THE ROLE OF CLIMATOLOGICAL NORMALS IN A CHANGING CLIMATE

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THE WCDMP "GUIDELINES" SERIES

In recognizing the need for National Meteorological Services (NMHSs) to improve their climate data and monitoring services, the WMO' Commission for Climatology (CCl) placed a high priority on the distribution of guidelines for the NMHSs.

Within the World Climate Data and Monitoring Programme, under the Open Programme Area Group (OPAG I) on Climate Data and Data Management the Expert Team on Data Management initiated the preparation of this guidelines Document. These guidelines are intended to provide NMHSs with information on best practices in climate data management and assist them in making the transition from older databases, such as CLICOM, to the kind of systems that are providing much greater utility, security and robustness.

The Guidelines document was drafted by a sub-group of the CCl Expert Team on Climate Data Management and reviewed externally. During its first meeting in Nairobi, 1-3 November 2006, the newly appointed Expert Team by the fourteenth CCl session (Beijing, China , 3-10 November 2005), proposed to make a second revision of the document and provided few updates.

It should be kept in mind that this Technical Document, like the other technical documents published under the WMO WCDMP series, is intended to provide guidance in the form of best practices that can be used by Members. Because of the diversity of NMHSs, with respect to size and stage of technological development, it may not have a significant utility for specific Members. However, this document does cover a wide range of guidance that should provide some form of assistance to every Member.

The Role of Climatological Normals in a Changing Climate

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1. Introduction

Climatological normals have long filled two major purposes. Firstly, they form a benchmark or reference against which conditions (especially current or recent conditions) can be assessed, and secondly, they are widely used (implicitly or explicitly) for predictive purposes, as an indicator of the conditions likely to be experienced in a given location.

A discussion of the role, and appropriate practices for the calculation of climatological normals must consider these twin purposes. Decisions about climatological normals need to have regard to both purposes, recognizing that what is optimal for one might not be optimal for the other. This will be discussed in greater detail later in this document, but a single issue illustrates the problem as an introduction: where normals are used as a reference, there are benefits to having a standard period that is changed relatively infrequently (such as 1961-1990), but where there is a trend in an element (such as mean temperature), it is reasonable to expect that a more frequent updating and/or a shorter period of measurement will result in a normal with more predictive accuracy.

This document discusses in detail various considerations in the calculation of climatological normals. It also includes a comprehensive evaluation of the predictive capabilities of normals of various lengths and frequencies of updating, an assessment of possible statistical descriptors of climate over and above traditional climatological normals, and a discussion of uncertainties arising from data inhomogeneities and gaps.

2. Definitions

The *Technical Regulations* and earlier editions of *Guide to Climatological Practices* contain a number of explicit definitions, as well as terms which are not formally defined but have a clear meaning. These terms are:

<u>Averages:</u> The mean of monthly values of climatological data (which may be monthly means or totals) over any specified period of time (no specific definition). These are also referred to in the 2nd edition (1983) of the *Guide to Climatological Practices* as ‘provisional normals’.

<u>Period averages:</u> Averages of climatological data computed for any period of at least ten years starting on 1 January of a year ending with the digit 1 (*Technical Regulations)*.

<u>Normals:</u> Period averages computed for a uniform and relatively long period comprising at least three consecutive ten-year periods (*Technical Regulations*).

<u>Climatological standard normals:</u> Averages of climatological data computed for the following consecutive periods of 30 years: 1 January 1901 to 31 December 1930, 1 January 1931 to 31 December 1960, etc. (T*echnical Regulations*).

This terminology is used throughout the remainder of this document.

The definitions above refer only to the mean of monthly values. However, in practice many publications on climatological normals include statistics such as extreme values of an element over a specified period, or other parameters relating to the statistical properties of that element, such as quintile boundaries for monthly precipitation values. For the purpose of this document such statistics are also included in the discussion of averages and normals.

Two further definitions which are used through the remainder of this document are:

<u>Element:</u> An aspect of climate which can be statistically described, such as daily maximum or minimum temperature, precipitation, or vapour pressure.

Parameter: A statistical descriptor of a climate element. Most commonly this is the arithmetic mean, but it can also include values such as the standard deviation, percentile points, number of exceedances of a threshold, or extreme values.

3. The historical development of the concept of climatological normals

The historical development of the concept of climatological normals is described by Guttman (1989). The term 'normal' first appeared in the meteorological literature in 1840, and was first put into formal effect in 1872, when the International Meteorological Committee resolved to compile mean values over a uniform period in order to assure comparability between data collected at various stations.

Over much of the following century, the dominant paradigm was one in which climate is essentially constant on decadal to centennial timescales, and that variations from this constant state over a specific period of time were artifacts of sampling. It followed from this concept that long-term averages would converge to this constant state given a sufficiently long averaging period. After much international discussion in the late 19th and early 20th centuries, 30 years was settled on as a suitable averaging period.

The concept of the 30-year climatological standard normal dates from 1935, when the Warsaw conference of the International Meteorological Committee recommended that the period 1901-1930 be used as a world-wide standard for the calculation of normals. In 1956, WMO recommended the use of the most recent available period of 30 years, ending in the most recent year ending with the digit 0 (which at that time meant 1921-1950). This decision was guided, at least in part, by increased knowledge of long-term climatic fluctuations, although a 1967 report by a working group of the Commission for Climatology (Jagannathan et al., 1967) still took the view that:

"For the most part, large-scale climatic fluctuations consist of non-linear variations that oscillate in an irregular long-period manner round a long-term climatological average."

Despite the 1956 WMO recommendation, the *Technical Regulations* continue to define a climatological standard normal as per section 2 above.

