbers: 11004, 11052 (current)

2003 Instrumentation: HP

Reference Stations: 11019, 11045, 18012, 16044, 18079, 12038, 18106

Last Season Bias Adjustment:-0.8



Season/Year	Strength	Cause
DJF02	-1.0	
DJF95	+1.4	new AWS sep94, hum probe mar95??
MAM71	-0.7	
JJA59	+0.6	not sig, pval=0.09

Initial Adjustment: 0.0

10.24 Galiwinku

This is not an especially reliable station, but it fills in a spatial gap. The observations are not of high temporal resolution throughout, and do often occur at odd times. There are a limited number of nearby reference stations. The breakpoints in the 60s on the chart below are not included in the final list. They appear to be 'random walk' artefacts of the homogenization process. Quality: **Fair.**

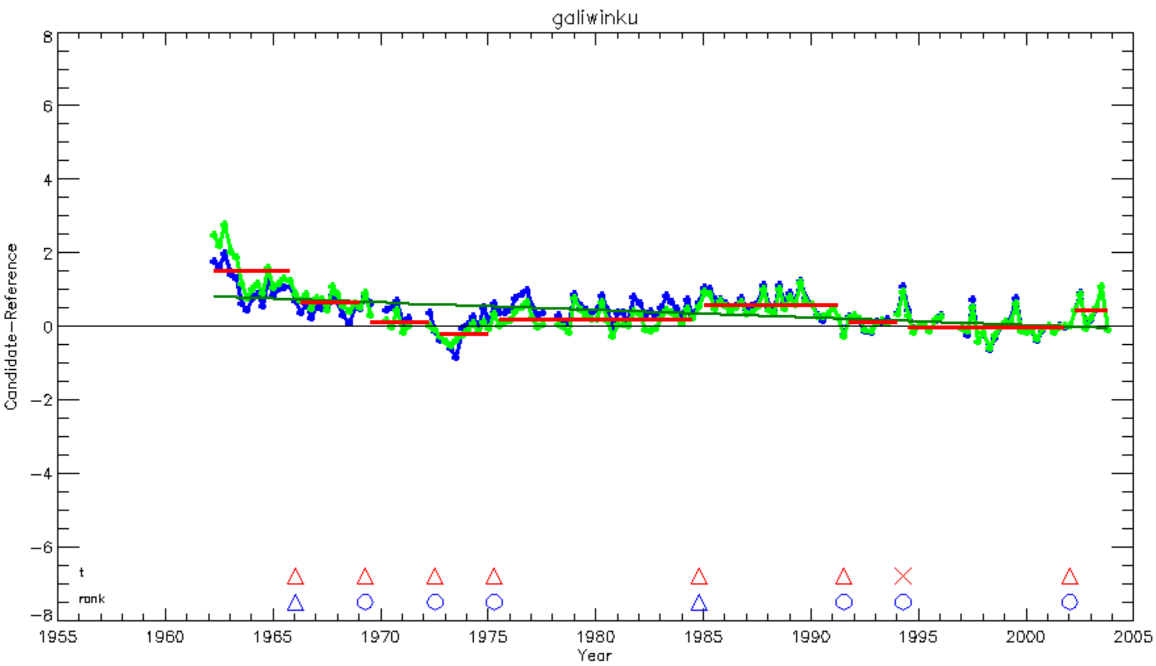
Locations: -12.0280 135.5648

Station Number: 14504

2003 Instrumentation: Hg

Reference Stations: 14401, 14400, 14508, 14512, 14507, 14008, 14090, 14011, 14161, 14042, 14402

Last Season Bias Adjustment: -0.1



Season/Year	Strength	Cause
DJF02	+0.5	
JJA91	-0.5	
SON84	+0.5	
MAM75	+0.4	
JJA72	-0.3	

Initial Adjustment: +0.5

10.25 Geraldton

Station has good time resolution and an adequate number of reference stations. All reference stations are at least 250 km away. The station moved to its current location in 'the early-1960s'. Quality: **Good.**

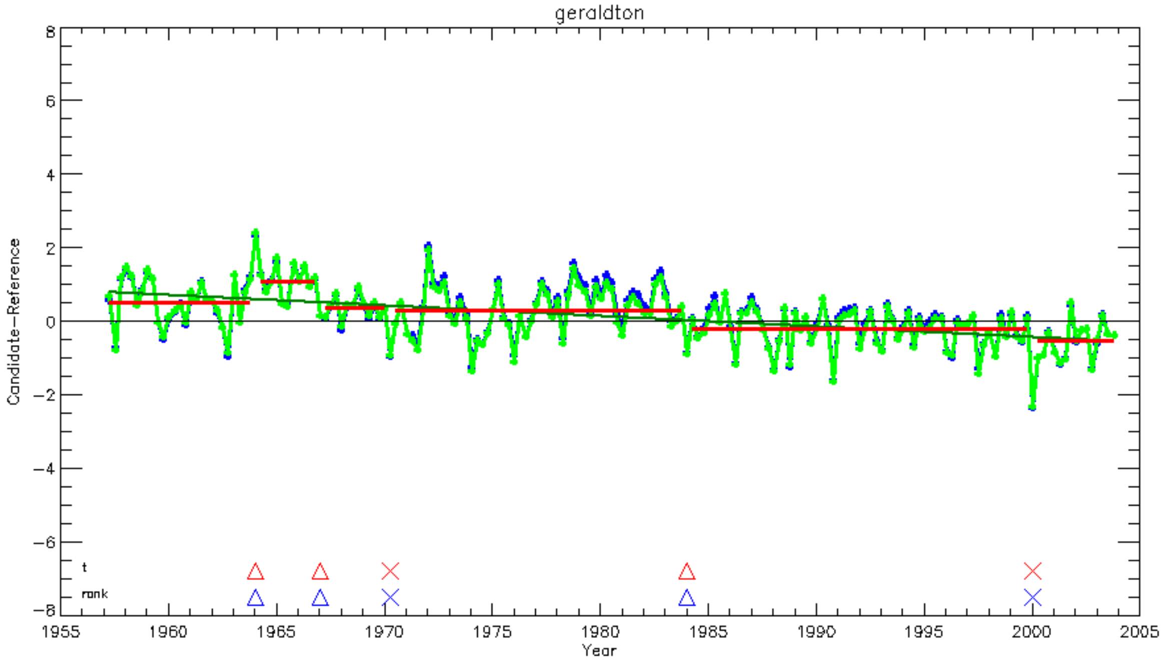
Location: -28.7953 114.6975

Station Number: 8051

2003 Instrumentation: PRT

Reference Stations: 9021, 8039, 8137, 9114, 10035, 10007, 9034, 10515

Last Season Bias Adjustment: -0.4



Season/Year	Strength	Cause
DJF00	-0.2	Not sig
DJF84	-0.6	
DJF67	-0.7	
DJF64	+0.7	Site move??

Initial Adjustment: -0.5

10.26 Giles

This station is remote, so reference stations are fewer and farther away than the ideal. Time resolution is good, but pre-1978 observations are at odd times as the station operated on SA time for many years. Quality: **Fair.**

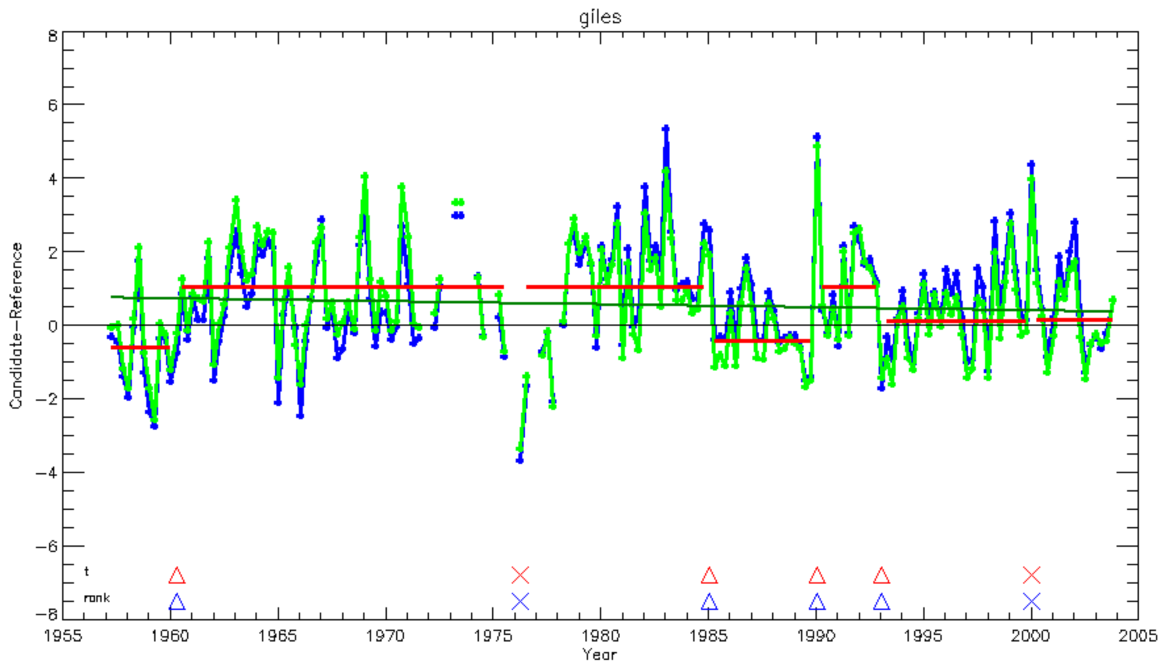
Location: -25.0431 128.3010

Station Number: 13017

2003 Instrumentation: PRT

Reference stations: 15603, 15511, 15590, 17043, 15526, 15635, 16085

Last Season Bias Adjustment: +0.7



Season/Year	Strength	Cause
DJF93	-1.2	
DJF90	+1.4	
DJF85	-1.6	
MAM60	+1.9	

Initial Adjustment: +0.2

10.27 Hobart

Good time resolution with nearby reference stations. Quality: **Good.**

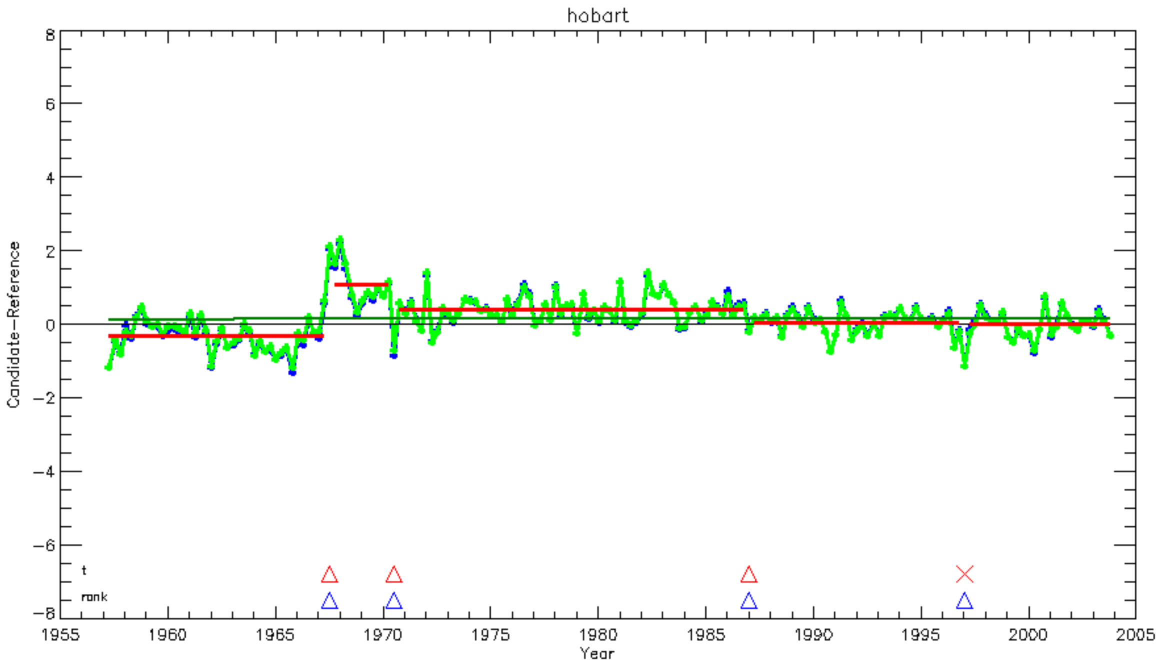
Location: -42.8908 147.3269

Station Number: 94029

2003 Instrumentation: PRT

Reference Stations: 94069, 94008, 91104, 95003, 92038, 92027, 91237

Last Season Bias Adjustment: -0.3



Season/Year	Strength	Cause
DJF87	-0.4	
JJA70	-0.7	
JJA67	+1.5	

Initial Adjustment: 0.0

10.28 Kalgoorlie

Station has good temporal resolution. Reference stations are a bit far away in some instances, but some relatively nearby stations are also included. Quality: **Good**

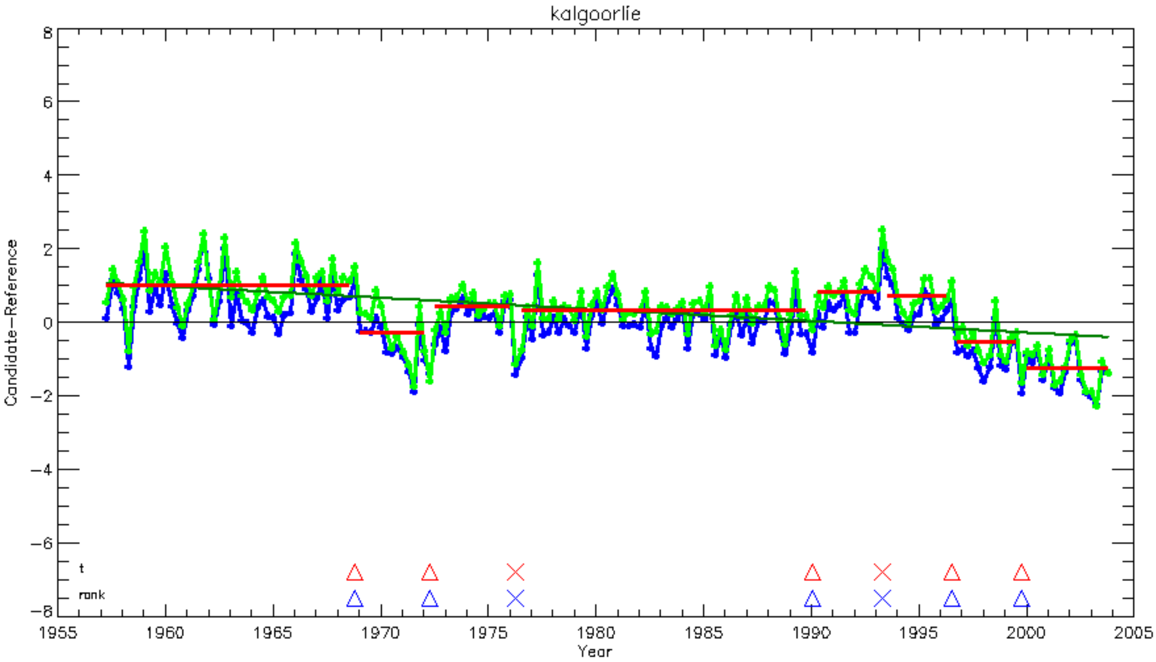
Location: -30.7847 121.4533

Station Number: 12038

2003 Instrumentation: PRT

Reference Stations: 12065, 12074, 11045, 11019, 10092, 7139, 7057, 10007, 11017

Last Season Bias Adjustment: -1.4



Season/Year	Strength	Cause
SON99	-0.7	
JJA96	-1.3	AWS epoch
DJF90	+0.5	
MAM72	+0.7	
SON68	-1.3	

Initial Adjustment:-1.2

10.29 Kalumburu

Only 2 or 3 observations a day are present through majority of the record. There is also a period of missing data. A few nearby reference stations, but most are far away. Since this project has started, the station has closed in 2005 and has been replaced with an AWS (station number 1019). Quality: **Fair**

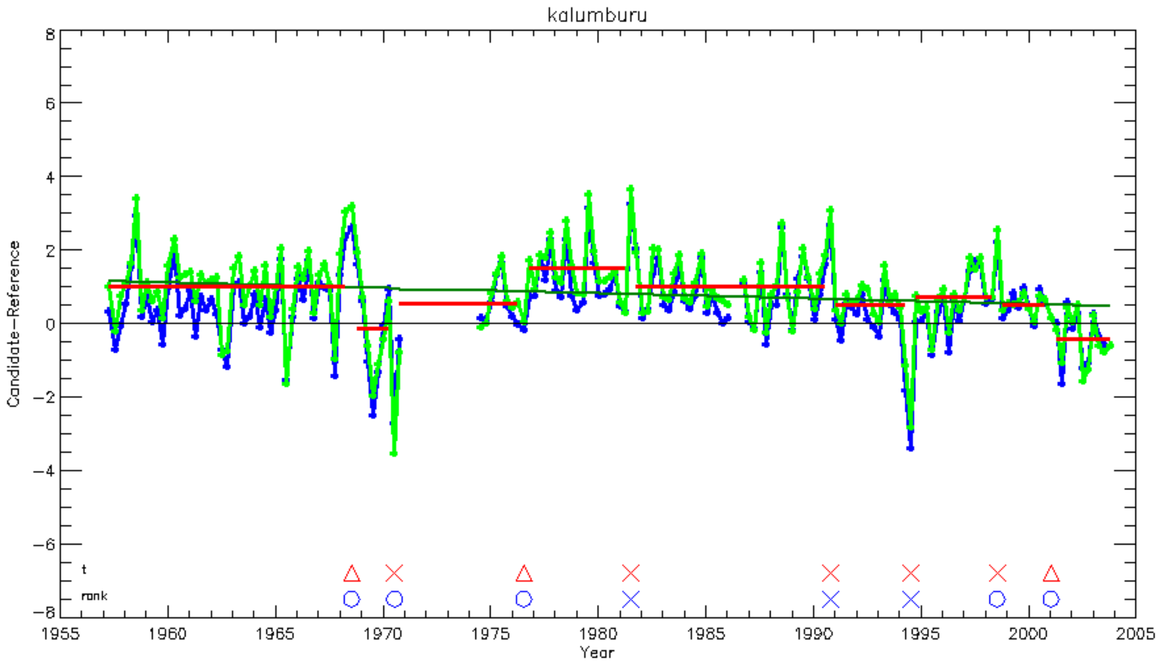
Location: -14.2961 126.6431

Station Number: 1021

2003 Instrumentation: Hg

Reference Stations: 1005, 1012, 1013, 1009, 3003, 14938, 14015, 14090, 1007

Last Season Bias Adjustment: -0.6



Season/Year	Strength	Cause
DJF01	-1.0	
SON90	-0.4	not sig
JJA81	-0.4	not sig
JJA76	+1.1	at data gap
JJA70	+0.7	not sig
JJA68	-1.1	

Initial Adjustment: -0.4

10.30 Katanning

This station is a composite station, with the join in this dataset coming in February 1999. The station only has observations at 0900 and 1500 until late-1987, good temporal resolution after that. Adequate reference station spacing and numbers. Metadata indicates a site move in July 1987. Quality: **Good**