It is now well-established (IPCC, 2001) that global mean temperatures have warmed by 0.6 ± 0.2°C over the period from 1900 to 2000, and that further warming is expected as a result of increased concentrations of anthropogenic greenhouse gases. Whilst changes in other elements have not taken place as consistently as for temperature, it cannot be assumed for any element that the possibility of long-term secular change of that element can be ruled out. The importance of such secular trends is that they reduce the representativeness of historical data as a descriptor of the current, or likely future, climate at a given location. Furthermore, the existence of climate fluctuations on a multi-year timescale (Karl, 1988), to an extent greater than can be explained by random variability, suggests that, even in the absence of long-term anthropogenic climate change, there may be no steady state towards which climate converges, but rather an agglomeration of fluctuations on a multitude of timescales.

The near-universal acceptance of the paradigm of a climate undergoing secular long-term change has not, as yet, resulted in any changes in formal WMO guidance on the appropriate period for the calculation of normals (including climatological standard normals). The most recent extensive WMO guidance on climatological normals, published in 1989 (WMO, 1989), did not address the question of averaging periods, but rather concentrated on which elements and parameters should be used, calculation procedures and treatment of missing data.

4. Criteria potentially usable in the assessment of appropriate averaging periods

The dual principal purposes of climatological normals, as described above, mean that a number of criteria could be used for the assessment of appropriate averaging periods. Some of these are criteria which can only be assessed subjectively; others, notably the predictive accuracy of climatological normals, can be assessed objectively. The choice of an appropriate averaging period will depend on the application to which the normals are being put, and hence the relative importance of the criteria below. Some of the criteria (such as (b) and (c)) are, at least to some extent, mutually inconsistent.

A non-exhaustive list of criteria includes:

(a) Minimizing the prediction error when normals for a given period are used to predict conditions in an independent future period;
(b) Having a set of normals that is as up-to-date as possible, in order to maximize the perceived relevance of those normals in the community;
(c) Having a set of normals that is stable over a long period, in order to minimize the amount of work required in recalculating normals, and associated data such as anomalies;
(d) Maximizing the number of stations for which normals are available for a given parameter;
(e) Having a set of normals for a period which is uniform across an observation network for all stations and/or parameters, in order to provide a common basis for spatial comparison;
(f) Having an averaging period that the general public can relate to and appears 'logical';
(g) Having a set of normals which can be calculated simply using widely available commercial software.

The predictive accuracy of climate averages is the criterion from this list which is most amenable to objective assessment, and will form the basis of the discussion in sections 6 and 7. This should not necessarily be taken as a recommendation that maximizing the predictive accuracy of climate averages should be the main criterion for the assessment of appropriate averaging periods, an issue which will be discussed further in section 12.

5. To what extent do traditional climatological normals provide an adequate description of the climate?

Traditionally, climatological normals have focused on the mean value of a climate element over a period of time. Several authors, extending back to Landsberg (1944) and more recently including Guttman (1989) and Kunkel and Court (1990), have argued that the arithmetic mean of an element is an inadequate description of the climate, and that many applications require information about other aspects of that element's frequency distribution, or other characteristics of the element's statistical behaviour, such as the frequency of extended periods when its value is above a threshold (which will be a function of both the element's frequency distribution and its autocorrelation).

In the context of climatological normals, this raises the question of which parameters can be used to provide additional information about an element's frequency distribution. This can take the form of either providing parameters which define an idealized frequency distribution which can be considered representative of the element concerned, or parameters based on some aspect of the empirically-derived frequency distribution of the element.

There have been many attempts to determine which idealized distributions are most appropriate for given climate elements. Amongst the most common distributions used for this purpose are the Gaussian ('normal') and gamma distributions. Both of these distributions can be completely specified with either two or three parameters. However, idealized distributions do not necessarily match real data. For example, it has been widely assumed (e.g. Thom (1973) and

Klein and Hammons (1975), as well as the 1983 edition of the *Guide to Climatological Practices*) that daily maximum and minimum temperatures approximately follow the Gaussian distribution, but Trewin (2001a) found that this was not the case for Australian data. New et al. (2002) found that, whilst the gamma distribution was generally suitable for fitting to monthly precipitation data, there were some systematic biases in its representation of the expected frequency of extreme values, an issue which is considered further in section 9.2.5.

A more common approach has been to calculate parameters associated with the empirically-derived frequency distribution. Common parameters used for this purpose include the number of days where an element is above or below a specified level (e.g. the number of days with temperatures greater than 30°C), the values of various quantiles of an element (e.g. the 10th or 90th percentile), and the extreme high and low values of an element over a specified period. The most frequent parameters of this type exchanged nationally and internationally are the number of days with measurable precipitation (typically using a threshold of 0.2 or 1.0 mm), and the limits of precipitation quintiles. Because of their common use, precipitation quintiles are discussed in detail in section 9.2.

6. The predictive accuracy of climate averages

6.1 Previous analyses of the predictive accuracy of climate averages

A number of previous authors have attempted to evaluate the averaging period which should be used in order to optimize the predictive value of a climate average. Such studies include those of Lamb and Changnon (1981), Dixon and Shulman (1984), Angel et al. (1993), Huang et al. (1996) and Srivastava et al. (2003). These studies all address the question: in order to maximize the predictive skill for a climate variable in year *n* using the mean of *k* years ending in year *n-1*, what is the optimal value of *k*? The major difference between the studies is in the climate parameters for which the predictive skill is being evaluated, and in the metrics used for evaluation.

All five studies evaluate their results separately at each station, aggregating their results over time by sub sampling a longer data set. As an example, Lamb and Changnon (1981) used a data set covering the period 1901-1979, and calculated differences for each year in the period 1931-1979 between the value in that year and means for the previous 5, 10, 15, 20, 25 and 30 years; they then aggregated their results over the 49 years from 1931-1979.

Where we define the number of samples used as *m*, the first year of the sampling period as year *a*, the value in year *n* as X_n, the *k*-year mean ending in year *n* as $\overline{X}_{k,n}$, and the difference between the value in year *n* and the *k*-year mean ending in year *(n-1)* as $d_{k,n} = X_n - \overline{X}_{k,(n-1)}$, then metrics used for evaluating results in the five studies include:

- Ranking: the number of occasions within the *m* samples that the value of $d_{k,n}$ is lower for a given value of *k* than it is for any other value of *k*.
- Mean absolute error (MAE): defined using the equation

$$E_k = \left(\sum_{n=a}^{a+m-1} | d_{k,n} | \right) / m$$

- Root-mean-square (RMS) error: defined using the equation

$$E_k = \sqrt{\left(\sum_{n=a}^{a+m-1} (d_{k,n})^2 \right) / m}$$

- The correlation of anomaly values in year *n* (calculated with respect to a fixed reference period) with the anomaly of the *k*-year mean ending in year *n-1* with respect to that same reference period:

$$COR_k = \frac{\sum_{n=a}^{a+m-1} (\overline{X}_{k,(n-1)} - \overline{X}_{ref})(X_n - \overline{X}_{ref})}{\sqrt{\sum_{n=a}^{a+m-1} (\overline{X}_{k,(n-1)} - \overline{X}_{ref})^2 \sum_{n=a}^{a+m-1} (X_n - \overline{X}_{ref})^2}}$$

Where $\overline{X}_{ref}$ is the mean of *X* over some fixed reference period.

Whilst the detailed results of these studies vary, they typically find an optimal averaging period at each station which is substantially lower than 30 years. As examples, Srivastava et al. (2003) found values of 5 to 20 years were typical for maximum and minimum temperature at Indian stations, Huang et al. (1996) found values of 5 to 15 years for mean temperature in the United States, and Angel et al. (1993) values of around 11 years for heating degree days in Illinois. Differences between different metrics are discussed by Dixon and Shulman (1984), who note that, relative to the MAE and RMS methods, the 'ranking' method tends to produce shorter optimal averaging periods, as a short averaging period is more likely to produce either very small or very large errors than a longer one.

Most of these studies calculate optimal averaging periods separately for each station. Huang et al. (1996) also address two additional questions: firstly the extent to which the additional predictive skill, over and above that from a climatological standard normal, from the use of an optimal averaging period is drawn from the shorter period and that to which it is drawn from the annual updating of the optimal averages, and secondly the impact on the results if they are evaluated field-wide across all stations with a fixed averaging period, rather than allowing the averaging period to vary between stations. They find that, at individual stations, the additional predictive skill is partly derived from the shorter period and partly from annual updating, but that once the averaging period is fixed field-wide, the length of the period has very little effect on the predictive skill over the range 10 to 30 years, with any additional skill beyond that from the climatological standard normal being almost entirely derived from the more frequent updating. This is an important result if one is considering the appropriate averaging period to be used across an entire network.

6.2 Variables chosen for evaluation of predictive accuracy of climatic averages

The following variables were chosen for evaluation of predictive accuracy of climatic averages:

(a) Those parameters which were defined as 'Principal Climatological Surface Elements' in WMO (1989). These are:

- Total precipitation
- Number of days with precipitation greater than, or equal to, 1.0 mm.
- Mean daily maximum temperature
- Mean daily minimum temperature
- Mean sea level pressure
- Total sunshine duration (evaluated in this study as mean daily sunshine duration)
- Mean vapour pressure

(b) Upper-air parameters that are transmitted in CLIMAT TEMP messages, or form the basis of such variables. These are:

- Mean geopotential height

- Mean temperature
- Mean *u* and *v* components of vector wind
- Mean wind steadiness ratio

Mean dew point is also transmitted in CLIMAT TEMP messages, but was not included in this study because of a lack of available dew point data from Australian radiosonde stations prior to 1991.

To provide an illustration of conditions over a substantial range of the atmosphere, these parameters were evaluated separately at the 500 and 200 hPa levels.

In order to provide a consistent benchmark for comparison, daily values of mean sea level pressure and vapour pressure were calculated as the mean of the values observed at 0900 and 1500 local time, and only 0000 UTC observations were used for the upper-air measurements. Whilst WMO (1989) recommends that mean sea level pressure be calculated as the mean of the 4 observations at 0000, 0600, 1200 and 1800 UTC, vapour pressure as the mean of either 24 or 8 equally spaced observations during the day, and upper-air averages should be calculated separately for the hours of 0000, 0600, 1200 and 1800 UTC, the hours chosen were used in order to maximize the amount of historical data available for analysis. (Australian observation practice has historically been to make surface observations at 0000, 0300, 0600, …, 2100 local clock time; it has only been since the introduction of automatic weather stations in the mid-1990's that any significant quantities have been available at 0000, 0600,… UTC, or at time resolutions finer than three-hourly.)

Precipitation quintiles form a special case which is discussed in detail in section 9.2.

6.3 Data used for evaluation of predictive accuracy of climatic averages

Australian data were used for the evaluation of the predictive accuracy of climatic averages, as suitable international data sets were not available to the author. (Whilst the GSN or similar data sets would be suitable for some analyses, evaluation of the adjustment procedures described in section 7.2 requires a data set of similar spatial density to that which would be available to a national meteorological service within its own territory). It cannot necessarily be assumed that the results, in detail, would hold in other climates, and the carrying out of a similar analysis in other regions would be a valuable addition to the knowledge base in this field.