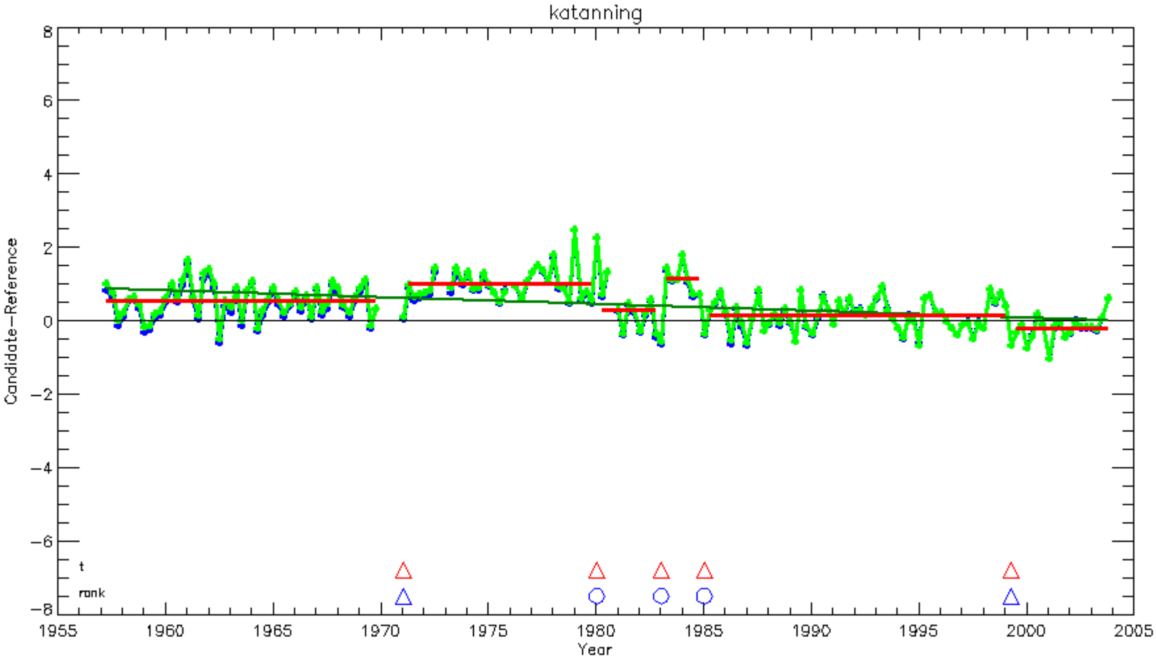
Location: -33.6856 117.6064 (current), -33.6886 117.5553

Station Numbers: 10579, 10916 (current)

2003 Instrumentation: HP

Reference Stations: 10592, 9581, 10648, 9573, 9592, 9538, 9034

Last Season Bias Adjustment: +0.6



Season/Year	Strength	Cause
MAM99	-0.4	site move, AWS install, composite join
DJF85	-1.1	
DJF83	+0.8	
DJF80	-0.7	
DJF71	+0.4	

Initial Adjustment: -0.2

10.31 Launceston AP

The station has a high time resolution throughout the record. Reference stations are within 160 km of the locale and with the exception of the first year or so of the record, at least 4 reference stations are available. Quality: **Good.**

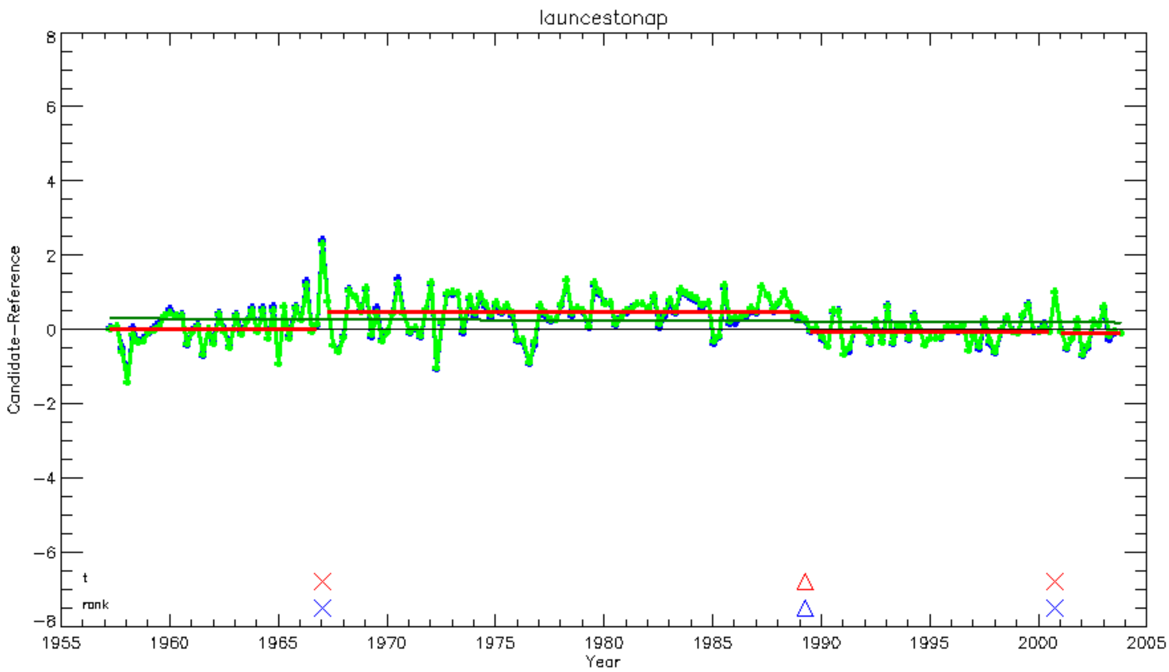
Location: -41.5411 147.2019

Station Number: 91104

2003 Instrumentation: PRT

Reference Stations: 94029, 94008, 91057, 94069, 97053, 91237, 95003, 92027

Last Season Bias Adjustment: -0.1



Season/Year	Strength	Cause
MAM89	-0.6	
DJF67	+0.5	not sig, but large

Initial Adjustment: -0.1

10.32 Laverton

The station has high temporal resolution, and reference stations are all within 190 km. At least four stations are available throughout. Quality: **Good**

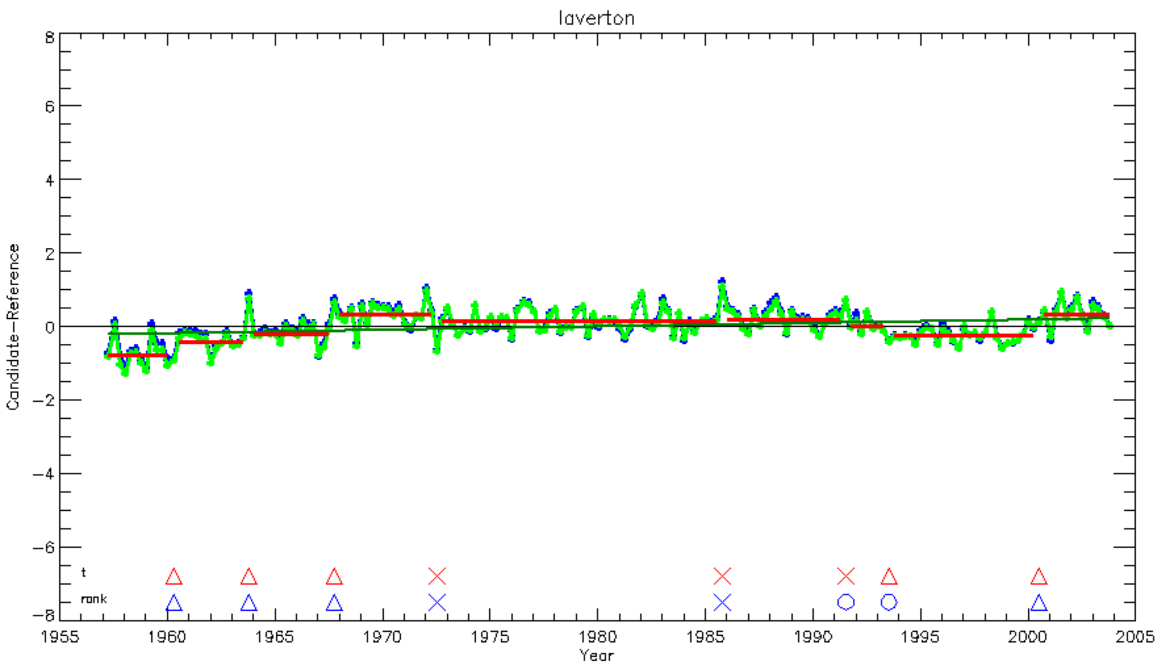
Location: -37.8564 144.7564

Station Number: 87031

2003 Instrumentation: HP

Reference Stations: 86071, 86282, 80015, 82002, 88110, 89002, 81003, 87100, 86351

Last Season Bias Adjustment: 0.0



Season/Year	Strength	Cause
JJA00	+0.6	
JJA93	-0.3	
JJA91	-0.2	not sig
JJA72	-0.2	not sig
SON67	+0.5	
SON63	+0.2	
MAM60	+0.4	

Initial Adjustment: +0.3

10.33 Longreach

A composite station with the two stations joined in this analysis in January 1968. Prior to the join, only 0900 and 1500 observations are available; much better resolution afterward. In the early 2000s, huge negative biases due to instrumentation problems as described in Lucas (2006) are seen at the end of the record. Reference stations are OK, ranging from 100 to 400 km distant. At least four are available throughout the record. Quality: **Fair**

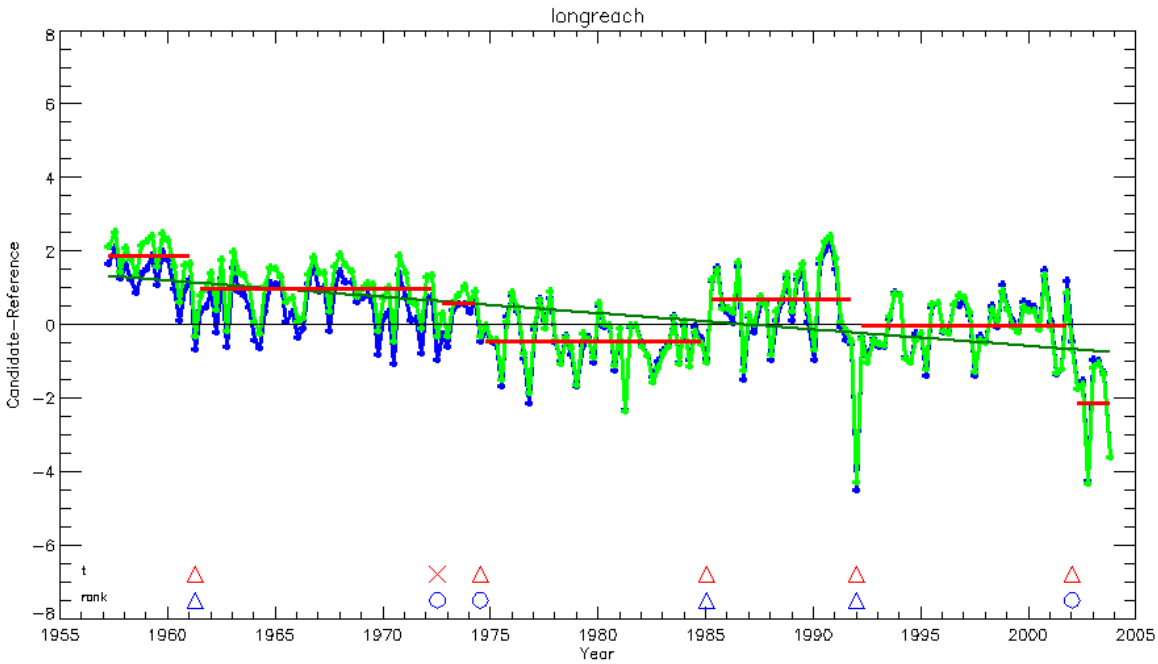
Location: -23.4372 144.2769 (current), -23.45 144.25

Station Numbers: 36030, 36031 (current)

2003 Instrumentation: PRT

Reference Stations: 37051, 36143, 44021, 35069, 30045, 36026, 36007, 35019

Last Season Bias Adjustment: -3.6



Season/Year	Strength	Cause
DJF02	-2.2	
DJF92	-1.0	
DJF85	+1.2	
JJA74	-0.8	
JJA72	-0.3	not significant
MAM61	-0.9	

Initial Adjustment:-2.1

10.34 Mackay

This station did not open until 1959. The temporal resolution is high. Reference stations are few in number, with some close and some far away. Distances range from 11 to 450 km. Quality: **Good**.

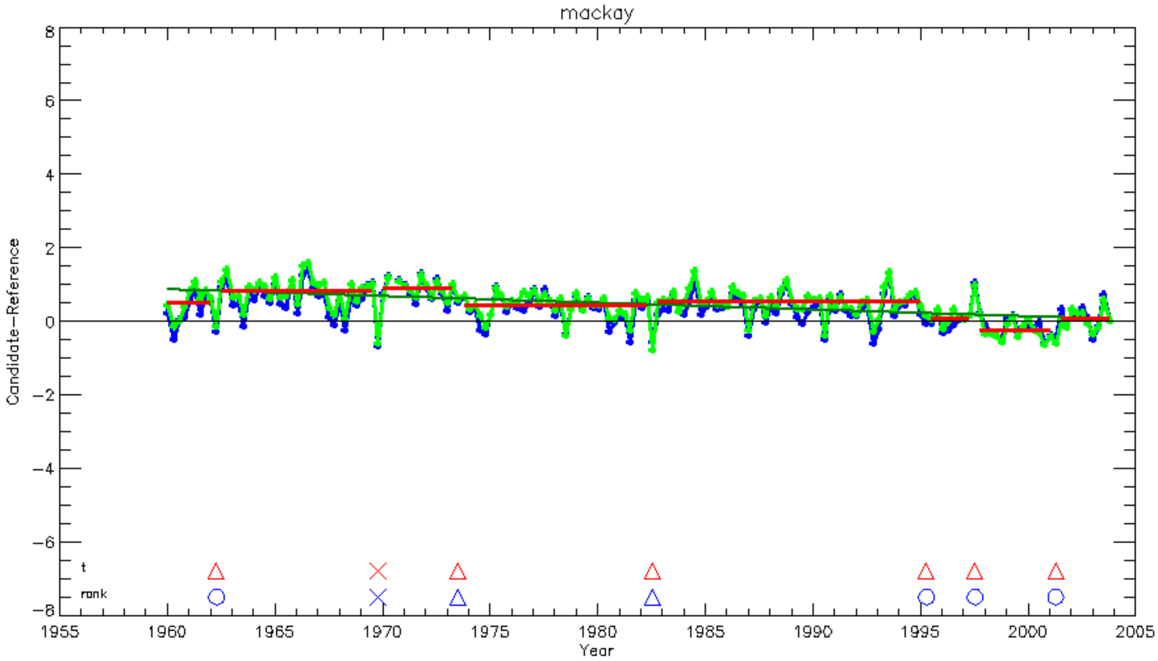
Location: -21.1183 149.2150

Station Number: 33119

2003 Instrumentation: PRT

Reference Stations: 33047, 33065, 32078, 32004, 39083, 32040

Last Season Bias Adjustment: 0.0



Season/Year	Strength	Cause
MAM01	+0.3	
JJA97	-0.3	AWS epoch
MAM95	-0.4	
JJA82	+0.3	
JJA78	-0.2	2nd pass
MAM75	+0.2	2nd pass
JJA73	-0.4	
MAM62	+0.4	

Initial Adjustment: +0.1

10.35 Meekatharra

Later data have a strong negative bias, presumably associated with problems described in Lucas (2006). There is a high temporal resolution in the observations. The reference stations are a bit far away, ranging between 100 and 400 km. Several periods have 3 or fewer stations making up the reference series, including the early 1970s and the post-1997 period. Quality: **Good**

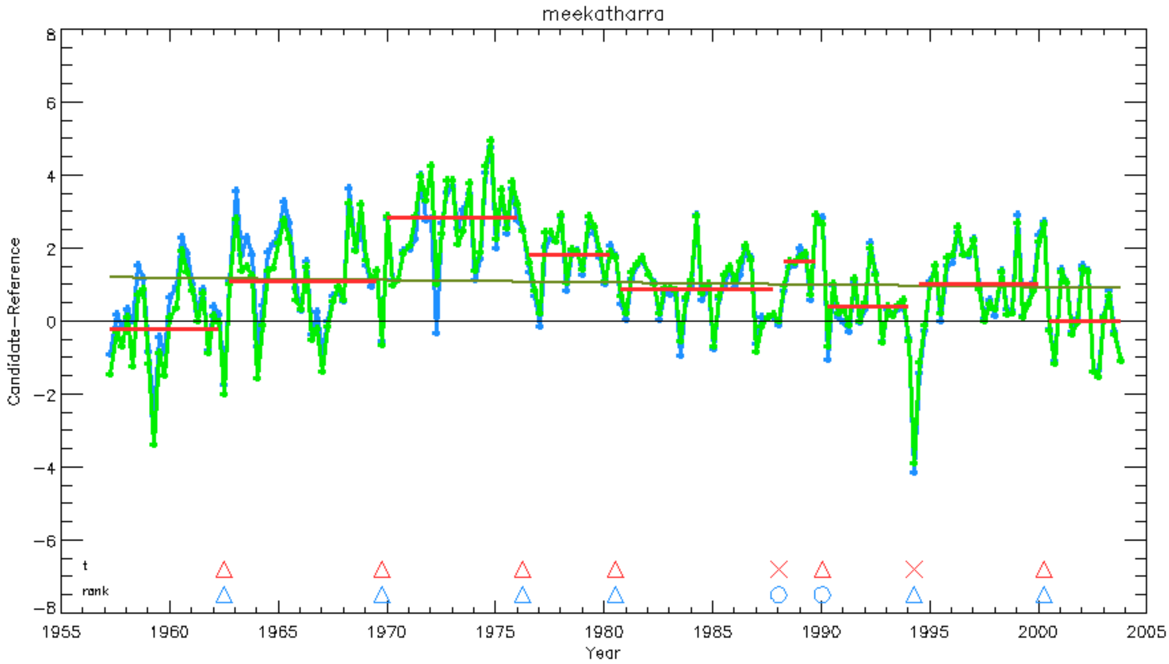
Location: -26.6136 118.5372

Station Number: 7045

2003 Instrumentation: PRT

Reference Stations: 7057, 7139, 7017, 7161, 12038, 7600, 12314, 12090, 6099

Last Season Bias Adjustment: -1.1



Season/Year	Strength	Cause
MAM00	-1.2	
MAM94	+0.6	only rank sum test significant
DJF90	-1.3	
DJF88	+0.8	
JJA80	-0.9	
MAM76	-1.2	
SON69	+1.6	
JJA62	+1.2	

Initial Adjustment: 0.0

10.36 Melbourne

This is the station in the city, not the airport. The reference stations are within 200 km, generally much closer. At least four are available at all times. The temporal resolution of the data is high throughout. Quality: **Good.**

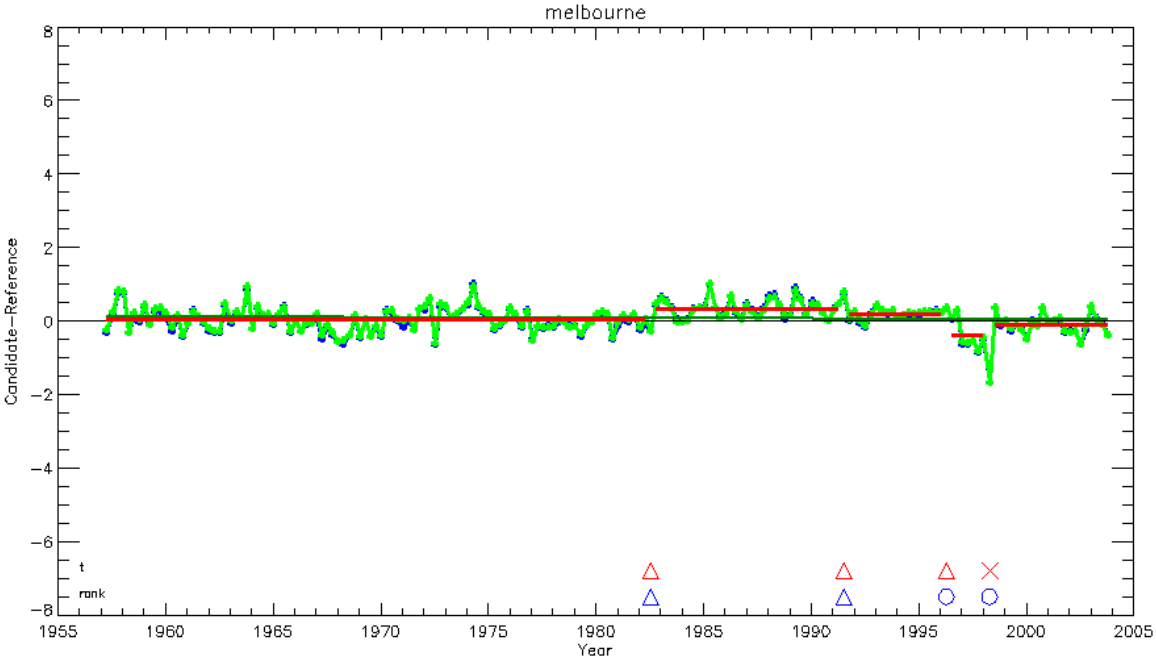
Location: -37.8075 144.9700

Station Number: 86071

2003 Instrumentation: PRT

Reference Stations: 86351, 86282, 89002, 86127, 87031, 85072, 81003, 85093

Last Season Bias Adjustment: -0.4



Season/Year	Strength	Cause
MAM98	+0.3	not sig
MAM96	-0.6	AWS epoch??
JJA91	-0.2	
JJA82	+0.3	

Initial Adjustment: -0.1

10.37 Mildura

Temporal resolution at the station is very good. The reference stations range from 5 to 325 km distant. There are generally four reference stations available at all times. Quality: **Good**

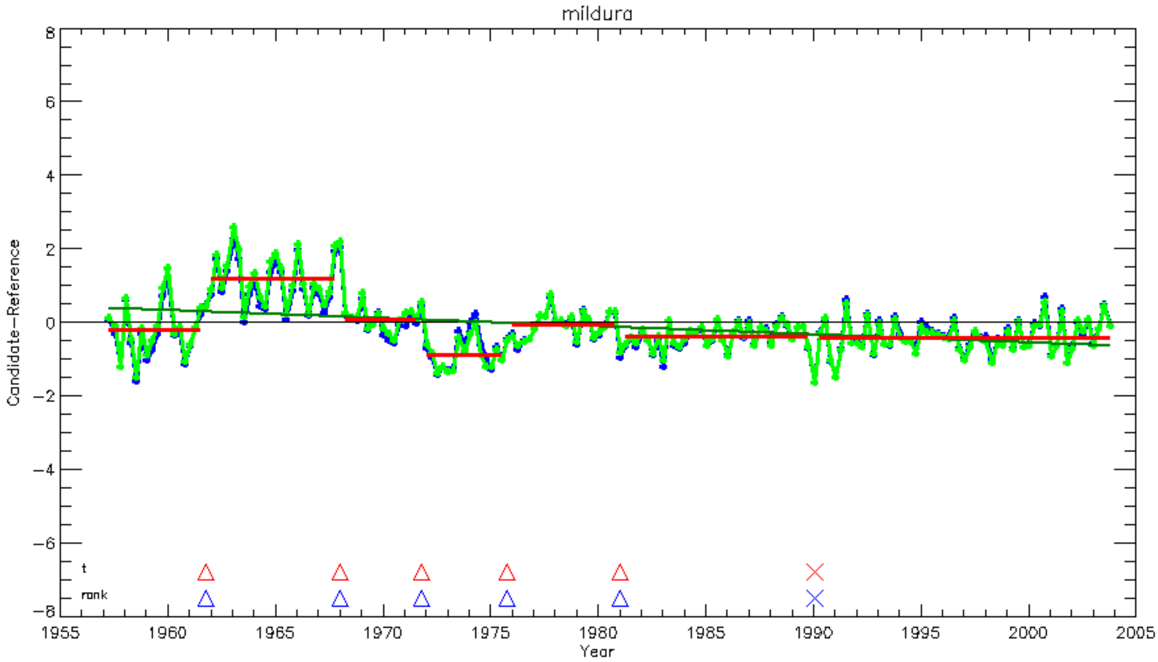
Location: -34.2306 142.0839

Station Number: 76031

2003 Instrumentation: PRT

Reference Stations: 76047, 49002, 24024, 77042, 24016, 76026, 74128, 80015, 75031, 78031

Last Season Bias Adjustment: -0.1



Season/Year	Strength	Cause
DJF90	-0.1	not sig, AWS install
DJF81	-0.5	
SON75	+0.8	
SON71	-1.0	
DJF68	-1.0	
JJA61	+1.5	

Initial Adjustment:-0.4

10.38 Miles

This station is a composite with the join coming in October 1997. Observations are only available at 0900 and 1500 before the join. There is also a period of missing data in the early-1970s. Generally good reference station availability in both time and space, with stations ranging from 120-320 km distant. With a few very brief exceptions, at least 4 stations are available. Quality: **Good to Fair**.

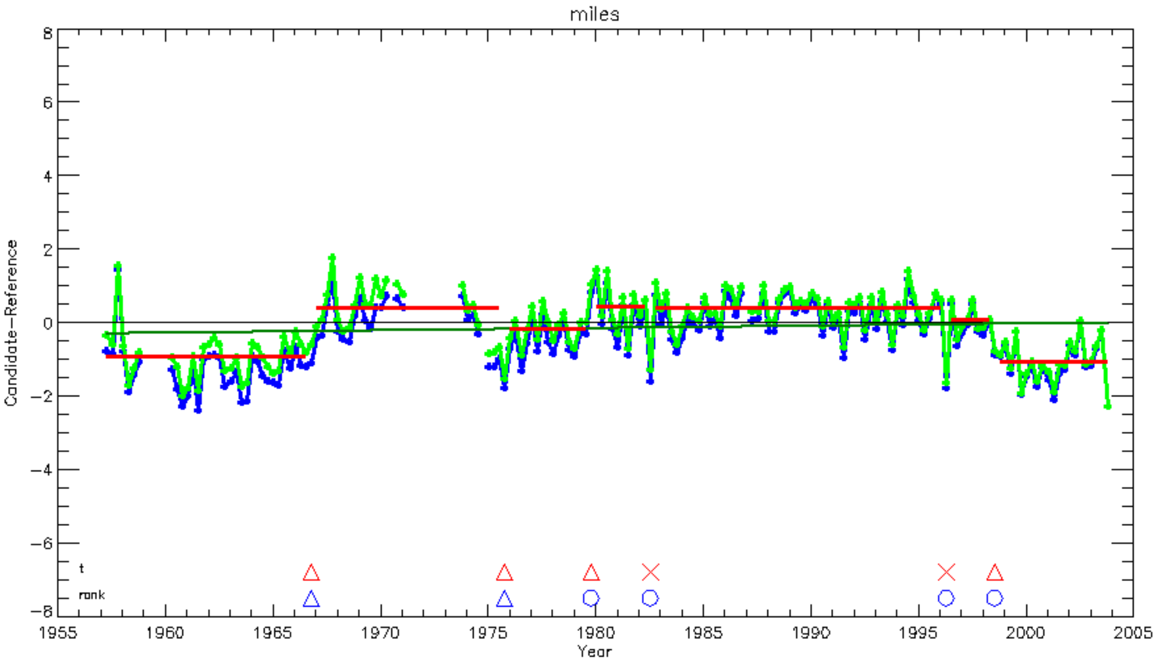
Location: -26.6569 150.1819 (current), -26.6581 150.1844

Station Numbers: 42023, 42112 (current)

2003 Instrumentation: PRT

Reference Stations: 43015, 35070, 43034, 41038, 52020, 41100, 41095, 53048, 53027, 41521

Last Season Bias Adjustment:-2.3



Season/Year	Strength	Cause
JJA98	-1.1	site join -- nov97, AWS
MAM96	-0.3	not sig
SON79	+0.6	
DJF77	+0.8	2nd pass
SON75	-0.9	
DJF75	-0.6	2nd pass
SON66	+1.6	

Initial Adjustment:-1.1

10.39 Moree

The station is a composite with 2 joins; one in March 1964, the other in May 1995. The AWS becomes the official observation when installed with the second site move. Temporal resolution is poor (0900 and 1500 only) early on and moderate in the middle. Reference station coverage is adequate, aside from a brief period in the late-1960s. All stations are relatively close, the furthest being 270 km away. Quality: **Good**

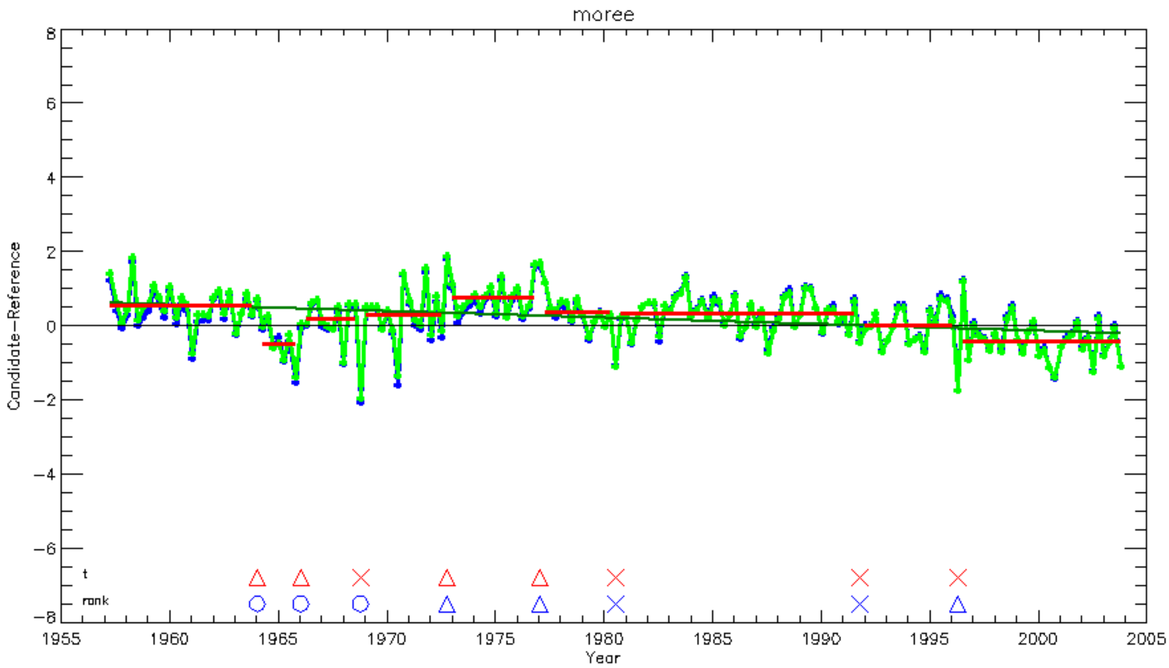
Location: -29.4914 149.8458 (current)

Station Numbers: 53027, 53048, 53115 (current), -29.5, 149.9, 29.4819 149.8383

2003 Instrumentation: PRT

Reference Stations: 41038, 41095, 64008, 41100, 55024, 53030, 61051, 43109

Last Season Bias Adjustment: -1.1



Season/Year	Strength	Cause
MAM96	-0.3	AWS install, may95, only rank sum sig
SON91	-0.3	not sig
DJF77	-0.4	
SON72	+0.4	
DJF66	+0.7	
DJF64	-0.9	site change mar 64

Initial Adjustment:-0.4

10.40 Mt Gambier

Good time resolution throughout the record. Generally an adequate number of reference stations, although there is a brief period in the 1970s when only 3 stations are available. Reference stations are nearby, less than 200 km in all cases. Quality: **Good.**

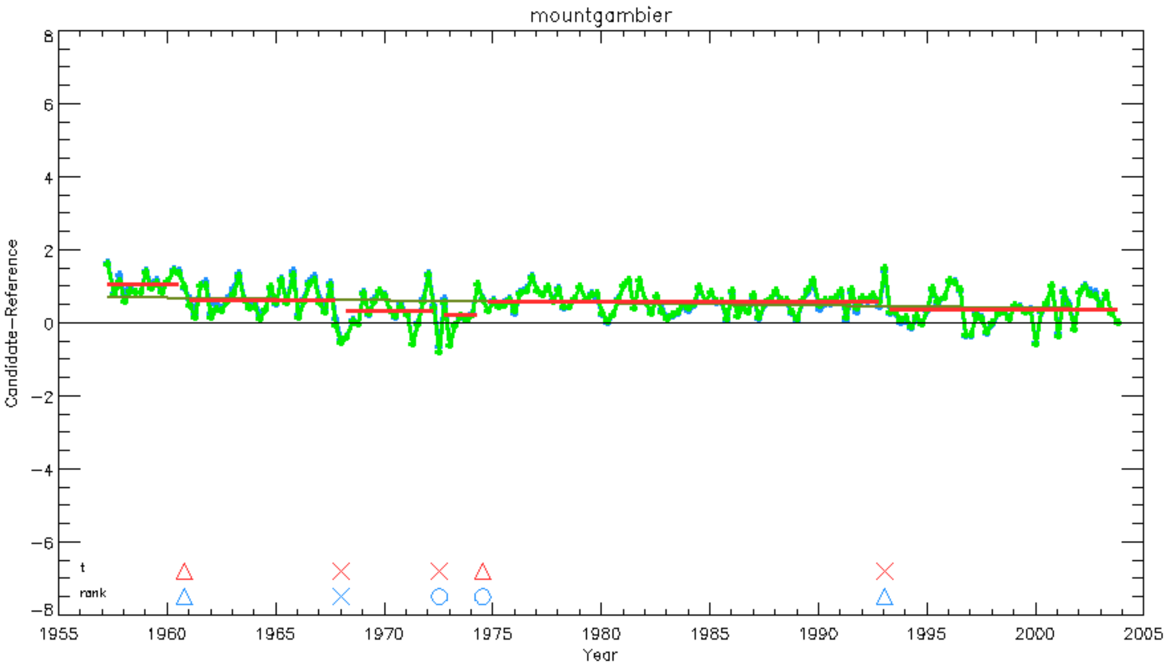
Location: -37.7473 140.7739

Station Number: 26021

2003 Instrumentation: PRT

Reference Stations: 90135, 90048, 25507, 26026, 78031, 26023, 90172, 79023, 26005

Last Season Bias Adjustment:-0.6



Season/Year	Strength	Cause
DJF00	+0.4	2nd pass
SON96	-0.6	2nd pass; AWS epoch.
SON94	+0.4	2nd pass
DJF93	-0.2	only rank sum significant
JJA74	+0.5	
DJF68	-0.3	not sig
SON60	-0.5	

Initial Adjustment:-0.2, plev=0.05

10.41 Normanton

This station is a composite, with the join occurring in May 2001. Only 0900 and 1500 observations are available before 1987. Reference stations are generally distant, ranging from 135 to 525 km away. Only 2 or 3 stations are available in the first part of the record. Quality: **Fair**.

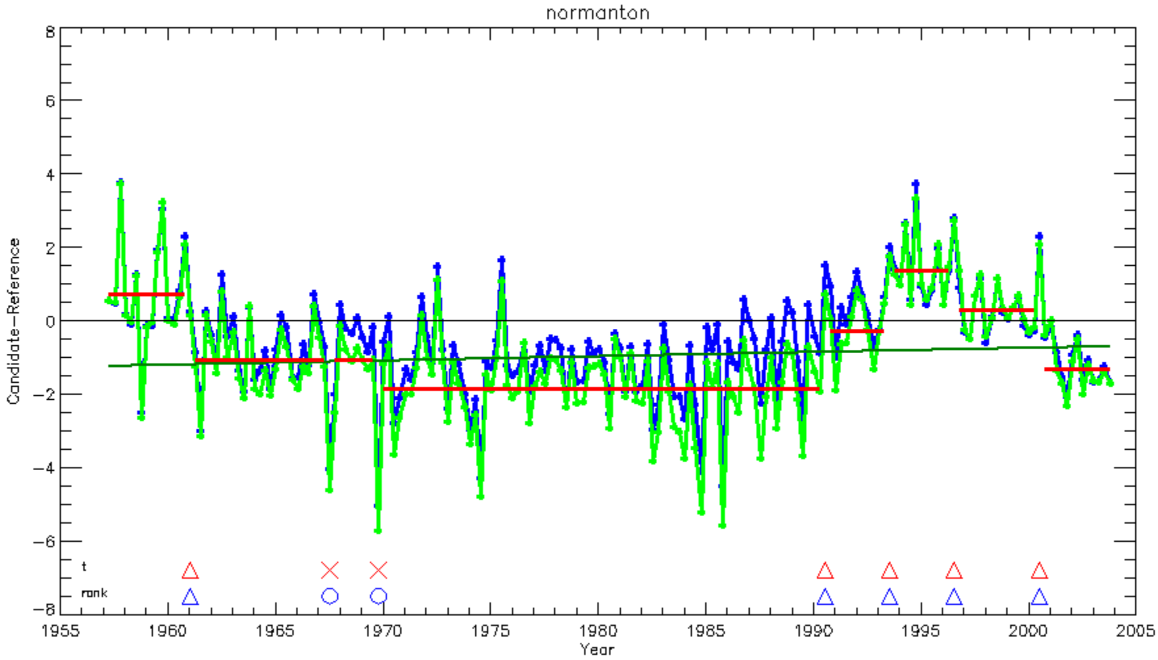
Location: -17.6872 141.0733 (current), -17.6706 141.0672

Station Numbers: 29041, 29063 (current)

2003 Instrumentation: HP

Reference Stations: 30045, 14707, 29012, 29025, 29127, 30018, 32025, 31037

Last Season Bias Adjustment: -1.7



Season/Year	Strength	Cause
JJA00	-1.6	site join, AWS may01?
JJA96	-1.1	
JJA93	+1.6	
JJA90	+1.6	screen change may90
SON69	-0.5	not sig, but seems real
DJF61	-1.8	

Initial Adjustment: -1.3

10.42 Nowra

This is a composite station with good temporal resolution. The join occurred in November 2000. Before 1965, most Decembers have a significant portion of the data missing around Xmas as the naval personnel running the station were on leave during this period. Good set of reference stations, all within 200 km of the candidate station. Quality: **Good.**

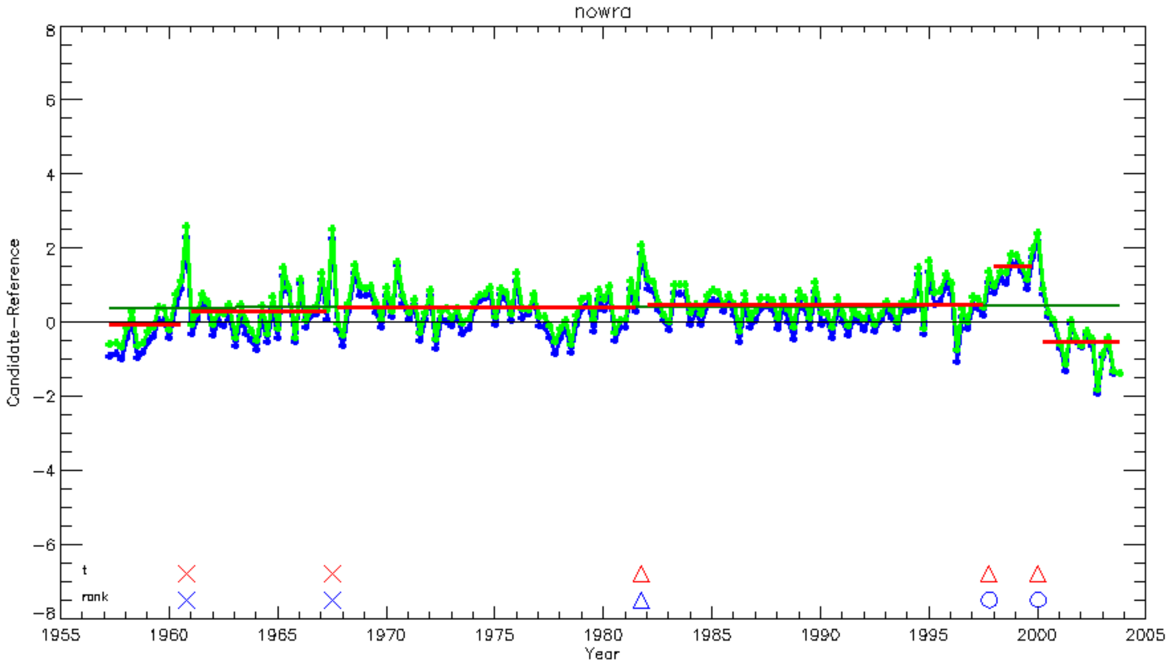
Location: -34.9469 150.5353 (current), -34.9449 150.545