The basic set of surface stations used for the analyses in this section consists of 32 stations. These stations are chosen as those stations which are included in the Australian Bureau of Meteorology's high-quality daily temperature data set (Trewin, 2001b) and have monthly mean values of daily maximum and minimum temperature defined in the Bureau's climate database for all months in the period from 1961-1990 inclusive. (This does not necessarily mean that those monthly values fully meet the criteria of WMO (1989) for missing data, as described in section 10.)

The analyses for mean sea level pressure, vapour pressure, total monthly precipitation and number of days with precipitation greater than or equal to 1 mm were carried out using the subset of these 32 stations which had monthly data defined for the variable in question for all months in the 1961-2003 period. This set consisted of 30 stations for maximum and minimum temperature, 26 stations for mean sea level pressure, 24 for total monthly precipitation, 14 for number of days with precipitation greater than or equal to 1 mm, and 17 for vapour pressure. Due to the paucity of Australian sunshine duration data (there are only 8 Australian stations which are still open and commenced sunshine duration observations in 1961 or earlier), all 7 stations which have monthly sunshine duration data for all months in the period 1961-2003 were used, whether or not they were in the original 32-station set.

For the upper-air analyses, 9 stations were used. The criteria for inclusion were that the station was still open as of the end of 2003, and had no missing monthly data in the 1961-1990 period. (It was not feasible to require complete data for the full 1961-2003 period, as May 1994 upper-air data are missing from the Bureau of Meteorology database for virtually all Australian stations, due to a data ingest problem).

No explicit consideration was taken of data homogeneity in the choice of station, although most gross inhomogeneities for surface data were excluded by virtue of the original inclusion of the stations in the Australian Bureau of Meteorology's high-quality daily temperature data set. Three urban stations (Sydney, Melbourne and Hobart) are included in the set, although in all three cases the impact of urbanization on temperatures had largely stabilized by 1970, and hence averages taken from the 1961-1990 period (or some subset of it) can be considered reasonably comparable with data from the post-1990 period. The impact of data inhomogeneities on climate averages is discussed more extensively in Section 11.

The locations of the stations used are shown in Figure 1, whilst their locations, and the variables for which they are used, are shown in Appendix A.

6.4 Procedures used for evaluation of predictive accuracy of climate averages

For each of the parameters under consideration as described in section 6.2, the following procedures were carried out for each station in each of the 12 months:

(a) Comparison of averaging periods ending in 1990 with 1991-2000 means

This test was intended to investigate the predictive accuracy of an average of a given length ending in a fixed year, when tested against a fixed period of data (the 'evaluation period') independent of the averaging period.

For each station *x* and averaging length *k*, the difference between the mean value of the parameter for the period between the years (1990 – *k* + 1) and 1990, and its mean value for the period 1991-2000, was calculated.

These differences were then aggregated over all stations and months. Two metrics were calculated using definitions analogous to those in section 6.1: the mean absolute error (MAE) and the root-mean-square (RMS) error.

(b) Comparison of averaging periods ending in 1990 with periods sub sampled from 1961-1990

This test was intended to identify the extent to which the results from the tests in (a) were attributable to sampling issues, and the extent to which they were attributable to climate change making data towards the end of the 1961-1990 period more representative of likely conditions in 1991-2000.

This test was carried out as in section (a), except that, for each averaging length *k*, instead of using the *k* consecutive years ending in 1990, a set of *k* years randomly sub sampled from within the 1961-1990 period was used. Note that this method is equivalent to that in section (a) when carried out for *k* = 30.

(c) Comparison of averaging periods ending in 1990 with averaging periods ending in 2000

In this section, an evaluation period of 2001-2003 was used (instead of 1991-2000), in order to allow a comparison of averaging periods ending in 1990 and 2000 to be carried out using independent data.

For each averaging length *k*, the difference between the mean value of the parameter for an averaging period of *k* years ending in year *n*, and its mean value for the period 2001-2003, was calculated separately for *n* = 1990 and *n* = 2000.

For each of the two cases, these differences were then aggregated over all stations and months, again using the MAE and RMS metrics.

6.5 Evaluation of predictive accuracy of climate averages

6.5.1 Surface data

(a) Comparison of averaging periods ending in 1990 with 1991-2000 means

The MAE and RMS errors for averaging periods ranging from 1 to 30 years ending in 1990 are shown in Figs. 2(a) to 2(g).

For all parameters, the error (using either metric) is maximized for an averaging period of 1 year. It then generally declines with increasing averaging period before leveling off, with only small fluctuations, at a point that varies between parameters but is generally between 10 and 15 years. As an (arbitrary) benchmark, the minimum number of years required for a MAE which is no more than 10% greater than that for an averaging period of 30 years ranges from 7 years for mean sea level pressure to 21 years for mean vapour pressure.

The only parameter for which a 30-year averaging period shows a substantially worse error than that for some shorter period is mean sea level pressure (MSLP), where the MAE is minimized for an averaging period of 11 years and the RMS error for one of 13 years (Fig. 2(c)). This is most probably attributable to the nature of trends in the Australian MSLP field, rather than a more general characteristic of MSLP fields which might be expected to be replicated elsewhere in the world. MSLP averaged over the Australian region (defined here as 10-45°S, 110-155°E) increased by approximately 0.7 hPa between 1960 and 1980, before leveling off after 1980 (NCEP/NCAR reanalysis, through KNMI Climate Explorer). As a result, means dominated by the 1980-1990 period are likely to be more representative of 1991-2000 than those drawing from earlier periods (although for very short periods this effect is outweighed by the impact of sampling error). When averaging periods ending in 2000 are considered (part (c) of this section) 30-year averages show similar errors to those for periods in the 10-20 year range.