Station Numbers: 68076, 68072 (current)

2003 Instrumentation: HP

Reference Stations: 66062, 66037, 68034, 69018, 67033, 61078, 67019

Last Season Bias Adjustment:-1.4



Season/Year	Strength	Cause
DJF00	-2.0	site move.
SON97	+1.9	AWS epoch?
DJF95	+0.3	
SON60	+0.2	

Initial Adjustment: -0.5

10.43 Oodnadatta

This station has a large data gap in the middle of the record. The gap coincides with a period when the original station closed. An alternate station was operating during the gap, but the data were of too poor quality to be used. The original station later reopened. Three to six reference stations are available for use, ranging from 175 to 450 km away. Quality: **Fair**

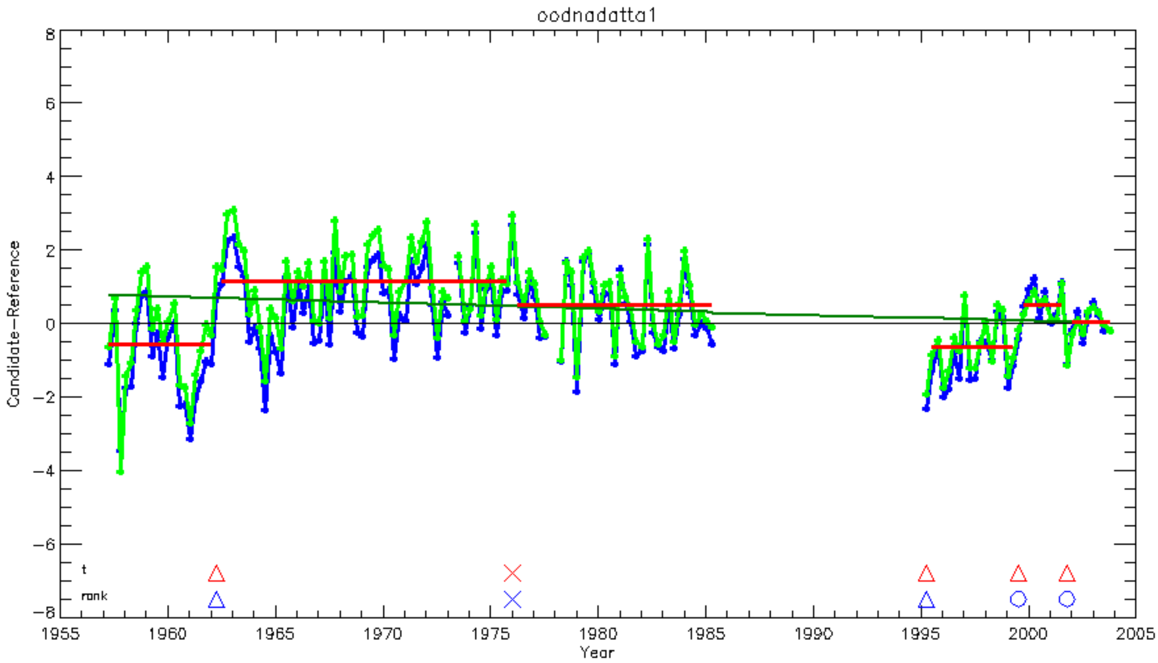
Location: -27.5439 135.4408

Station Number: 17043

2003 Instrumentation: HP

Reference Stations: 16007, 15526, 16065, 16044, 16001, 16085, 17005, 17110

Last Season Bias Adjustment:-0.2



Season/Year	Strength	Cause
SON01	-0.5	
JJA99	+1.1	
MAM95	-1.0	site reopen
DJF76	-0.5	
JJA64	-0.7	
MAM62	+2.0	

Initial Adjustment: 0.0

10.44 Perth AP

The temporal resolution at this station is good, as is the location of the reference stations. There are several site moves and instrumentation changes which produce some of the breakpoints in the analysis. The site moves are in March 1988 and October 1997, each about 2 km. Quality: **Good**

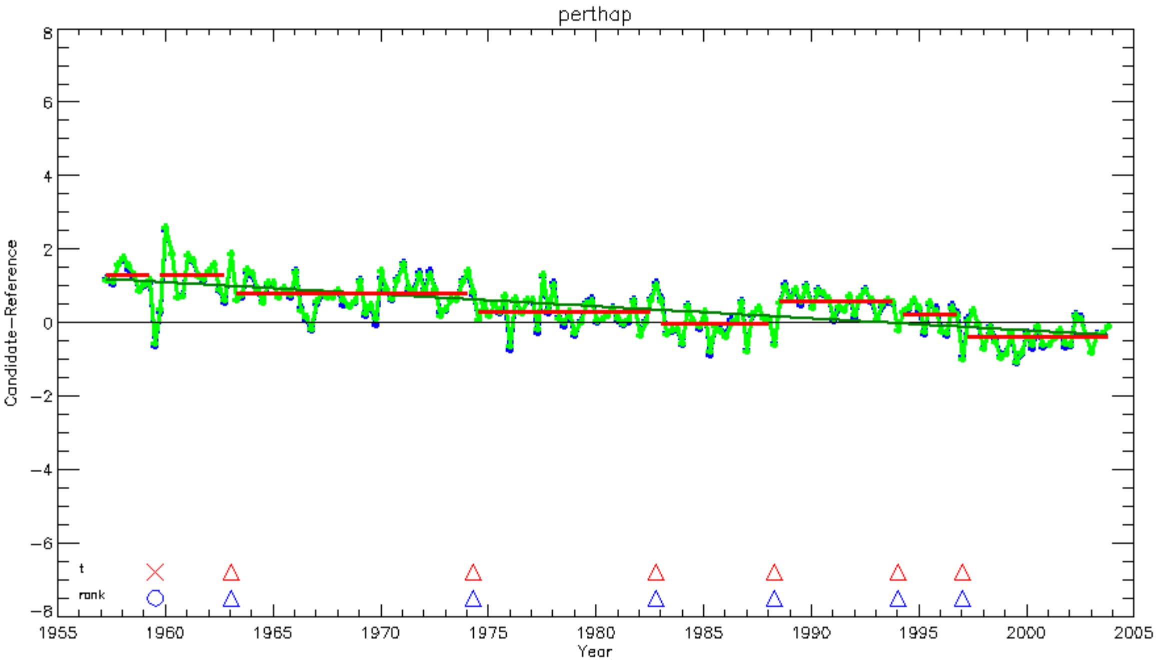
Location: -31.9275 115.9764

Station Number: 9021

2003 Instrumentation: PRT

Reference Stations: 9034, 9172, 9538, 9534, 10648, 10515, 10592

Last Season Bias Adjustment:-0.1



Season/Year	Strength	Cause
DJF97	-0.7	site move; AWS epoch
DJF94	-0.3	
MAM88	+0.7	site move
SON82	-0.3	
MAM74	-0.6	
DJF63	-0.5	

Initial Adjustment: -0.4

10.45 Port Hedland

Data temporal resolution and coverage is OK, but reference stations are very sparse at times. Only 2 or 3 acceptable reference stations are available for much of period before 1970.The plot below suggests the possibility of a likely breakpoint in late-2002 which is unable to be identified using the methodology here. A site move is reported in March 1981. Quality: **Fair**

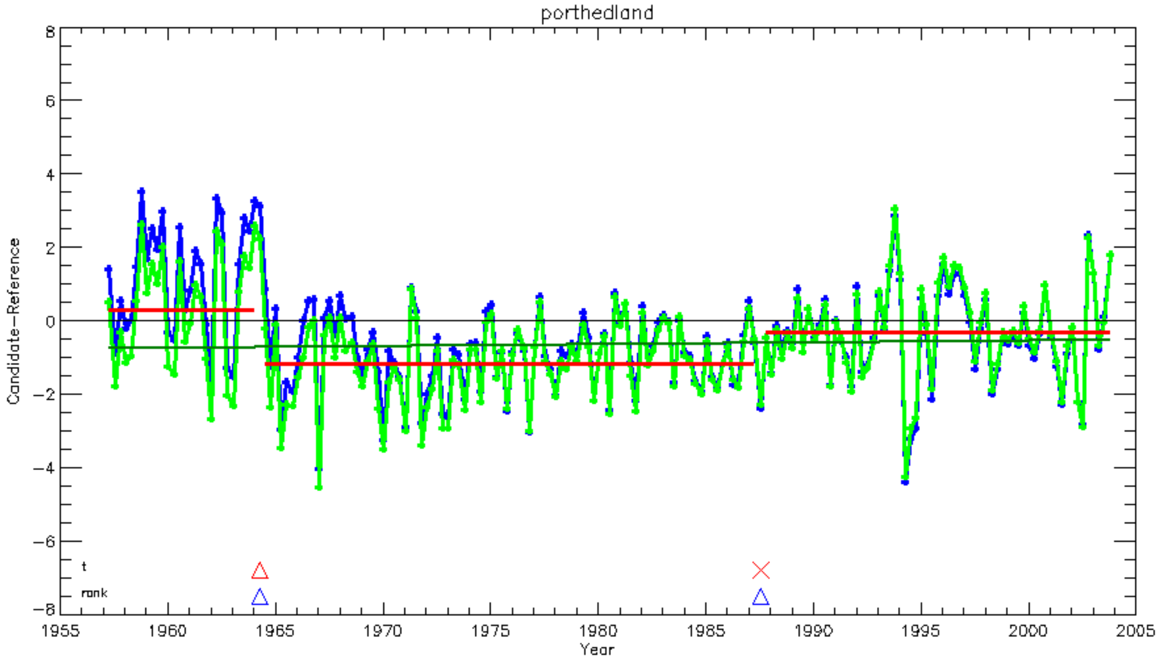
Location: -20.3725 118.6317

Station Number: 4032

2003 Instrumentation: PRT

Reference Stations: 4074, 4020, 5061, 4019, 4035, 4083, 4028, 5008

Last Season Bias Adjustment: +1.8



Season/Year	Strength	Cause
JJA87	+0.5	
MAM64	-1.4	

Initial Adjustment: -0.3

10.46 Rabbit Flat

This is a composite station. The sites were joined in November 1996. The station opened in 1969. Only observations at 0900 and 1500 are available until after the AWS is installed. The station and siting quality are somewhat less than ideal. Due to the remote locale of the station, the reference stations are very distant, with the closest being ~300 km and the furthest nearly 600 km. However, this station fills an important spatial gap in an otherwise data sparse region. The AWS becomes the sole measurement upon installation. Quality: **Fair**.

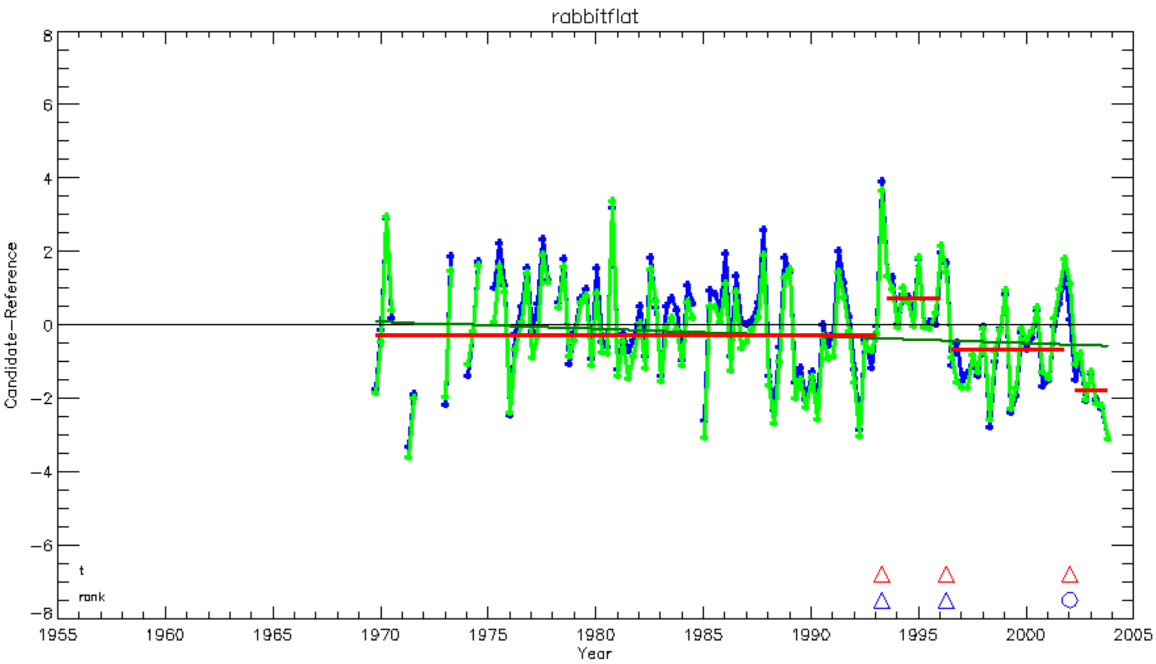
Location: -20.1824 130.0148 (current), -20.1883 130.0161

Station Number 15548, 15666 (current)

2003 Instrumentation: PRT

Reference Stations: 15135, 15528, 15590, 13017, 15511

Last Season Bias Adjustment: -3.1



Season/Year	Strength	Cause
DJF02	-1.4	
MAM96	-1.6	site move dec96?
MAM93	+1.0	

Initial Adjustment: -1.8

10.47 Richmond, NSW

This station is a composite station, with the join occurring in December 1993. The temporal resolution is fair to good. An adequate number of reference stations are available throughout. All are within 170 km of the station. AWS becomes official measurement upon installation. The AWS initially had a PRT, but this was replaced with a humidity probe in late-1999. There are several other changes to the AWS in the late-1990s and early-2000s which could be responsible for the observed breakpoints. Quality: **Good**.

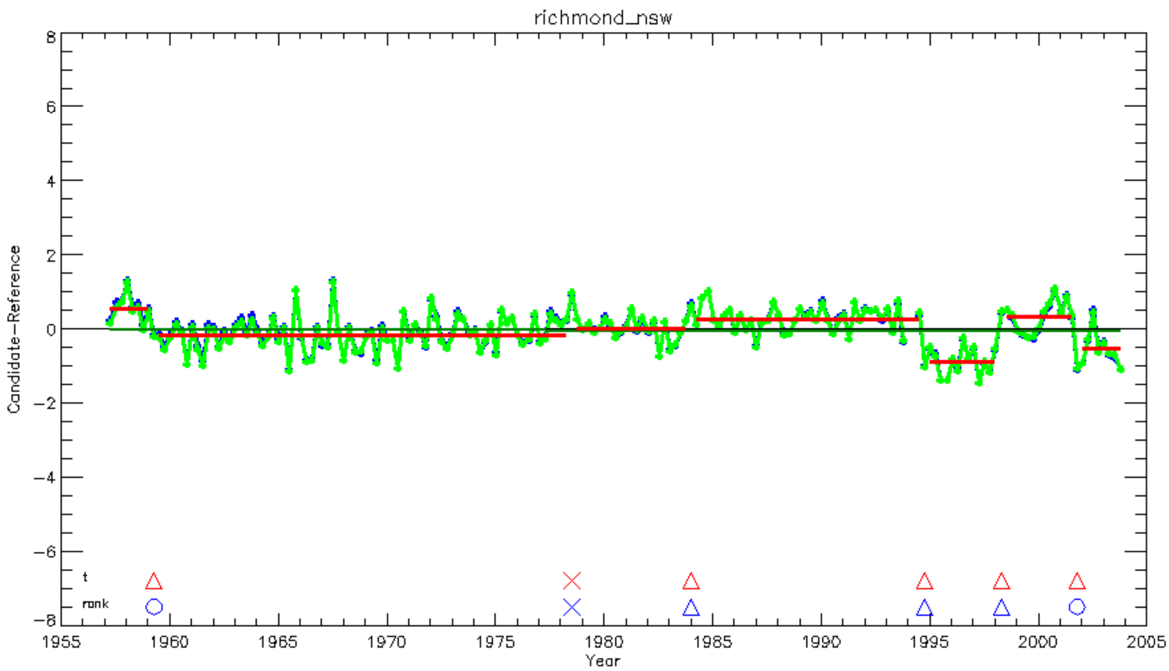
Location: -33.6004 150.7761 (current), -33.6022 150.7794

Station Numbers: 67033, 67105 (current)

2003 Instrumentation: HP

Reference Stations: 66062, 66037, 61078, 61086, 68034, 68076

Last Season Bias Adjustment: -1.1



Season/Year	Strength	Cause
SON01	-0.9	hum probe change?
MAM98	+1.2	AWS changes??
SON94	-1.2	Site join jun 1994
DJF84	+0.3	
MAM59	-0.9	

Initial Adjustment: -0.5

10.48 Richmond, QLD

The reference stations are generally distant, ranging from 180-520 km away. Only 0900 and 1500 observations are available before 1987 and after 1998. The station does fill in a large gap in the spatial coverage, though. This station is one of the few that does not include a switch to an AWS. Quality: **Fair.**

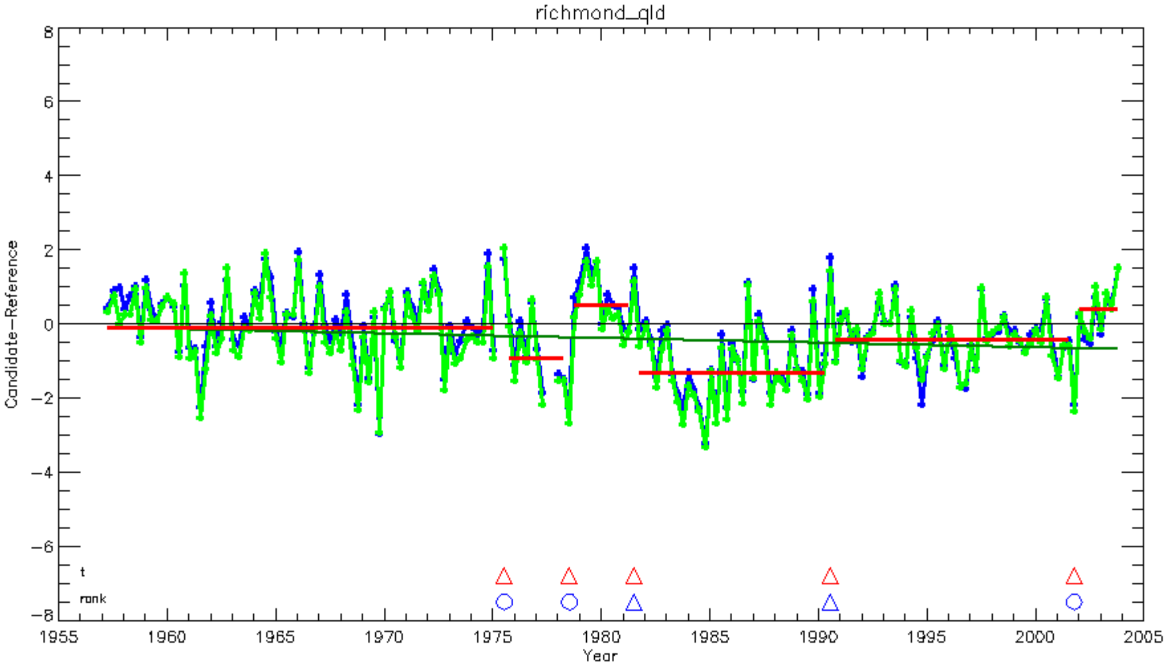
Location: -20.7289 143.1425

Station Number: 30045

2003 Instrumentation: Hg

Reference Stations: 36030, 36143, 36007, 37051, 36031, 36026, 29127, 35019

Last Season Bias Adjustment: +1.5



Season/Year	Strength	Cause
SON01	+0.7	
JJA90	+0.8	
JJA81	-2.0	
JJA78	+1.4	
JJA75	-0.9	