Averages of mean maximum and minimum temperatures do not show similar behaviour, despite experiencing trends over 1961-2000 which are of comparable size to the MSLP trends when expressed in terms of the interannual variability of the parameter. In contrast to MSLP, Australian temperatures show only a small upward trend from 1961-1975, followed by a steady upward trend from 1975-2000, and hence the 1980s saw mean values generally lower than the 1990s, unlike the situation for MSLP when mean values were generally similar.

(b) Comparison of averaging periods ending in 1990 with periods sub sampled from 1961-1990

A comparison of prediction errors for the 1991-2000 period from averaging periods ending in 1990 with those of identical length randomly sub sampled from the 1961-1990 period is shown in Figs. 3(a) to 3(g). As the MAE and RMS metrics give similar results, only MAE results are shown.

For the four parameters which do not show a substantial secular trend in Australia over the 1961-2000 period (rainfall amount, number of rain days, mean vapour pressure, total sunshine), the results are similar: random sub sampling produces lower prediction errors for averaging periods shorter than about 10 years (6 years for rain days), with no appreciable differences for longer periods. (As noted earlier, by definition, the two techniques will produce results which converge at an averaging period of 30 years).

For maximum and minimum temperature and MSLP, fixed averaging periods ending in 1990 produce lower errors than random sub sampling for averaging periods in the 10 to 20 year range for temperature, and the 5 to 15 year range for MSLP. For shorter periods random sub sampling performs better, whilst for longer periods the two methods produce similar results. This is an indicator of the benefits derived from having an averaging period including recent data, for some lengths of period averages, for a parameter which shows a substantial trend.

(c) Comparison of averaging periods ending in 1990 with averaging periods ending in 2000

A comparison of prediction errors for the 2001-2003 period from averaging periods ending in 1990 and 2000 is shown in Figure 4. As in (b) above, only the MAE results are shown. Note that, because of the different evaluation period (2001-2003 instead of 1991-2000), the MAE results for averaging periods ending in 1990 will differ from those shown in (a) and (b) above. In particular, mean maximum temperature and total monthly precipitation show much higher errors for a 2001-2003 evaluation period than for 1991-2000, as 2001-2003 was very warm over Australia (the all-Australian mean maximum temperature for 2001-2003 was higher than that for any other three-year period in the 1961-2003 time span), and was also substantially drier than normal at most of the stations used in this study.

For most parameters and averaging period lengths, averaging periods ending in 2000 produce lower prediction errors than those ending in 1990, although in most cases differences are relatively small: for example, they are typically in the order of 0.1°C for mean maximum temperature and 0.05°C for mean minimum temperature. The former difference is of comparable magnitude to the difference (0.11°C) between the 1961-1990 and 1971-2000 averages for all-Australian mean maximum temperature.

6.5.2 Upper-air data

(a) Comparison of averaging periods ending in 1990 with 1991-2000 means

The MAE and RMS errors for averaging periods ranging from 1 to 30 years ending in 1990 are shown in Figs. 5 and 6.

As for surface data, for all parameters, the error (using either metric) is maximized for an averaging period of 1 year. In the case of most of the wind-related variables (u, v and steadiness), the MAE and RMS errors decline with increasing averaging length before leveling off from 10 years onwards (although the decline is slower at 500 hPa than at 200 hPa).

Temperature and geopotential height behave somewhat differently. In both cases, the errors are minimized for averaging periods between about 4 and 12 years, and then steadily increase with increasing averaging length. Except for 200 hPa temperatures, these parameters show similar errors for averaging periods of 3 years to those for 30 years.

Both temperature and geopotential height, particularly the latter, in the Australian region show large step changes around the early 1980's. In the case of temperature, much of this increase has been attributed to inhomogeneities in the record associated with instrument changes around 1983 and 1987-88 (Parker et al., 1997). No formal study has been carried out as to the extent to which the geopotential height increase is a real climatic phenomenon and the extent to which it is an artifact of instrument changes. Whatever the causes, the large step changes, as for surface MSLP, increase the predictive utility of recent data relative to pre-1980 data.

(b) Comparison of averaging periods ending in 1990 with periods sub sampled from 1961-1990

A comparison of prediction errors for the 1991-2000 period from averaging periods ending in 1990 with those of identical length randomly sub sampled from the 1961-1990 period is shown in Figs. 7 and 8. As the MAE and RMS metrics give similar results, only MAE results are shown.

The random sub samples produce substantially larger prediction errors than fixed periods ending in 1990 over most averaging periods for geopotential height at both 200 and 500 hPa, and for temperature at 500 hPa. As discussed in the previous sections, these are all parameters where the data show large changes over the course of the 1961-1990 period, and as such, data late in the 1961-1990 period would be expected to show lower prediction errors than data drawn from throughout that period.

For averaging periods between 5 and 20 years, random sub samples of wind data, as well as 200 hPa temperatures, generally perform slightly worse than periods ending in 1990, but the differences are much smaller than those observed for other variables, and at 500 hPa they are almost indistinguishable.

<u>(c) Comparison of averaging periods ending in 1990 with averaging periods ending in 2000</u>

A comparison of prediction errors for the 2001-2003 period from averaging periods ending in 1990 and 2000 is shown in Figs. 9 and 10. As in (b) above, only the MAE results are shown.

For most parameters, prediction errors using data ending in 2000 are smaller than those using data ending in 1990 for most averaging period lengths, the exception being the *u* component of wind at 500 hPa, and wind steadiness at both levels.

The difference is particularly marked for geopotential height at both levels, and for 500 hPa temperatures. Again, this is consistent with the large observed trends in these parameters over the 1961-1990 period.