Initial Adjustment:+0.4

10.49 Rockhampton

Temporal resolution of data is very good. There are at least 4 reference stations at all times, but they are a bit far away, ranging from 150 – 300 km. Quality: **Good**

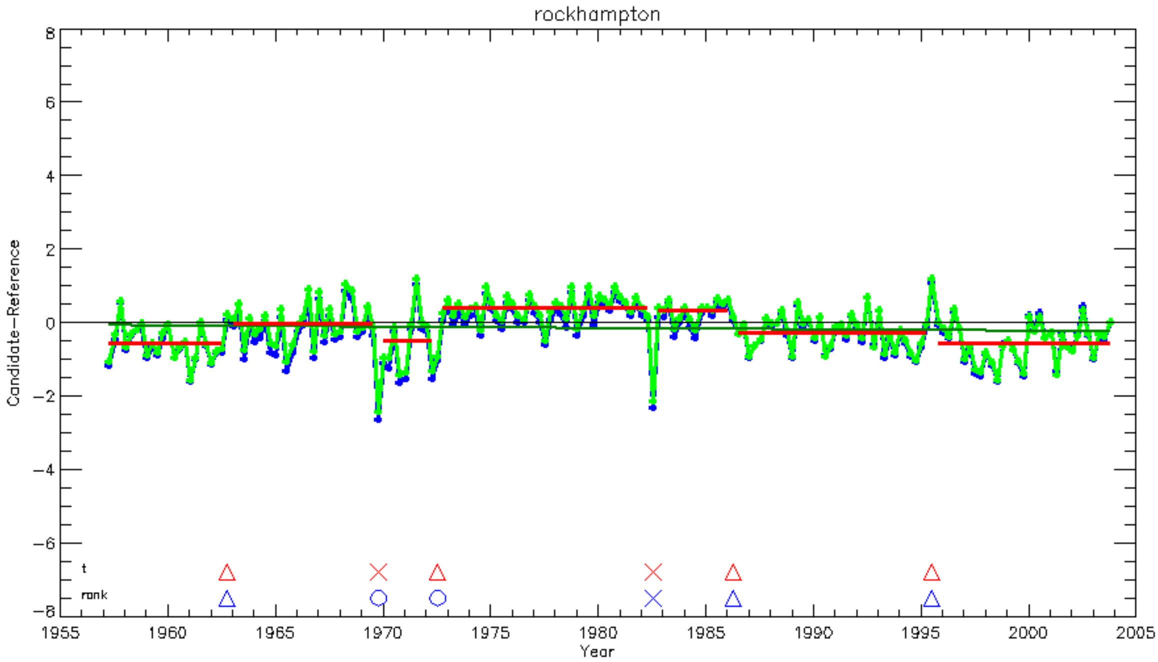
Location: -23.3769 150.4761

Station Number: 39083

2003 Instrumentation: PRT

Reference Stations: 33065, 33047, 40428, 35019, 39122, 33119, 39039, 39015, 39128

Last Season Bias Adjustment: 0.0



Season/Year	Strength	Cause
JJA95	-0.4	AWS epoch, but way too early??
MAM86	-0.5	
JJA72	+0.9	
SON69	-0.5	not sig, pval=.066
SON62	+0.5	

Initial Adjustment:-0.6

10.50 East Sale

Good time resolution throughout. There are at least 4 reference stations at all times. The reference stations are roughly 45-200 km away. Quality: **Good**

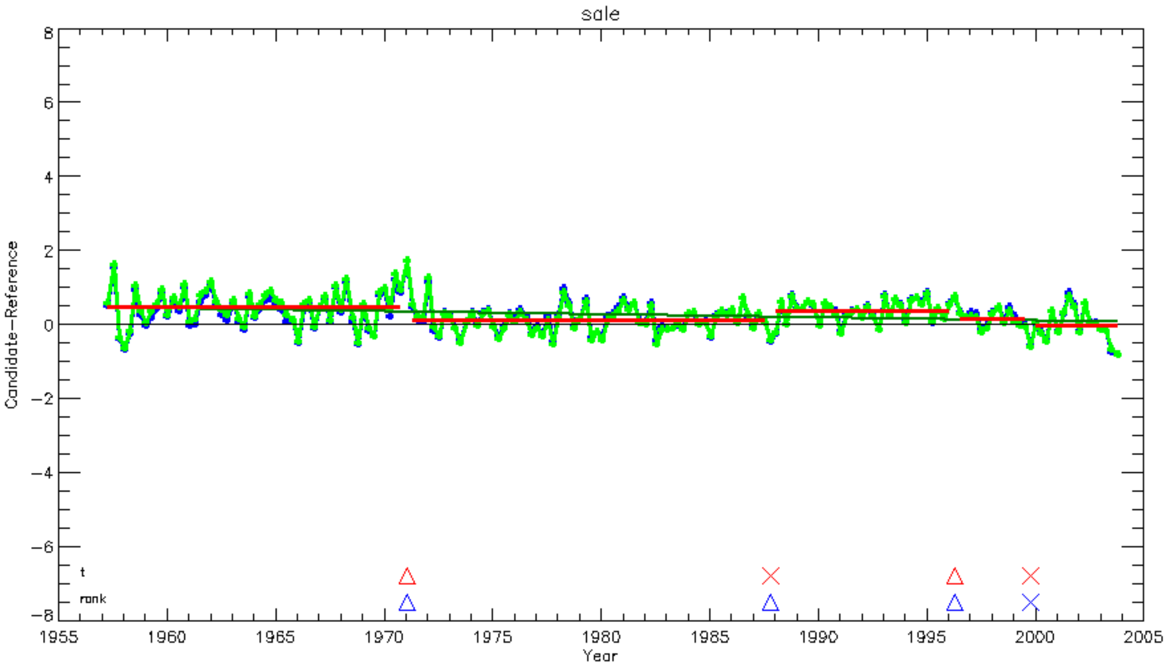
Location: -38.1156 147.1322

Station Number: 85072

2003 Instrumentation: PRT

Reference Stations: 85279, 84083, 86127, 86282, 84030, 86071, 87031, 85277, 85152, 85096

Last Season Bias Adjustment: -0.8



Season/Year	Strength	Cause
SON99	-0.2	Not significant
MAM96	-0.3	AWS install jun96
SON92	+0.2	2^{nd} pass
SON87	+0.2	Only rank sum test significant
DJF71	-0.4	

Initial Adjustment: 0.0

10.51 Sydney

This is the location at Observatory Hill, not the airport. The time resolution is very good, as are the spacing and availability of the reference stations. Quality: **Good**

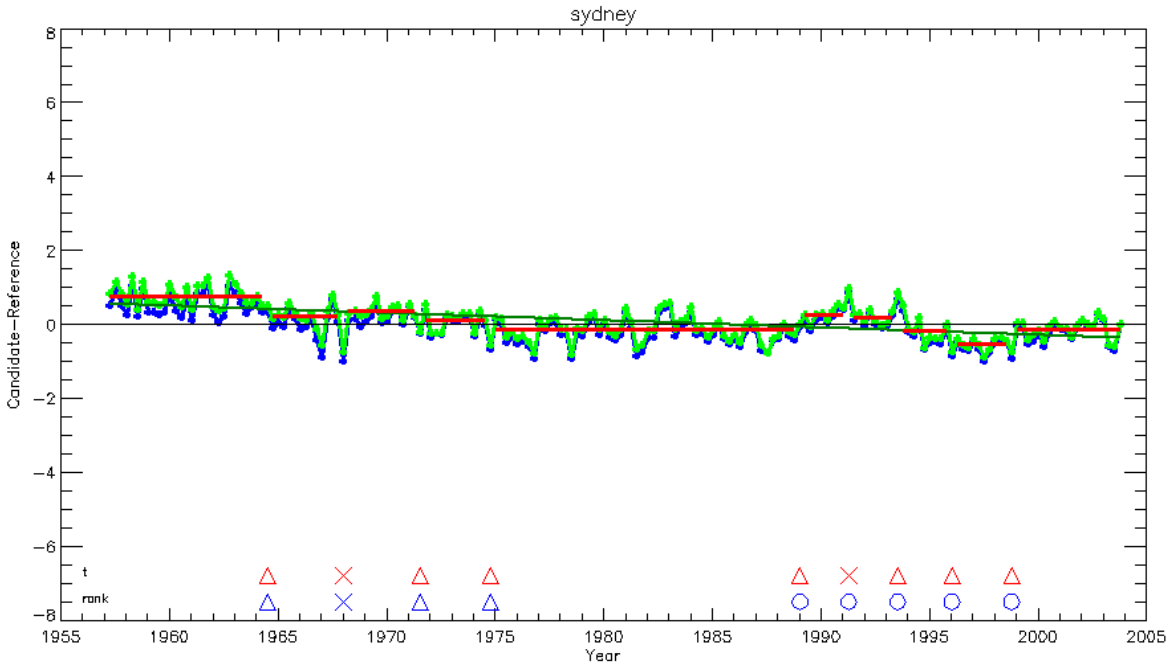
Location: -33.8607 151.2050

Station Number: 66062

2003 Instrumentation: PRT

Reference Stations: 66037, 61078, 67033, 68076, 61086, 66131, 67019

Last Season Bias Adjustment: 0.0



Season/Year	Strength	Cause
SON98	+0.5	
DJF96	-0.4	
JJA94	-0.3	2nd pass
JJA93	-0.3	
DJF89	+0.5	
SON74	-0.3	
JJA71	-0.2	
JJA64	-0.6	

Initial Adjustment: -0.1

10.52 Tennant Creek

This is a composite station with the join occurring in July 1969. Only 0900 and 1500 observations are available before the join, with better time resolution afterwards. Reference stations are generally quite far away, with most being over 400 km distant. Further, extended periods only have 3 reference stations available prior to 1975. The observations after 1969 are collected at a meteorological office, and so are of good quality. Quality: **Good to Fair**.

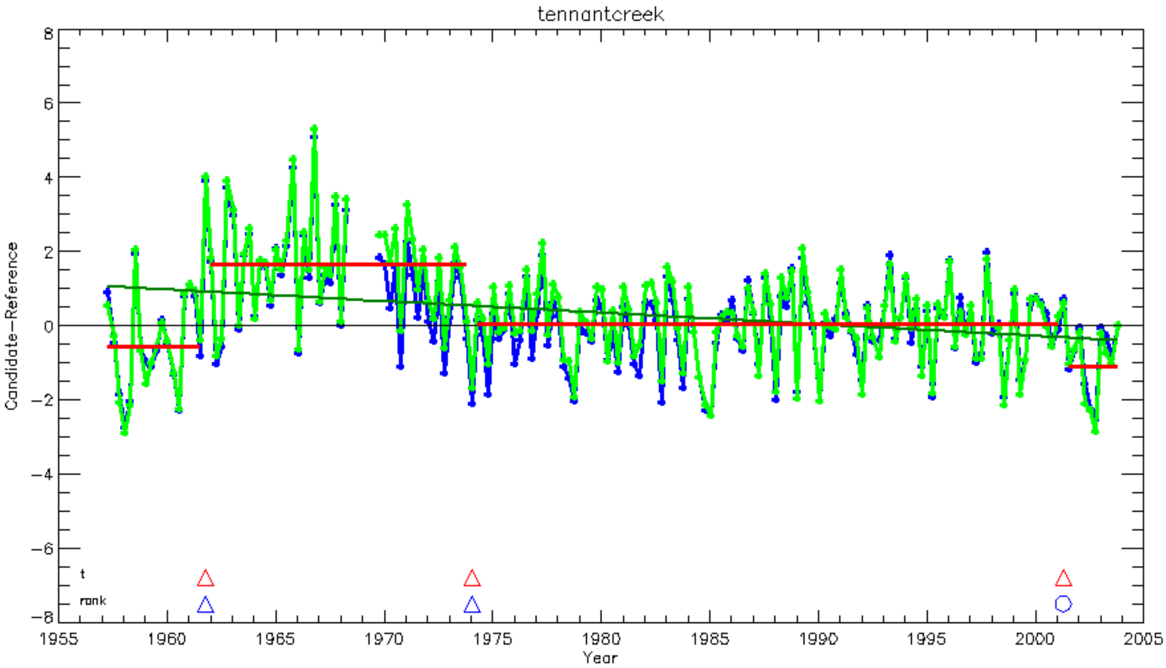
Location: -19.6423 134.1833 (current), -19.6475 134.1896

Station Numbers: 15087, 15135 (current)

2003 Instrumentation: PRT

Reference Stations: 29127, 15602, 15548, 37043, 15590, 15085, 37010

Last Season Bias Adjustment: 0.0



Season/Year	Strength	Cause
MAM01	-1.0	
SON94	-0.8	
DJF74	-1.1	
SON61	+2.2	

Initial Adjustment: -1.1

10.53 Tibooburra

Only 0900 and 1500 observations are available before 1987. Resolution is not especially good after that time. Several extended missing data periods in 1970s. Some brief periods also only have 2-3 reference stations, and these stations are generally on the order of 250-400 km away. Quality: **Fair.**

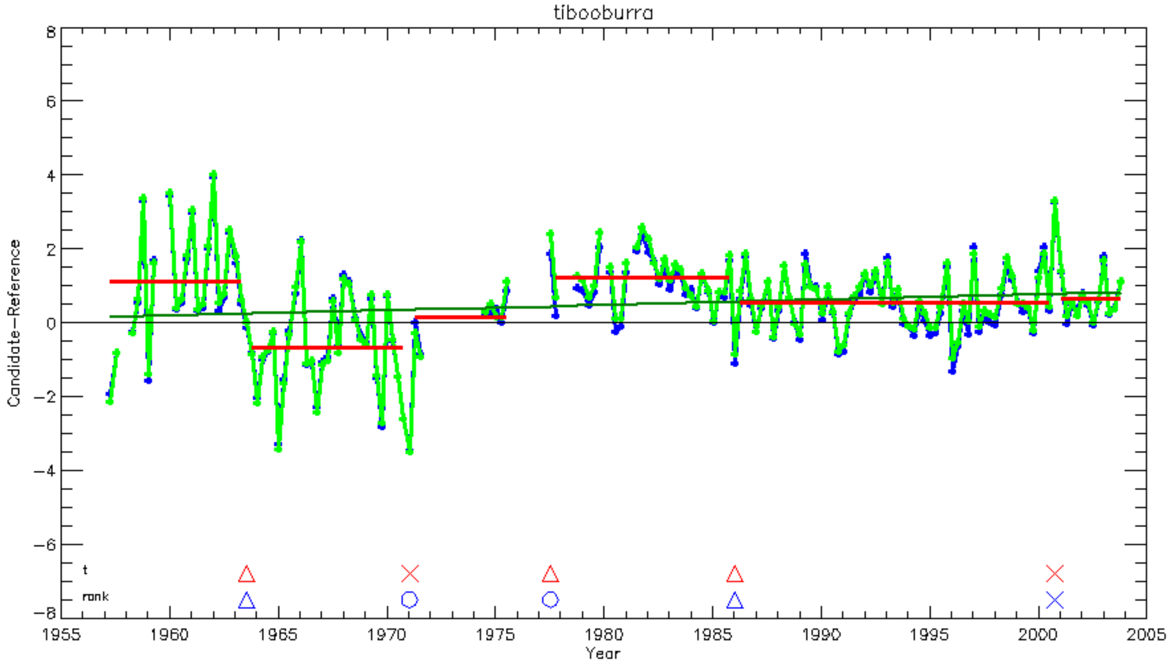
Location: -29.4358 142.0083

Station Number: 46037

2003 Instrumentation: Hg

Reference Stations: 46042, 17099, 46043, 17005, 48027, 19017, 47007, 17096, 48013

Last Season Bias Adjustment: 1.1



Season/Year	Strength	Cause
DJF86	-0.6	
DJF77	+1.3	
DJF71	+0.8	Not significant, noisy
JJA63	-2.4	

Initial Adjustment: +0.6

10.54 Townsville

Excellent time resolution is observed throughout the record. Four to eight reference stations at all times. A small site move (200 m) noted in Dec 1994. Stations are on the order of 100-300 km away. Quality: **Good**

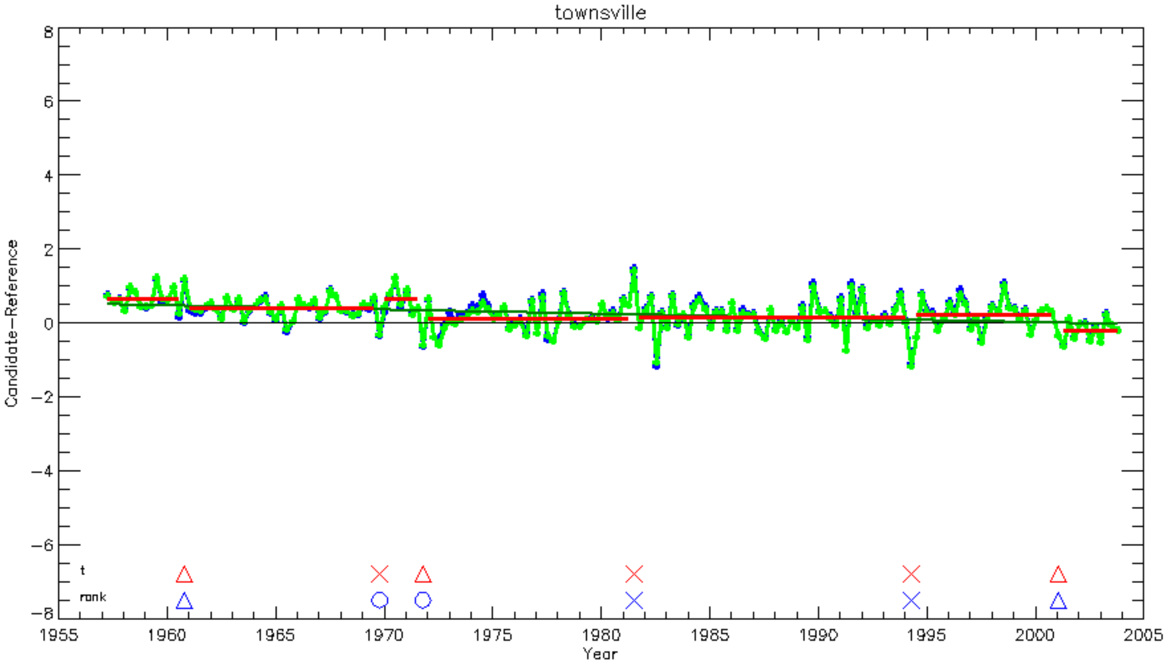
Location: -19.2478 146.7669

Station Number: 32040

2003 Instrumentation: PRT

Reference Stations: 32078, 32004, 32037, 32025, 33047, 34002, 31011, 33013

Last Season Bias Adjustment: -0.2



Last Season Bias Adjustment: -0.2

Season/Year	Strength	Cause
DJF01	-0.4	New AWS?
SON71	-0.5	
SON69	+0.2	
SON60	-0.3	

Initial Adjustment: -0.2

10.55 Wagga Wagga

Five to nine reference stations at all times. All are within 250 km. Temporal resolution is also good. Quality: **Good**.