7. The use of short-term stations

7.1 The incorporation of short-period climate information into climatological normals

Whichever period is chosen for the calculation of climatological normals, it is likely that there will be many stations which have some data available, but not enough to satisfy those requirements which are in place for the minimum amount of data required for the calculation of a climatological normal. This is illustrated by the results in Table 1, which show that only 16% of those Australian stations which have some temperature measurements in the 1961-1990 period have enough observations to satisfy the monthly data completeness requirements of WMO (1989) for the calculation of a climatological standard normal for 1961-1990, whilst the equivalent figure for precipitation is 32%.

Whilst short-period data on their own may be useful for some applications, in many cases it is desirable to have data which are comparable to climatological standard normals. As an example, in mapping climate variables, it is important for all the mapped observations to be with respect to a standard period.

The use of spatial interpolation to estimate the values of climate parameters at points where there are no observations is a field which has been studied extensively (e.g. Koch et al., 1983; Seaman and Hutchinson, 1985; Hutchinson, 1998). Less attention has been given to the use of short-period observations to modify a spatially interpreted parameter field, but Sansom and Tait (2004) found that the use of a small amount of data from a location substantially improved the accuracy of temperature and rainfall fields at that location over that which could be achieved by spatial interpolation alone. Perry and Hollis (2005) used regression-based techniques, based on observed data (minimum 4 years), to infill missing monthly data in the 1961-1990 period at stations with incomplete data over that period to provide a complete notional set of 1961-1990 data at stations for which they were seeking to calculate normals.

Jones and Trewin (2002) found that the accuracy of interpolation of a temperature field improved as a function of the number of stations with available data, although the incremental improvement with the inclusion of additional stations decreased as the total number of available stations increased.

7.2 Adjusting short-period climate information for use in climatological normals

As a test of the potential for gaining additional information from stations with small amounts of data by adjusting parameters based on values from surrounding stations, the tests in section 6.4 were repeated, except that the value of the parameter for each month was adjusted as described below, for the variables:

- Mean monthly maximum and minimum temperature
- Total monthly precipitation
- Mean monthly mean sea level pressure

These parameters were chosen because of the existence of a substantial network of stations in Australia, outside the 24 to 30 stations chosen for analysis, that could be used to adjust data at the candidate station.

For a monthly value X_n of parameter X in year n, the adjusted value $X_{ad,n}$ was calculated as

$X_{ad,n} = X_n - a_n$ (temperature and pressure), $X_{ad,n} = X_n / a_n$ (precipitation)

where a_n is the interpolated anomaly (for temperature and pressure) or ratio (for precipitation) at the location of the candidate station. If $a_{j,n}$ is the anomaly value in year n and station j and there are N stations used in the interpolation, this is calculated as:

$$a_n = \sum_{j=1}^{N} w_j a_{j,n} \qquad w_j = 0.5^{d^2/gD^2}$$

where d is the distance between station j and the candidate station (in kilometers) and g and D are parameters set to g = 1.0 and D = 200. This is effectively a single-pass Barnes analysis starting with a zero first-guess field.

For precipitation, there was a lower bound of 0.1 on a_n, in order to prevent outliers arising from the interpolation of a few small non-zero values during the tropical dry season.

Anomalies and ratios were calculated with respect to a 1981-1990 mean at all stations with 8 or more years of data in the 1981-1990 period. This period was chosen, following some experimentation, to maximize the number of stations available for use in the interpolation.

The single-pass Barnes analysis procedure was chosen for illustrative purposes. Many more sophisticated interpolation methods exist: Jones and Trewin (2000) show that some of these methods substantially outperform the Barnes scheme in the interpolation of mean monthly temperature fields. It is likely that these methods would further enhance the ability to incorporate short-period climate information in climatological normals.

The results of this procedure are shown in Figure 11. For all parameters, an average based on adjusted data showed substantially superior predictive accuracy to that using unadjusted data for averaging periods less than 8 to 10 years. For temperature and precipitation, the predictive accuracy using 1 year of adjusted data was comparable with that using 4 to 5 years of unadjusted data, whilst for MSLP 1 year of adjusted data produced comparable results to those obtainable for all averaging periods from 2 to 30 years. This result is probably attributable to the long decorrelation length scales of MSLP anomalies relative to those of temperature and rainfall.

For averaging periods longer than 10 years, for temperature and precipitation, averages based on unadjusted data have somewhat more predictive accuracy than those based on adjusted data, although the differences are relatively small. This suggests that, for averaging periods longer than 10 years (the point where, as described in section 6.5.1 above, the incremental increase in predictive skill with increasing averaging period length becomes minimal or non-existent), the observed data at a point is a better representation of the climate at that point than is a combination of observed data at that point and data from neighbouring stations.

8. Extreme values

Extreme values are often included with published climatological normals or averages. The most common values published are the highest and lowest temperatures recorded in a specified period, and the highest daily, and highest and lowest monthly, precipitation recorded in a specified period. In some cases the extremes are drawn from the same period over which normals or averages are calculated; in other cases, the extremes cover all years during which observations have been made.

The use of a standard period for the calculation of extremes is most useful where it is desired to estimate the highest or lowest value that can be expected in a given period, as well as where spatial analyses, or other analyses that require a common reference period, are being carried out. Many users of climate data will, however, be interested in the highest or lowest values ever recorded at the location, in which case all available years of record should be used, subject to not including data which are grossly unrepresentative of observation standards (see also section 11 below).