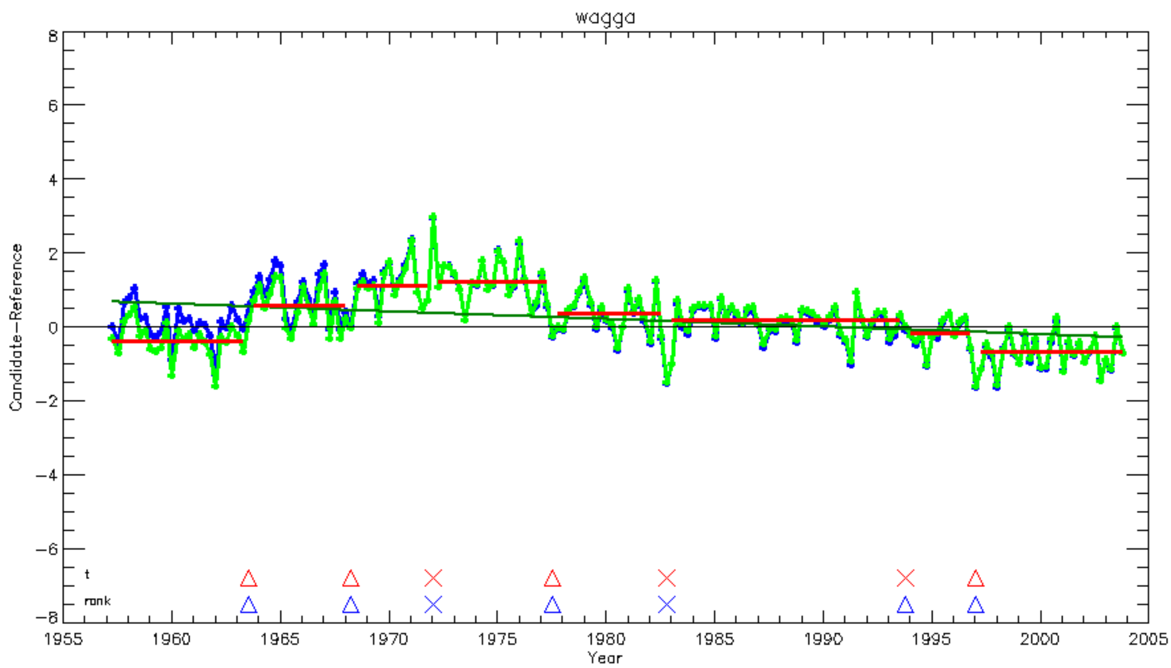
Location: -35.1583 147.4573

Station Number: 72150

2003 Instrumentation: PRT

Reference Stations: 74034, 82002, 72023, 74128, 63023, 73009, 75031, 73007, 65026

Last Season Bias Adjustment:-0.7



Season/Year	Strength	Cause
DJF97	-0.5	AWS epoch.
SON93	-0.3	Only rank sum test significant
JJA77	-0.8	
MAM68	+0.6	
JJA63	+1.1	

Initial Adjustment: -0.7

10.56 Weipa

This is a composite station, with the join occurring inthis dataset during November 1992. The station has a poor time resolution in the beginning of record with observations only available at 0900 and 1500. There are also extended periods of missing data. Reference stations are distant and many are not of particularly good quality. The AWS becomes the official measurement with the site move. The station fills an important spatial gap. Quality: **Fair**

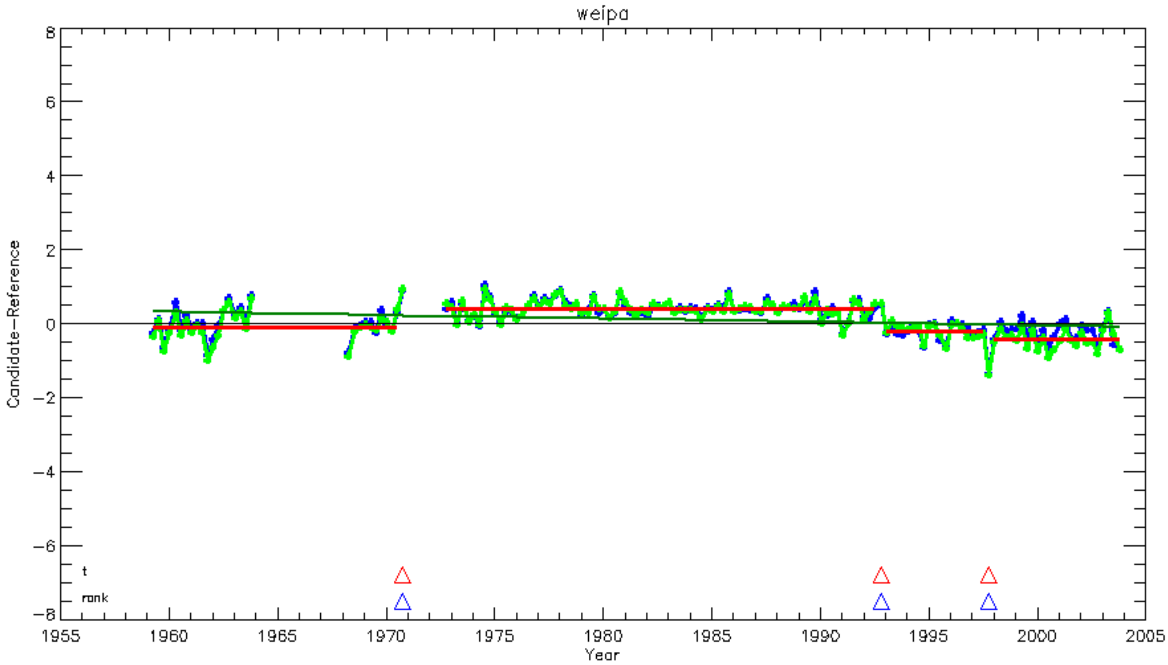
Location: -12.6778 141.9208 (current), -12.6267 141.8836

Station Numbers: 27042, 27045 (current)

2003 Instrumentation: PRT

Reference Stations: 28008, 27006, 27022, 31037, 31011, 31017, 27005

Last Season Bias Adjustment: -0.7



Season/Year	Strength	Cause
SON97	-0.2	
SON92	-0.5	Site move, AWS install.
SON70	0.3	

Initial Adjustment: -0.4

10.57 Williamtown

Good time resolution throughout record. Five to eight reference stations at all times. All stations are within 250 km of the site. Quality: **Good.**

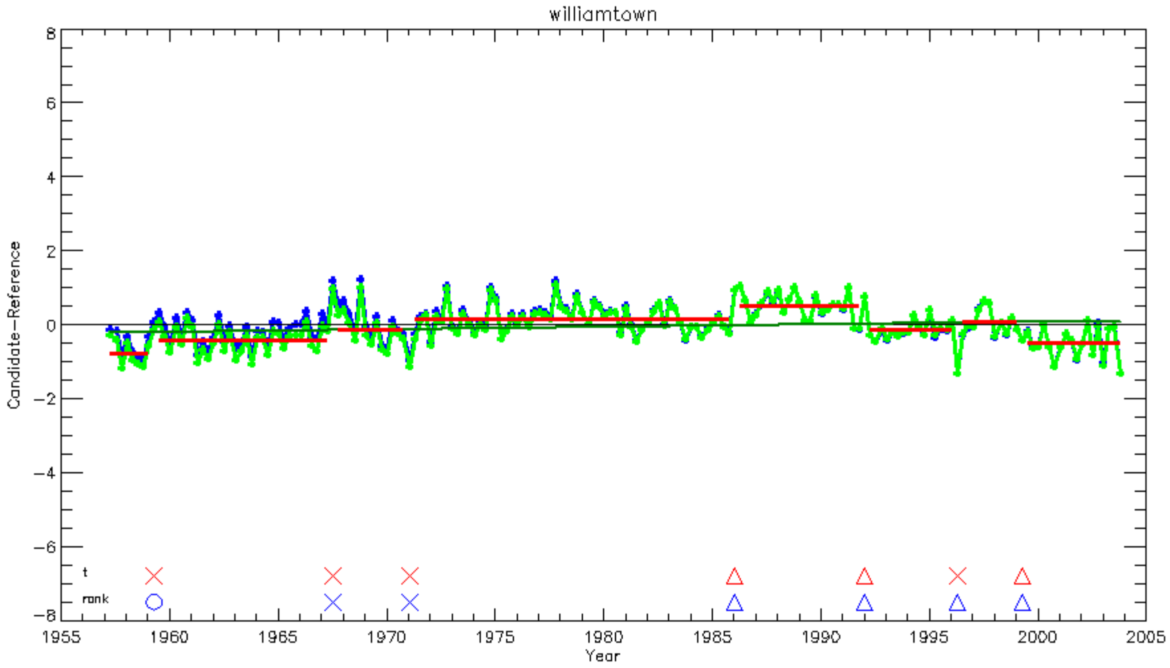
Location: -32.7939 151.8386

Station Number: 61078

2003 Instrumentation: PRT

Reference Stations: 67033, 66037, 61089, 66062, 61086, 59017, 68102, 55024

Last Season Bias Adjustment: -1.3



Season/Year	Strength	Cause
MAM99	-0.5	AWS, screen change
MAM96	+0.2	Only rank sum significant, pval=.054
DJF92	-0.6	
DJF86	+0.5	
DJF71	+0.2	Not sig
JJA67	+0.3	Not sig
MAM59	+0.3	Not sig, pval=.051

Initial Adjustment: -0.5

10.58 Woomera

Good time resolution throughout. There are at least 4 reference stations at all times, and as high as 10 in some periods. These stations are perhaps a bit further away then ideal, but not too bad given the remoteness of the station. Quality: **Good.**

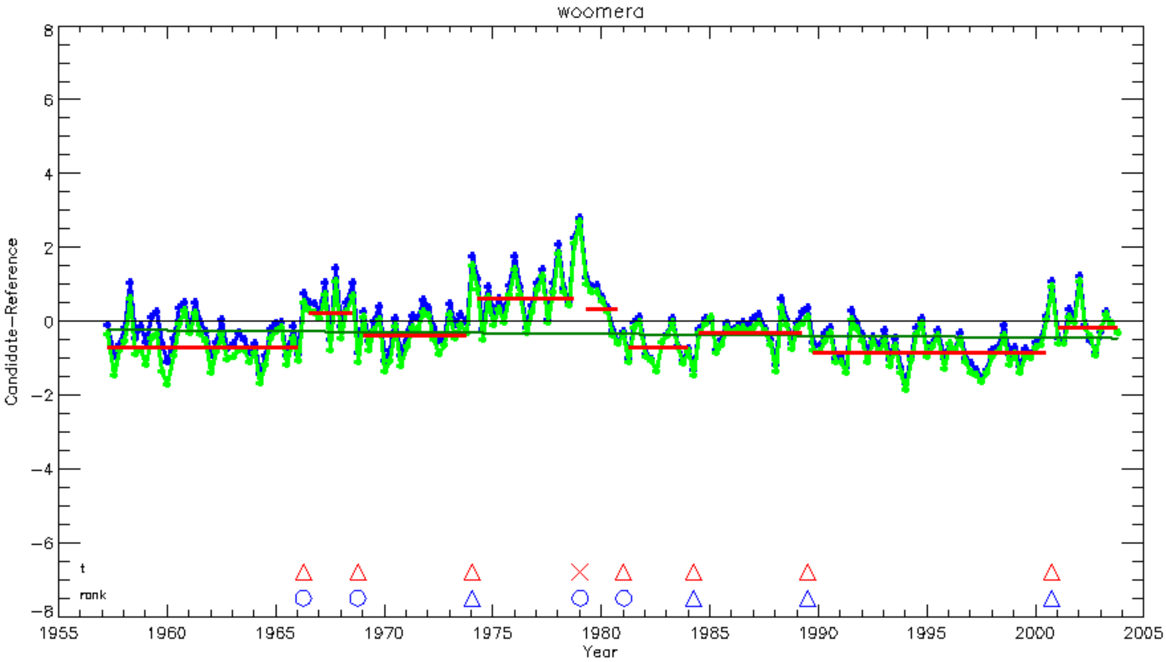
Location: -31.1558 136.8054

Station Number: 16001

2003 Instrumentation: PRT

Reference Stations: 17110, 16065, 19066, 16032, 18040, 17005, 16007, 22008, 16044, 18012, 19062

Last Season Bias Adjustment: -0.3



Season/Year	Strength	Cause
SON00	+0.8	
JJA89	-0.4	
MAM84	+0.4	
DJF81	-1.0	
DJF79	-0.3	
DJF74	+1.0	
SON68	-0.6	
MAM66	+1.1	

Initial Adjustment: -0.1

11 APPENDIX B. LIST OF REFERENCE STATIONS USED

The table details the station number, name, elevation and geographical location of the reference stations used in this study. This information is gathered from the sitesDB metadata website available in the Bureau of Meteorology.

Station ID	Station Name	Elevation (m)	Latitude	Longitude
1005	Wyndham Port	20	-15.4644	128.1000
1007	Troughton Island	6	-13.7542	126.1485
1009	Kuri Bay	12	-15.4875	124.5222
1012	Mitchell Plateau	315	-14.7925	125.8258
1013	Wyndham	11	-15.4872	128.1247
1021	Kalumburu	23	-14.2961	126.6431
3003	Broome	7	-17.9492	122.2336
3007	Derby PO	8	-17.3044	123.6292
3030	Bidyadanga	11	-18.6844	121.7803
3032	Derby Aero	6	-17.3706	123.6611
3080	Curtin Aero	78	-17.5736	123.8217
4019	Mandora	7	-19.7419	120.8436
4020	Marble Bar Comp	182	-21.1756	119.7497
4028	Pardoo Station	9	-20.1067	119.5803
4032	Port Hedland	6	-20.3725	118.6317
4035	Roebourne	12	-20.7767	117.1456
4074	Goldsworthy	45	-20.3422	119.5206
4083	Karratha Aero	7	-20.7097	116.7742
5007	LearmonthAP	5	-22.2406	114.0967
5008	Mardie	11	-21.1906	115.9797
5016	Onslow	4	-21.6364	115.1117
5061	Dampier Salt	6	-20.7278	116.7483
6025	Hamelin Pool	15	-26.4008	114.1667
6044	Denham	9	-25.9261	113.5319
7017	Cue	453	-27.4233	117.8994
7057	Mount Magnet	426	-28.0647	117.8431
7139	Paynes Find	339	-29.2708	117.6836
7151	Newman	544	-23.3683	119.7314
7161	Errabiddy	450	-25.4636	117.1361
8025	Carnamah	268	-29.6889	115.8869
8039	Dalwallinu	335	-30.2772	116.6619
8051	Geraldton	33	-28.7953	114.6975
8093	Morawa	274	-29.2103	116.0089
8137	Wongan Hills	283	-30.8917	116.7186
8251	Kalbarri	6	-27.7119	114.1650

Station ID	Station Name	Elevation (m)	Latitude	Longitude
9021	Perth AP	15	-31.9275	115.9764
9034	Perth RO	19	-31.9500	115.8667
9114	Lancelin	4	-31.0164	115.3300
9172	Jandakot Aero	30	-32.1011	115.8794
9500	Albany	3	-35.0289	117.8808
9515	Busselton Shire	4	-33.6611	115.3456
9519	Cape Naturaliste	109	-33.5372	115.0189
9534	Donnybrook	63	-33.5719	115.8247
9538	Dwellingup	267	-32.7103	116.0594
9542	Esperance Aero	142	-33.6825	121.8275
9573	Manjimup	286	-34.2508	116.1450
9581	Mt Barker_WA	300	-34.6250	117.6361
9592	Pemberton	174	-34.4478	116.0433
9631	Esperance Downs RS	158	-33.6031	121.7828
9741	Albany	68	-34.9414	117.8022
10007	Bencubbin	359	-30.8081	117.8603
10035	Cunderdin	236	-31.6597	117.2511
10092	Merredin	315	-31.4756	118.2789
10515	Beverley	199	-32.1083	116.9247
10536	Corrigin	295	-32.3292	117.8733
10579	Katanning	310	-33.6886	117.5553
10592	Lake Grace	286	-33.1006	118.4647
10622	Ongerup	286	-33.9644	118.4889
10633	Ravensthorpe	232	-33.5797	120.0461
10648	Wandering Comp	280	-32.6814	116.6756
11017	Balladonia	148	-32.4581	123.8653
11019	Eyre	5	-32.2464	126.3008
11045	Balgair	162	-31.0900	125.6589
12038	Kalgoorlie	365	-30.7847	121.4533
12046	Leonora	376	-28.8836	121.3303
12065	Norseman	277	-32.1981	121.7794
12074	Southern Cross	355	-31.2319	119.3281
12090	Yeelirrie	487	-27.2842	120.0931
13012	Wiluna	521	-26.5914	120.2250
13017	Giles	598	-25.0431	128.3010
14008	Cape Don	19	-11.3167	131.7667
14011	Minjilang	35	-11.1456	132.5688
14015	Darwin	30	-12.4242	130.8925
14042	Oenpelli	6	-12.3263	133.0581
14090	Middle Point	10	-12.5781	131.3145
14161	Darwin RO	27	-12.4667	130.8333
14198	Jabiru AP	26	-12.6594	132.8939

Station ID	Station Name	Elevation (m)	Latitude	Longitude
14213	Gunn Pt Prison Farm	20	-12.2522	131.0428
14400	Maningrida	11	-12.0482	134.2263
14401	Warruwi	19	-11.6502	133.3796
14402	Milingimbi	4	-12.1239	134.9078
14507	Alyangula Police	20	-13.8483	136.4198
14508	Gove	52	-12.2741	136.8203
14512	Nhulunbuy Dtw	20	-12.1939	136.7637
14707	Wollogorang	60	-17.2122	137.9462
14938	Mango Farm	15	-13.7379	130.6834
15034	Wonarah	240	-19.8983	136.3358
15085	Brunette Downs	218	-18.6388	135.9467
15087	Tenant Creek	377	-19.6475	134.1896
15135	Tennant Creek	376	-19.6423	134.1833
15511	Curtin Springs	490	-25.3139	131.7571
15526	Finke PO	267	-25.5833	134.5667
15528	Yuendumu	667	-22.2562	131.8017
15548	Rabbit Flat	340	-20.1883	130.0161
15590	Alice Springs	546	-23.7951	133.8890
15602	Jervois	328	-22.9495	136.1444
15603	Kulgera	508	-25.8425	133.3022
15635	Yulara Aero	492	-25.1897	130.9736
16001	Woomera	167	-31.1558	136.8054
16007	Coober Pedy	215	-29.0054	134.7551
16032	Nonning	200	-32.5226	136.4926
16044	Tarcoola	120	-30.7111	134.5694
16065	Andamooka	76	-30.4490	137.1692
16085	Marla Police Stn	323	-27.3002	133.6201
17005	Leigh Creek	194	-30.4667	138.4075
17043	Oodnadatta	116	-27.5439	135.4408
17096	Moomba	39	-28.1125	140.2102
17099	Arkaroola	318	-30.3110	139.3357
17110	Leigh Creek	259	-30.5963	138.4219
18012	Ceduna	15	-32.1297	133.6976
18040	Kimba	263	-33.1394	136.4209
18044	Kyancutta	57	-33.1332	135.5552
18069	Elliston	4	-33.6501	134.8880
18079	Streaky Bay	13	-32.7963	134.2116
18106	Nullarbor	64	-31.4492	130.8976
18139	Polda	37	-33.5085	135.2928
19017	Hawker	315	-31.8846	138.4350
19062	Yongala	515	-33.0287	138.7489
19066	Port Augusta Power	7	-32.5280	137.7900

Station ID	Station Name	Elevation (m)	Latitude	Longitude
	Stn			
22008	Maitland	185	-34.3745	137.6733
23031	Waite Inst	115	-34.9697	138.6331
23034	Adelaide AP	2	-34.9524	138.5204
23057	Northfield Res Cent	77	-34.8533	138.6517
23083	Edinburgh RAAF	16	-34.7042	138.6194
23321	Nuriootpa	274	-34.4767	139.0047
23733	Mount Barker	360	-35.0639	138.8509
24016	Renmark	20	-34.1711	140.7494
24024	Loxton Res Cen	30	-34.4390	140.5978
24521	Murray Bridge	33	-35.1234	139.2592
25507	Keith	29	-36.0980	140.3556
26005	Cape Northumberland	5	-38.0573	140.6725
26023	Naracoorte	58	-36.9564	140.7402
26026	Robe	3	-37.1628	139.7560
27005	Coen PO	195	-13.9447	143.2006
27006	Coen AP	160	-13.7636	143.1172
27022	Thursday Island MO	58	-10.5853	142.1200
28004	Palmerville	204	-16.0008	144.0758
28008	Lockhart River AP	17	-12.7850	143.3050
29012	Croydon Township	116	-18.2044	142.2447
29025	Julia Creek PO	122	-20.6569	141.7458
29127	Mount Isa Aero	340	-20.6778	139.4875
29141	Cloncurry AP	186	-20.6664	140.5050
30018	Georgetown PO	291	-18.2922	143.5483
30045	Richmond_QLD	211	-20.7289	143.1425
31011	Cairns	3	-16.8736	145.7458
31017	Cooktown Mission	6	-15.4486	145.1861
31029	Herberton PO	899	-17.3875	145.3842
31034	Kairi Res Stn	714	-17.2150	145.5656
31037	Low Isles LH	2	-16.3842	145.5592
31084	Fitzroy Island LH	124	-16.9267	146.0033
31108	Walkamin DPI	594	-17.1347	145.4281
32004	Cardwell Eden St	5	-18.2581	146.0206
32025	Innisfail	8	-17.5250	146.0344
32037	South Johnstone Exp Stn	18	-17.6056	145.9969
32040	Townsville	8	-19.2478	146.7669
32078	Ingham Composite	11	-18.6494	146.1769
33013	Collinsville PO	186	-20.5539	147.8469
33047	Te Kowai Exp Stn	13	-21.1642	149.1192
33065	St Lawrence PO	17	-22.3458	149.5356

Station ID	Station Name	Elevation (m)	Latitude	Longitude
33119	Mackay	30	-21.1183	149.2150
34002	Charters Towers	310	-20.0781	146.2614
35019	Clermont PO	267	-22.8250	147.6414
35069	Tambo PO	395	-24.8819	146.2564
35070	Taroom PO	199	-25.6408	149.7958
36007	Barcaldine PO	266	-23.5544	145.2883
36026	Isisford PO	205	-24.2589	144.4406
36030	Longreach	191	-23.4500	144.2500
36031	Longreach	192	-23.4372	144.2769
36143	Blackall Township	283	-24.4242	145.4653
37010	Camooweal	231	-19.9225	138.1214
37043	Urandangi	173	-21.6119	138.3136
37051	Winton PO	181	-22.3908	143.0386
38003	Boulia	162	-22.9117	139.9039
39015	Bundaberg	14	-24.8667	152.3467
39039	Gayndah	106	-25.6258	151.6094
39083	Rockhampton	10	-23.3769	150.4761
39122	Heron Island Res Stn	3	-23.4422	151.9131
39128	Bundaberg	27	-24.8885	152.3235
40004	Amberley	27	-27.6297	152.7111
40126	Maryborough	11	-25.5181	152.7111
40211	Archerfield AP	12	-27.5717	153.0078
40214	Brisbane RO	38	-27.4778	153.0306
40223	Brisbane AP	4	-27.4178	153.1142
40264	Tewantin	8	-26.3919	153.0408
40428	Brian Pastures	120	-25.6550	151.7450
40842	Brisbane AP	4	-27.3917	153.1292
41038	Goondiwindi PO	217	-28.5481	150.3075
41095	Stanthorpe	792	-28.6617	151.9339
41100	Texas PO	297	-28.8544	151.1681
41521	Goondiwindi AP	218	-28.5211	150.3256
43015	Injune PO	400	-25.8428	148.5669
43030	Roma PO	300	-26.5719	148.7897
43034	St George	201	-28.0361	148.5814
43109	St George	199	-28.0489	148.5942
44021	Charleville	302	-26.4156	146.2452
45015	Quilpie AP	199	-26.6125	144.2578
46042	White Cliffs PO	151	-30.8506	143.0897
46043	Wilcannia	75	-31.5631	143.3747
47007	Broken Hill	315	-31.9759	141.4676
48013	Bourke	106	-30.0917	145.9358
48015	Brewarrina Hospital	115	-29.9614	146.8651

Station ID	Station Name	Elevation (m)	Latitude	Longitude
48027	Cobar	260	-31.4853	145.8292
48030	Cobar	251	-31.5000	145.8000
49002	Balranald	61	-34.6398	143.5610
49019	Ivanhoe PO	85	-32.8999	144.2995
50031	Peak Hill PO	285	-32.7235	148.1902
50052	Condobolin Ag Res Stn	195	-33.0664	147.2283
51039	Nyngan AP	173	-31.5495	147.1961
52020	Mungindi PO	160	-28.9786	148.9899
53027	Moree	207	-29.5000	149.9000
53030	Narrabri West PO	212	-30.3401	149.7552
53048	Moree	212	-29.4819	149.8383
55024	Gunnedah	307	-31.0261	150.2687
57095	Tabulam	555	-28.7551	152.4507
58012	Yamba	29	-29.4333	153.3633
58037	Lismore	11	-28.8070	153.2628
58130	Grafton Olympic Pool	9	-29.6833	152.9283
58131	Alstonville Tropical	140	-28.8521	153.4556
58158	Murwillumbah	18	-28.3408	153.3784
59001	Bellingen PO	15	-30.4519	152.8979
59017	Kempsey	10	-31.0770	152.8235
59030	South West Rocks	117	-30.9225	153.0870
60026	Port Macquarie	7	-31.4399	152.9110
61051	Murrurundi PO	466	-31.7631	150.8362
61078	Williamtown	9	-32.7939	151.8386
61086	Jerrys Plains PO	90	-32.4972	150.9093
61089	Scone SCS	216	-32.0632	150.9272
62013	Gulgong PO	475	-32.3634	149.5329
63023	Cowra Res Cent	381	-33.8088	148.7072
64008	Coonabarabran	505	-31.2712	149.2714
64009	Dunedoo PO	388	-32.0163	149.3953
65012	Dubbo	260	-32.2388	148.6089
65026	Parkes	324	-33.1439	148.1633
65034	Wellington	305	-32.5635	148.9503
65091	Cowra AP Comp	300	-33.8452	148.6535
66037	Sydney AP AMO	6	-33.9411	151.1725
66062	Sydney	39	-33.8607	151.2050
66131	Riverview Observ	40	-33.8258	151.1556
67019	Prospect Dam	61	-33.8193	150.9127
67033	Richmond_NSW	19	-33.6022	150.7794
68034	Jervis	85	-35.0936	150.8048
68076	Nowra	109	-34.9449	150.5450

Station ID	Station Name	Elevation (m)	Latitude	Longitude
68102	Bowral	690	-34.4864	150.4021
69018	Moruya	17	-35.9093	150.1532
69049	Nerriga Composite	630	-35.1165	150.0847
70014	Canberra	578	-35.3049	149.2014
70263	Goulburn	650	-34.7208	149.7420
72023	Hume Reservoir	184	-36.1040	147.0329
72043	Tumbarumba PO	645	-35.7781	148.0121
72150	Wagga	212	-35.1583	147.4573
73007	Burrinjuck Dam	390	-35.0008	148.5969
73009	Cootamundra PO	318	-34.6411	148.0236
74034	Corowa AP	143	-35.9887	146.3574
74128	Deniliquin	93	-35.5269	144.9520
75031	Hay	93	-34.5194	144.8545
75032	Hillston AP	122	-33.4915	145.5249
75039	Lake Cargelligo AP	169	-33.2833	146.3707
76026	Merbein CSIRO	56	-34.2133	142.0400
76047	Ouyen	50	-35.0694	142.3158
77042	Swan Hill PO	70	-35.3406	143.5533
78031	Nhill	133	-36.3347	141.6367
79023	Polkemmet	141	-36.6522	142.1053
79040	St Arnaud	240	-36.6189	143.2631
80015	Echuca Aerodrome	96	-36.1661	144.7631
81003	Bendigo	225	-36.7533	144.2825
82002	Benalla	169	-36.5483	145.9703
82011	Corryong	313	-36.2003	147.8956
82042	Strathbogie	502	-36.8472	145.7308
83025	Omeo Comparison	685	-37.1011	147.5981
84030	Orbost	41	-37.6917	148.4589
84083	Lakes Entrance	43	-37.8692	147.9961
85072	Sale	5	-38.1156	147.1322
85093	Warragul	140	-38.1731	145.9483
85096	Wilsons Prom	89	-39.1297	146.4244
85152	Wonwran Prison	93	-38.4856	146.6717
85277	Noojee	275	-37.9039	145.9719
85279	Bairnsdale AP	49	-37.8817	147.5669
86071	Melbourne	31	-37.8075	144.9700
86127	Wonthaggi	51	-38.6089	145.5950
86282	Melbourne AP	113	-37.6750	144.8422
86351	Bundoora	83	-37.7164	145.0453
87031	Laverton	16	-37.8564	144.7564
87100	Pt Lonsdale LH	12	-38.2939	144.6142
88109	Mangalore AP	141	-36.8900	145.1828

Station ID	Station Name	Elevation (m)	Latitude	Longitude
88110	Castlemaine Prison	330	-37.0811	144.2392
89002	Ballarat Aerodrome	435	-37.5128	143.7914
89085	Ararat Prison	295	-37.2775	142.9811
90048	Heywood Forestry	26	-38.1353	141.6319
90135	Casterton Showgrounds	73	-37.5908	141.4131
90172	Warrnambool AP	75	-38.2919	142.4353
91057	Low Head	28	-41.0567	146.7883
91104	Launceston AP	170	-41.5411	147.2019
91237	Launceston	5	-41.4208	147.1206
92027	Orford	15	-42.5517	147.8775
92038	Swansea PO	10	-42.1258	148.0747
94008	Hobart AP	4	-42.8389	147.4992
94029	Hobart	51	-42.8908	147.3269
94069	Grove	63	-42.9844	147.0758
95003	Bushy Park	27	-42.7111	146.8967
97053	Strathgordon Village	322	-42.7694	146.0444

12 APPENDIX C. REPRINT OF 'AN EXAMINATION OF DEWPOINT BIASES INTRODUCED BY DIFFERENT INSTRUMENTATION'

This section contains a reprint of the Lucas (2006) paper originally published in the BMRC Research Letters. The whole thing is reprinted. Some sections, namely the discussion on Bureau humidity instrumentation, are substantially the same as written in the current document. The results and conclusions of the reprint are different from those presented here, though.

Introduction

Correctly determining the amount of atmospheric water vapour is crucial for understanding the observed circulation on all time scales. With the widespread deployment of Automatic Weather Stations (AWSs) in Australia since the 1990s have come new technologies for measuring humidity. As with all instrumentation, different techniques and methods result in different answers. Assisting the understanding of the causes and effects of the measurement differences produced by the various instruments used by the Bureau of Meteorology (BoM) to measure dewpoint is the aim of this paper.

This paper is an outgrowth of a project to produce a high-quality, homogenous humidity data base across Australia. A necessary step in the homogenization procedure is correcting the effects of changes in instrumentation. As the project progressed and the differences in dewpoint due to instrumentation effects became apparent, the need for a shorter contribution dedicated explicitly to this subject became obvious.

The approach for this study is a statistical examination of data from a wide range of stations. The responses of the instrumentation are examined on a seasonal to annual time scale and are based on the results of the homogenization procedure. In this document, a basic overview of the homogenization procedure is given. A complete description of the procedure is the subject of a BMRC Research Report currently under preparation. The methodology and instrumentation of atmospheric humidity measurement are reviewed. Dewpoint biases are estimated and analysed, based on the different instrument types. The sources of biases and the effects of climate variability are also examined. The main findings are summarized in the conclusions.

Creation of a Homogeneous Dewpoint Dataset

The goal of data homogenization is to remove the effects of station discontinuities -- for example, those caused by changes in station location and/or observation procedures -- from a time series of a variable (dewpoint in this case) at a given *candidate station.* Fifty-four candidate stations used in this study. Coverage extends across Australia. In general, these stations are high quality stations located at airports and meteorological offices. Some lower-quality stations, such as those at post offices, are included for spatial completeness. As a rule, these stations have nearly continuous observations extending from 1957 through 2003. Records at five stations start slightly later than this.

To homogenize the record at a candidate station, it must be compared to a *reference series* free from inhomogeneities. Since few, if any such stations exist in the records, a composite reference series must be created from *reference stations*. These are nearby stations with records of reasonable quality and length (pre-1980 is the criterion chosen here) and a humidity climate similar to the candidate station. Some leeway exists in the definition of 'nearby'; many remote Australian stations simply do not have any suitable stations within 200-300 km, forcing the selection of less-than-ideal reference stations. At a given candidate station, between 4 and 9 reference stations are chosen to create the reference series.

At the candidate and reference stations, time series of morning (0800 or 0900 LT) monthly median dewpoint are seasonally averaged (e.g. DJF, MAM…). The long-term seasonal means are removed from these series to create seasonal anomalies. These are the basic time series used in this analysis. To create the composite reference series, the technique described by Peterson and Easterling (1994) is generally followed. In this method, a consensus *difference series*, the difference of a given point from the previous one in the series, is derived from a correlation- and distance-weighted average of the difference series at the reference stations. Difference series minimize the effects of a discontinuity in a long record. The consensus series is then integrated backward in time to create a composite homogeneous reference series. The reference series is subtracted from the candidate series. This time series is subsequently used to identify inhomogeneities in the data.

Humidity Measurement Methodology and Instrumentation in the BoM

Psychrometric Method

In Australia, the psychrometric method is most often used to measure humidity in the atmosphere. In this method, the actual amount of vapour in the air is determined from two simultaneous, but separate temperature measurements: 1.) the ambient air ('dry-bulb') temperature and 2.) the wet-bulb temperature. The wet bulb temperature is measured by wrapping the bulb of the thermometer in a wick, which is kept wet with distilled water. This allows a measurement of the amount of cooling produced by evaporation, a quantity dependent on the relative humidity (RH). A value for station pressure is also required.

The various measurements are subsequently used in the semi-empirical psychrometric formula

$$e = e_w - Ap(T - T_w),$$

where e is the actual vapour pressure (i.e. the saturation vapour pressure at the dewpoint), e_w is the saturation vapour pressure at the wet-bulb temperature T_w, p is the pressure, T is the ambient air temperature and A is the psychrometric constant. Saturation vapour pressures are converted to and from their associated temperatures using the approximation derived by Alduchov and Eskridge (1996):

$$e = 6.1094 \exp\left(\frac{17.625T}{T + 243.04}\right).$$

The psychrometric constant A defined above is a critical term and a major source of uncertainty in the calculation. From a purely thermodynamic standpoint, $A = c_p(\varepsilon L)^{-1} \approx 6.46\times10^{-4}$ K^{-1} at $0^{o}C$.

However, the value of this ‘constant’ when making real-world measurements varies considerably based on a number of factors.

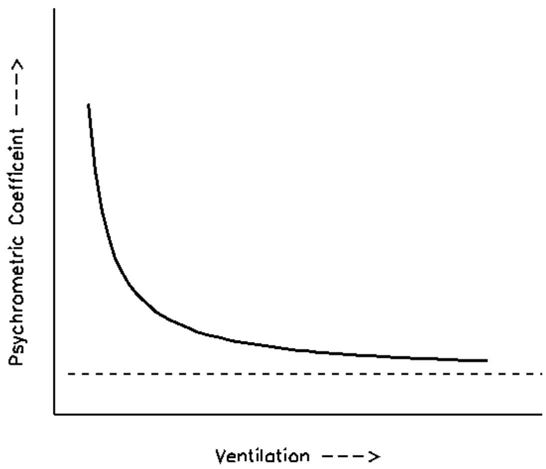


Fig 1. *Schematic diagram of variation of psychrometric coefficient A with changes in the ventilation of the instrument.*

The most important of these factors is the ventilation of the instrument and/or its shelter. Figure 1 shows schematically the response of *A* to changes in the ventilation. At low ventilation speeds, *A* is high. As ventilation increases, *A* decreases asymptotically. Another important factor in determining *A* is the design of the wet bulb sensor.

Psychrometric measurements made by the Bureau of Meteorology use ‘naturally ventilated’ screens, with values of *A* recommended by the CIMO Guide to be 7.7-8.0 $x10^{-4}$ K^{-1} for wet-bulb temperatures in excess of 0^oC. The standard Bureau value of $7.886x10^{-4}$ K^{-1} falls within this range, and is used in all calculations in this study.

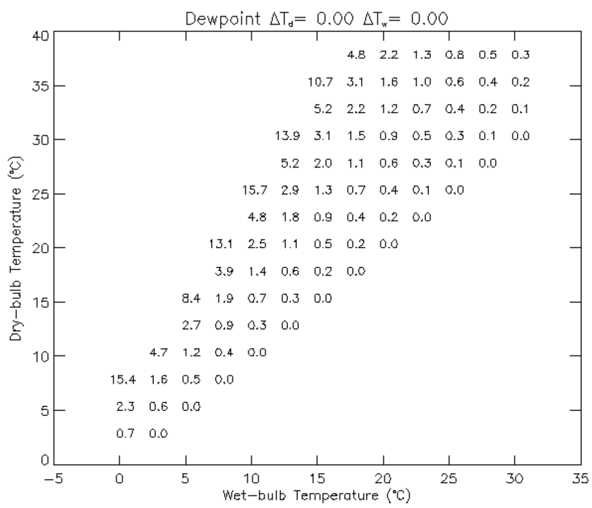


Fig 2. *Difference in dewpoint at selected dry-and wet-bulb temperatures due to a change in the value of the psychrometric coefficient. This plot is difference with A= $7.00x10^{-4}$ K^{-1} from A= $7.886x10^{-4}$ K^{-1}*

Figure 2 shows the sensitivity of the computed dewpoint to a change in the value of *A*. In the figure, the value of *A* is set to 7.000 x $10^{-4}K^{-1}$. (The reason for choosing this value will become apparent later). Dewpoints computed using this value of *A* are subtracted from those with the standard value. The lower value of *A* results in a higher dewpoint being measured. If the value of *A* used in Fig. 2 were the true value and the standard is instead used, then these numbers in the figure are the negative bias that results. This effect is more pronounced at lower RH, where the dewpoint errors can be quite large. The magnitude of this error reflects the non-linear relation between vapour pressure and dewpoint. Even at higher RH, the dewpoint errors are potentially on the order of 0.2 degrees or so.

Instruments Used to Measure Humidity

Historically, the primary instruments used to measure humidity have been mercury-in-glass (Hg) thermometers. These are standard instruments which derive temperature by measuring the rise and fall of a column of mercury as it expands and contracts with changes in temperature. These instruments were used over most of the country until the gradual introduction of AWSs, beginning in earnest in the early-1990s. They are still in use in many AWSs, as supplemental readings. Five candidate stations in the dataset exclusively used Hg thermometers in 2003 and Typically 50-75% of the reference stations employed Hg thermometers, although this number varies from around 15% to 100%

Most AWSs in the humidity database use values derived from platinum resistance thermometers (PRTs), which work by measuring the temperature–dependent change in the resistance of a conductor, in this case platinum. The instruments used in Australia are manufactured by Rosemount, and are referred to as ‘temperature probes’. AWSs using PRTs rely on the psychrometric method to measure humidity, with a dry- and wet-bulb probe. Of the 54 stations in the dataset, 39 use PRTs in 2003.