An issue which sometimes arises is that of how long a data set needs to be before extreme values from it can be considered meaningful (for example, in the context of reporting that a new record has been set at a station). To quantify this, the mean difference between the extreme values in random sub samples of *n* years and those in the full 1961-1990 period at that station for that month was calculated, for all values of *n* from 1 to 30 inclusive. This analysis was carried out for highest daily maximum temperature, lowest daily minimum temperature and highest daily precipitation, for each of the stations used in section 6.3 above.

The results of this analysis are shown in Figure 12. These indicate that, on average at Australian stations, the highest temperature on record for a given calendar month over a 12-year period would be expected to be within 1ºC of the 30-year extreme, whilst for low temperature extremes 8 years is sufficient. (The difference between the two reflects the fact that the frequency distribution of daily maximum temperatures at many Australian stations, particularly in the south, is strongly positively skewed, whereas the distribution of daily minimum temperature is less skewed). For the highest daily rainfall, the 10-year extreme is typically approximately 75% of the 30-year extreme. In all cases these results vary considerably by month and station.

9. Quantiles of climate data

9.1 The calculation of quantiles of climate data

Quantiles (also known as fractiles) are common statistical descriptors of the frequency distribution of a climate element. The quantiles in most common current use within WMO, because of their inclusion in CLIMAT messages, are quintiles of monthly precipitation, but the term also includes other percentile values including the median.

A major issue in the calculation of quantiles is that, whilst the nth percentile of a frequency distribution is defined as that point in the distribution below which n% of the values fall, there is no universally accepted method to estimate quantile values from a finite sample of data from that frequency distribution (Hyndman and Fan, 1996). The fundamental problem here is one of whether to treat the set of available observations as being the entire population, or merely a representative sample of a larger population. This leads to questions such as whether to treat the lowest observed value in a sample of *n* observations as being the 0th percentile (available data as entire population), the (100/*n*)th percentile (available data as representative sample of a larger population), or some other value.

Existing WMO guidance on the calculation of quantiles illustrates this absence of a universally accepted method. In the 1983 edition of the *Guide to Climatological Practices*, section 5.2.4.1, on the calculation of percentile values in general, recommends that the *k*-th percentile of a data set with *n* values be calculated as the [(*k/100)* x *(n+1)*]th lowest value, which would imply that the upper limits of quintiles 1, 2, 3 and 4 (*k* = 20, 40, 60 and 80) would be the 6.2th, 12.4th, 18.6th and 24.8th lowest values respectively in a 30-year data set. This is the 'set of available observations as representative of larger population' approach. However, section 8.2.1, on the specific calculation of precipitation quintiles for CLIMAT messages, specifies the 6.5th, 12.5th, 18.5th and 24.5th lowest values respectively.

(In this context, the *a*th lowest value of a data set, where *a* is not an integer, is determined by linear interpolation from the *m*th and *(m+1*-th lowest values, where *m* is the integer part of *a.*)

Theoretically, if the probability of any observed values falling in one of the five quintiles is to be equal, it is necessary for each quintile to be of equal width (with respect to rank). In the case of a 30-year data set where the lowest value is set as the lower bound of the 1st quintile and the highest value as the upper bound of the 5th quintile, this would imply that the 'width' of each quintile would be (30-1)/5 = 5.8, and hence that the upper bounds of quintiles 1, 2, 3 and 4 would be the 6.8th, 12.6th, 18.4th and 24.2th lowest values of the data set. This is the 'set of available observations as entire population' method. This is referred to as the 'entire population' calculation method for the remainder of this section.

Which of these two methods is appropriate depends on the context. If one is interested in describing what has occurred over a 30-year period, it is entirely appropriate to designate the highest (lowest) value as the 100th (0th) percentile (the second method). This also allows information to be provided, through the quintile bounds, on the highest and lowest values recorded in the averaging period. If instead one is interested in describing what might occur in the future, it is entirely inappropriate to treat the highest (lowest) observed value as an upper (lower) bound on what might occur in the future, in which case it is much more appropriate to designate the highest (lowest) value as the 96.77th (3.23th) (approximately) percentile. The two methods yield the same value for the median (50th percentile).

A further consideration is one of the representativeness and stability of quantiles calculated from a relatively small sample. This consideration is particularly acute for precipitation, which has a particularly high degree of interannual variability. Quantiles, particularly those towards the extremes of a frequency distribution, are highly sensitive to the presence (or absence) of a small number of outliers within an averaging period. An approach followed by a number of authors, notably New et al. (2002) in the calculation of a global normals data set, is, rather than calculating quantiles from the empirical distribution of the observed data, to instead fit an idealized distribution (such as the gamma distribution) to the data, based on parameters such as the mean and standard deviation which are less sensitive to individual outliers than an empirically-determined quantile value may be.

9.2 Evaluation of methods for calculating precipitation quintiles

9.2.1 Desirable characteristics in precipitation quintile values

For the purposes of this section, it is assumed that desirable characteristics of precipitation quintile values are as follows:

- The lower bound of the 1st quintile is the best estimate of the lowest value likely to be recorded in a period of *n* years, where *n* is the number of years being used in the calculation of the values, and that the upper bound of the 5th quintile is the best estimate of the highest value likely to be recorded during that period.
- The precipitation at a given station in a given month is equally likely to fall into the 1st, 2nd, 3rd, 4th or 5th quintiles (discounting the special case of stations/months where more than 20% of recorded values are zeroes).

9.2.2 Methods for evaluation of precipitation quintile value calculations

As is the case for mean values, a number of different metrics exist for evaluating precipitation quintile value calculations. Since, by definition, we do not know what the full frequency distribution of monthly precipitation is, an alternative approach is to compare the quintile values calculated using a given method with those empirically determined from a larger sample which is used as a reference.