At more remote stations, military bases and other stations where staff are not on hand to maintain the instruments (particularly the wet-bulb thermometer), electrical humidity measurements are made using a humidity probe (HP). This instrument does not require the techniques of psychrometry, but instead measures the humidity directly by measuring the change in capacitance of a thin film, a quantity dependent on the RH. These devices typically have a larger uncertainty in their measurement and are generally not reliable in the long term as they are subject to hysteresis and drift after exposure to very high RH and cloud (e.g. Strangeways 2001). Through 2003, the majority of AWSs with HPs installed used devices manufactured by Rotronics of Switzerland. Ten of the stations in the dataset used HPs in 2003.

The sitesDB metadata database also indicates that other instruments have been used to measure humidity at different times and different stations. Before the 1990s, many stations used hygrographs or thermohygrographs to record humidity as well. Other stations show the use of psychrometers and hair hygrometers in their records. In general, these instruments were not the ‘official’ measurement, but rather a supplemental one to the Hg thermometer standard.

Estimates of Dewpoint Bias in 2003

The dewpoint bias at a given candidate station is estimated by averaging the difference between the candidate and reference series seasonal anomaly over the last 4 seasons (DJF03, MAM03, JJA03 and SON03). Figure 3 shows a scatterplot of the calculated bias against the linear trend of the candidate series, shows a distinct skew towards negative biases in the estimates..

There are several possible sources of the observed bias. Potential sources of bias include errors in calibration, a bias in the mean due to the linear trend in the data or biases introduced by the different instruments used. Some combination of these effects in also possible

The instruments and their calibrations are typically checked once or twice a year. If the instrument exceeds its tolerance, it is repaired or replaced. The values of the offsets (for the electrical instruments) are recorded and stored in the sitesDB. Using the calibration information for the dry and wet bulb combination (PRTs) or errors in RH (HPs), an estimate of the dewpoint bias can be obtained. The HP calibration numbers are erratic in many cases, and are not particularly reliable. For the PRTs, the calibration offsets show a slight skew towards negative values. Most values are less than 0.3 degrees in magnitude, with a mean of –0.14 degrees. There is essentially no correlation between the observed PRT bias and the calibration offset (Tables 1 and 2).

Another possible explanation is a bias created by the long-term linear trend seen in the candidate series. If a negative trend is observed and the dewpoint is accurate at the end of 2003, then the seasonal means removed will be biased high and the seasonal anomalies will be negatively biased. In cases where a positive trend is observed, oppositely-signed seasonal means and anomalies will be seen. For the 47 years of the typical series, the effect should account for 0.235 degrees for every 0.1 degrees/decade of trend.

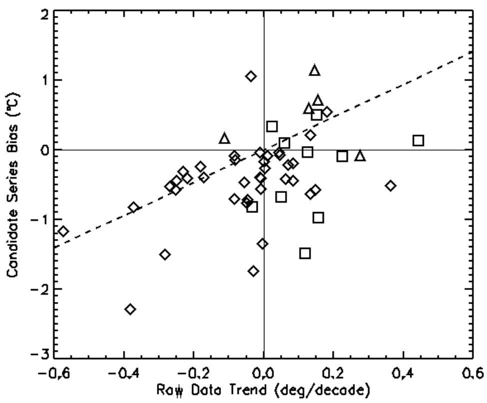


Fig 3. *Raw data trend against the calculated the observed bias in the candidate series for all 54 stations. Symbols refer to instrument type, where diamonds are PRTs, squares are HPs and triangles are Hg thermometers. The dashed line is the bias expected due to a linear trend.*

Figure 3 shows a scatterplot of the observed bias against the candidate series trend. The predicted bias due to the trend is plotted as the dotted line. At first glance, there is an apparent strong relationship between trend and bias, with a correlation of +0.44. However, the points with trends <-0.15 deg/decade are producing much of this correlation, and removing even some of these points greatly reduces the correlation. Still, there are several stations near the predicted ‘trend bias’ line and several of these fall within ± 25% of the predicted value, suggesting that this effect is responsible for some of the observed bias. With the exception of these cases, generally where a strong negative trend is observed, the trend in the raw data apparently has only a minor role in the producing the observed bias in the last year of the record.

More significantly, Fig. 3 shows that the type of instrument used in the last years of the record appears to have an effect on both the trend and the bias of the candidate series. At stations equipped with PRTs, the stations tend to have negative biases low and more negative trends. Candidate stations with Hg thermometers generally have both a positive bias and trend. Stations using HPs are mixed in their biases, but generally have positive trends. There are exceptions to this general behaviour for each instrument. In the next sections, possible explanations these observations of PRTs and HPs will be examined.

Sources of Instrumental Bias

Platinum Resistance Thermometers (PRT)

Thirty-six of the 39 candidate stations with PRT wet-bulb sensors show negative biases. A mathematical model of the average bias at stations using PRTs is constructed using multiple linear regression (e.g. Draper and Smith, 1981). The goal of this model is twofold. The first is to identify the important sources of the observed bias. The second is to estimate a typical offset of PRTs from Hg thermometers. Five variables in different combinations are tested. These variables are 1.) the fraction of reference stations with Hg thermometers (*Hg*); 2.) the annual average dewpoint (*DP*); 3.) the distance between the candidate and its nearest reference (*dist*); 4.) the linear trend in the raw data (*trend*); and 5.) the calibration offset based on the numbers in sitesDB(*cal*). The regression equation which explains the most variance with the lowest standard error is kept.

With all stations included, the trend is by far the dominant variable regardless of which combination is used. However, as noted in the previous section, the trend alone does not do a particularly good job at explaining the observed biases. Most points lie well off the predicted line. Including other variables does not result in a great improvement to the fit. The most significant regressions involve *Hg* and *trend*. Examining the residuals (not shown) for these fits reveals the existence of several outlier points.

These same outliers are also apparent in Fig. 3. Seven stations with strong positive (>0.5^{o}C) or negative (<-1.0^{o}C) biases are removed and the regression is rerun. Three of the deleted stations (Cape Leeuwin, Brisbane AP and Alice Springs) have artefacts in the data or analysis. The remaining four stations (Longreach, Meekatharra, Rabbit Flat and Kalgoorlie) have very strong negative biases. The source of these exceptional biases is explored further in a later section.

***Table 1**. PRT station correlations of potential regression variables with observed bias and regression coefficients for the variables selected for the outlier removed cases. See text for description of variables.*

variable	R	coefficients
constant	--	-0.170
Hg	-.433	-.450
DP	.344	1.72e-2
dist	-.251	-7.50e-4
trend	.262	--
cal	-.045	--

Table 1 summarizes the results of the regression analysis. Removing the outliers creates significant correlations of observed bias with *Hg* and *DP*. The correlation with *trend* is much reduced, and is now insignificant. The correlations with *cal* and *dist* are about the same. For the regression, the best fit is obtained with variables *Hg*, *DP* and *dist*. With these variables, about

36% of the variance is explained. The residual plots (not shown) do not suggest any outliers. Including *trend* reduces the significance of the fit and slightly increases the standard error.

For a PRT-equipped station with an annual average dewpoint of 10^{o}C, the regression equation predicts an offset of -0.4 to -0.5 degrees from a collocated Hg thermometer. The standard error of 0.2 for the regression is large, about 50% of the mean. However, BoM technical documents suggest that the model is at least capturing the gross effects responsible for the bias.

In a comparison of the response of Hg thermometers and PRTs across a variety of conditions, Warne (1998) found that Hg thermometers overestimate the dewpoint relative to PRTs. While both instrument types had errors, which increased with decreasing RH, the Hg thermometers generally performed more poorly.

Gorman (2003) compared dewpoints at an operational AWS using PRTs with a calibrated reference standard. In that study, the AWSs produced lower dewpoints, especially at lower ambient RH values. The wind speed was a crucial factor, suggesting this was a result of better ventilation of the screen, and a correspondingly lower value of *A*. Lowering *A* to 7.00×10^{-4} K^{-1} gave a better fit to the reference data. Physically, it was suggested that this was due to the ventilation characteristics of the small Stevenson screen being poorly characterized. However, a tabulation of the screen types at the candidate and reference stations reveals that the vast majority of screens in Australia during 2003 are of the 'small' type. Using this fact and the findings of Warne (1998), it is hypothesized that the difference in *A* are due to the ventilation characteristics of the PRT rather than the screen.

These findings are consistent with the biases observed at PRT-equipped candidate stations. Hg thermometers are the primary wet-bulb instrument at many reference stations. Further, PRT-derived dewpoints are artificially low due to uncertainties in *A*. These factors combine to produce a negative bias, which is more negative where *Hg* is larger and the humidity (*DP*) is lower. This reasoning is in general agreement with the regression model. The *dist* is likely an effect of the spatially-varying climate. The stations with large distances between them are generally in the drier remote interior of the continent with stronger humidity gradients.

Humidity Probes (HP)

At the HP stations, the observed bias response varies quite a bit. Four of the 10 stations have biases with a magnitude of less than 0.2 degrees (Fig. 3). Two have higher positive biases; four have strong negative biases. To investigate factors which influence the bias, a regression analysis is performed, using similar variables. Calibration data is very inconsistent at a given station for the HPs and hence not included. The annual average rainfall (*rain*) is included to reflect the propensity of the instrument to experience extremely high RH conditions, which can adversely affect its operation.

***Table 2**. HP station correlations of potential regression variables with observed bias and regression coefficients for the selected variables.*

variable	correlation	coefficients
constant	--	1.315

Hg	-.363	--
DP	-.752	-0.137
dist	.107	--
trend	.242	--
rain	-.369	-5.683e-4

The results of the analysis are shown in Table 2. With so few stations, only the correlation with *DP* is significant. Reasonably high (but insignificant) correlations are also seen with *Hg* and *rain*. In the regression, it is found that the fit using *DP* and *rain* has the lowest standard error. Including *Hg* also provides a good fit, although it is not as significant as without. For Australian-average rainfall (472 mm) and an mean dewpoint of 10^{o}C, a typical bias value of –0.3 degrees is estimated from the equation. However, the standard error is 0.37 and considerable variation should be expected as the variables used in the regression suggest that the main factor determining the bias is the climate where the instrument is placed. In drier climates with little rain, positive biases are indicated.

These results are consistent with the findings of BoM internal test reports on this HP. Huysing (1995) showed that the biases of the Rotronics probes varied with the ambient RH at the station, with positive biases at low RH and negative biases at high RH. This matches the direction of the regression with variable *DP*. Gorman (2001) suggests systematic errors in the probes due to 'inaccuracies in the potentiometer adjustment' on the order of 2%. This offset is not constant, but inconsistently varies with the RH. This is on top of a random error of 1%. These findings translate to a uncertainty in dewpoint on the order of 0.9^{o}C.

Analysis of the residuals indicates three points that have unusual behaviour. These stations are Bourke, Laverton and Camooweal. At Camooweal, the Rotronics probe was not used after 2002. Rather, a Vaisala humidity probe is used, which is shown by Gorman (2002) to have different response characteristics than the Rotronics HPs. The large residuals at Bourke and Laverton likely reflect the shortcoming of using an annual measure of humidity. While *DP* is nearly identical at the stations, the annual cycle of dewpoint at the stations is quite different. The large differences in the observed bias to nearly identical values of the predictor creates 'pure error' in the regression. Another possible explanation for this behaviour could be calibration differences in the probes.

Climate, the Psychrometric Coefficient and Bias

A 'typical bias' value of –0.4 to –0.5 for PRT-based humidity measurements is predicted by the regression equation. This value is broadly consistent with the suggestion of Gorman (2003) that a lower value of *A* is required for AWSs using PRTs (Fig. 2). This number is most suitable for use on seasonal to annual time scales. On, say, a daily time scale the bias may be much different depending on the weather. For normal meteorological variability, the biases typically 'average out' to produce something like the typical bias. However, if drier conditions persist due to longer-term climate influences the observed bias may vary considerably from the predicted value. Further, such climate anomalies are often regional in scope, rather than continent wide. These vagaries of climate response are likely partially responsible for the high standard error of the regression equation.

In much of Australia, conditions were generally hot and dry during 2002 and 2003. This was especially noteworthy in interior NSW and QLD (BoM, 2003; 2004), and was related, at least in

2002, to the warm phase of the El Nino-Southern Oscillation. Mean annual temperature anomalies were on the order of 0.5 to 1.5 degrees above the long-term mean in both years. Annual rainfall deciles ranged from 1-4, very much below average to average, with some portions of the region reporting the 'lowest ever' seasonal rainfall values. The higher temperatures and lack of rain produce generally lower values of RH.

This effect of these climate anomalies is illustrated in Fig. 4, the seasonally-averaged dewpoint time series of the candidate and reference station data from Longreach, QLD. A general downward trend in seasonal mean dewpoint is seen during this period at all stations and in the reference series. However, in JJA02, SON02 and SON03 in particular, the candidate station is well below both the reference series and the vast majority of reference stations. Calibration data collected from sitesDB suggest a calibration error in dewpoint on the order of –0.6 degrees at this station throughout 2002-3, but this is not large enough to account for the dewpoint anomalies seen here.

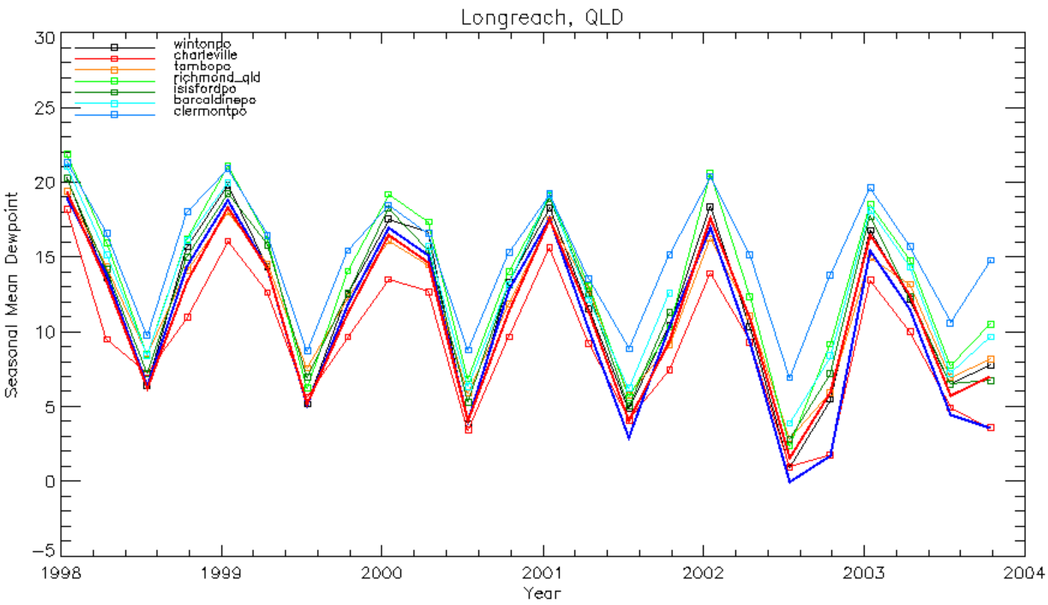


Fig 4. *Longreach, QLD. time series of seasonal mean dewpoint from 1998 to 2003. Shown are the raw candidate series(thick blue line), the computed reference series (thick red line) and the eight reference station series(thin lines with symbols, see legend at upper left) used in computing the bias. An additional offset of 3.5 degrees has been applied to the reference series.*

Similar variations were widespread during this time period among PRT stations, particularly in QLD and northern NSW. One such station is Charleville, QLD, also shown in Fig. 4. The dewpoints at Charleville mimic those at Longreach, further suggesting this is a climate impact on the value of *A*. Stations in the interior of WA also show this effect. The magnitude of the effect seems to vary. This may be due to differences in the climate response or other regional variations. Other factors, such as uncertainties in the calibration or other maintenance issues could also play a role.

Conclusions

Biases in humidity measurements are examined from a statistical standpoint. Carefully constructed humidity reference series from 54 stations across Australia are used to estimate biases during 2003. The majority of the humidity observations from stations which make up the composite reference series are made with traditional mercury-in-glass thermometers. The candidate stations use either Hg thermometers, platinum resistance thermometers or humidity probes. The bias is computed relative to this reference series. Potential causes of the bias include calibration errors, biases due to long-term trends and instrumental effects. The results suggest that instrumental biases are the most important.

Stations which rely on platinum resistance thermometers for their measurements generally have a dewpoint bias with a nominal value of –0.5 degrees. Stations which use humidity probes have a dewpoint bias with a nominal value of –0.3 degrees. As noted before, the bias is computed relative to the reference series; hence, it cannot be stated unequivocally which measurement is the correct one.

The results here indicate that the climate at the site of the dewpoint sensor plays a crucial role in the subsequent performance of the instrument. For the HPs, the amount of bias predicted by the regression depends solely on climate variables, namely the average annual dewpoint and the average annual rainfall. However, particular care should be taken in interpreting this result, due to the small sample size and the inherent uncertainty in HP design. The bias characteristics at HP stations is also likely to change as the Rotronics probes are phased out and replaced with Vaisala probes.

For the PRTs, the situation in regards to climate is more complex. The average annual dewpoint is one of three variables that influence the bias in the regression. The other two have to do with construction of the reference series. Physically, the amount of observed bias is consistent with an incorrect value of the psychrometric coefficient *A* associated with the PRT. The climate *variability* is also a factor, although not accounted for in the regression. During extended hot and dry periods, such as those associated with El Nino, the effect of the mischaracterization of *A* can be magnified, resulting in even larger biases. Such an effect was observed in 2002 and 2003.

The results of this study, together with the results of the referenced instrument test reports, provide a solid basis for further study of this problem. The amount of bias has been quantified and some mechanisms for the sources proposed. The uncertainty in the value of *A* needs to be addressed. Ideally, further experiments and instrument tests in both the laboratory and the field would be performed. The climate of the location where the instrument is sited should be accounted for in any such study.

References

Alduchov, O.A. and Eskridge, R.E. 1996: Improved Magnus form approximation of saturation vapor pressure. *J. Appl. Meteor.*, **35**, 601-609.

BoM, 2003: *Annual Australian Climate Summary 2002*. Available from http://www2.bom.gov.au/announcements/media_releases/climate/change/20030106.shtml

BoM, 2004: *Annual Australian Climate Summary 2003.* Available from http://www2.bom.gov.au/announcements/media_releases/climate/change/20040105.shtml

CIMO, Guide to Meteorological Instruments and Methods of observations, WMO No 8, World Meteorological Organisation, Ch 4.

Draper, N. R. and Smith, H. 1981: *Applied Regression Analysis, 2nd Ed*. John Wiley and Sons. 709 pp.

Gorman, J. 2001: Evaluation of the output variability of Rotronics MP101A humidity probes. BoM Instrument Test Report number 659, 13 pp.

Gorman, J. 2002: Evaluation of Vaisala HMP45D humidity probes. BoM Instrument Test Report number 661, 20 pp.

Gorman, J. 2003: AWS determination of dew point in the field. BoM Tech. Note 2003-0001_revision1, 27 pp

Huysing, P. 1995: Performance tests on a Rotronic MP101A humidity/temperature probe. BoM Instrument Test Report number 641, 5 pp.

Peterson, T. C. and Easterling, D. R., 1994: Creation of homogeneous composite climatological reference series. *Int. J. Climatol.*, **14**, 671-679.

Strangeways, I. 2003: *Measuring the Natural Environment, 2nd Edition*., Cambridge University Press, 534 pp.

Warne, J. 1998: The practical impacts of RTD and thermometer design on wet and dry bulb relative humidity measurements. BoM Instrument Test Report number 648, 6 pp.

The Centre for Australian Weather and Climate Research is a partnership between CSIRO and the Bureau of Meteorology.