The principal approach followed in this section is to use data from the full 1901-2000 period to provide a reference frequency distribution. In order to assess the effect of sampling error (as opposed to that of any secular trends) on the calculation of quintiles from smaller data samples, the following procedures were carried out for periods of *n* years, where *n* was taken as equal to 10, 20, 30, …, 90 years.

(a) 1000 sub samples of *n* years randomly chosen from the 1901-2000 period were generated, and quintile values were calculated for each sub sample, using the ‘entire population’ method described above. 95% confidence intervals were then calculated for each quintile value. The principal metric for evaluation, as an assessment of the stability of the quintile values, was the width of the 95% confidence interval.

(b) For 100 of these 1000 sub samples (the reduced number being necessitated by computing time considerations), a gamma distribution was fitted to the data. This followed the procedure followed by New et al. (2002), in which the parameters of the gamma distribution were calculated from the moments of the sample via

$\alpha = (\mu^2/\sigma^2)$, $\beta = (\mu/\sigma^2)$

where μ and σ are the mean and standard deviation of the sample.

Quintile values were then calculated for the distribution. This was done by setting the lower bound of the 1st quintile as being the (100/*n*)th percentile of the gamma distribution, on the basis that the probability of the (*n+1*)th value of a stationary time series being lower than any of the previous *n* values is (1/*n*) (e.g. Benestad, 2003). The upper bound of the 5th quintile was then set as the (100(*n*-1)/*n*)-th percentile, and the intermediate quintile points were set using 4 equally spaced values over the range from (100/*n*) to (100*(n-1)*/*n*).

95% confidence intervals were calculated for the quintile points from the sub samples as in (a) above. In addition, to assess any biases arising from the fitting of a distribution to the data, the mean value of the quintile points in the sub samples was calculated.

9.2.3 Data used in assessment of precipitation quintiles

The stations used in the assessment of precipitation quintiles were all those Australian stations for which a monthly precipitation value was available in the Australian Bureau of Meteorology database for every month from January 1901 to December 2000 inclusive. No assessment was made of data homogeneity or quality at these stations.

A total of 379 stations met these requirements. These stations were concentrated in south-eastern and south-western Australia (Figure 13, Appendix B), with only a few stations in tropical Australia. As such the results cannot be considered fully representative of the full Australian continent.

9.2.4 Confidence interval width for precipitation quintiles

The mean 95% confidence interval width for each of the 6 precipitation quintile boundary points is shown in Figure 14. Unlike the situation for mean values as described earlier, the width of the mean confidence interval declines steadily with increasing averaging period length. In part this is a consequence of the sub sampling procedure used, in which (by definition) the confidence interval width will converge to 0 for an averaging period of 100 years, but the lack of leveling-off of confidence interval widths in the 10-50 year averaging period range suggests that, whilst averaging periods longer than 10-20 years provide little additional utility in the calculation of mean values, they do provide additional utility in the estimation of other properties of the frequency distribution of a parameter.

For the three highest quintiles of the precipitation frequency distribution, the confidence interval width is greater for all averaging periods using raw data than using a fitted gamma distribution, indicating that the gamma distribution shows more stability under sampling variation than percentile points drawn directly from the raw data. This is particularly pronounced for the upper boundary of the 5th quintile (the estimate of the highest value in a 30-year period), but even for the other points, as an example, the confidence interval width using a gamma distribution based on 30 years of data is similar to that obtained using 40 years of raw data. There is no appreciable difference between the confidence interval widths for the two lowest quintile boundaries using the two techniques.

9.2.5 Potential biases using a fitted gamma distribution

Table 2 and Figure 15 show the differences between the quintile boundary points calculated from the mean values obtained from a gamma distribution based on the 30-year sub samples, and the boundary points from the full 100 years of data.

These indicate that, relative to the raw data, the gamma distribution tends to under-represent the frequency of extreme values at both ends of the distribution. In only 14% of cases is the upper boundary of the 1st quintile calculated using the gamma distributions less than that from the raw data, whilst for the lower boundary of the 5th quintile the corresponding figure is 83%. These findings are consistent with those of New et al. (2002), who found similar biases, which were particularly acute at stations with a large proportion of months with zero or near-zero precipitation.

9.2.6 Biases arising from different methods of calculating quintile boundary points

The final test which was carried out on precipitation quintiles was a comparison of the different methods of calculating quintile boundary points in finite data sets, as described in section 9.1 above. To avoid complications arising from the calculation of quintiles in data sets with zero values, only those station/month combinations where there were no zero monthly totals recorded in the 1961-1990 period were used.

Quintile boundaries were calculated using different methods for the 30 years 1961-1990. The frequency of monthly values in each of the quintile categories in a 10-year period of independent data, 1991-2000, was then calculated.

The results from this comparison are shown in Table 3. These results indicate that, as expected, the 'entire population' method gives the most even distribution of values between the five quintiles, with all five quintile values being recorded at a frequency within 0.7% of that which would be expected by chance (18.7%), assuming an equal probability of occurrence, compared with differences ranging between 1.6% and 2.5% for the other two methods. The 'entire population' method is also the only one of the three methods for which the null hypothesis that the five quintile values are equally probable is not rejected at the 99% level, using a chi-square test (although it is rejected at the 95% level).

10. Missing data

10.1 Guidelines on missing data in the calculation of climatological normals

The 1983 edition of the *Guide to Climatological Practices* recommended that a monthly value should not be calculated if more than 10 daily values are missing, or 5 or more consecutive daily values are missing. In the case of variables where the monthly value is a sum of daily values rather than a mean (e.g. rainfall, sunshine), a monthly value can only be calculated if either all daily values are available, or any missing days are incorporated in an observation accumulated over the period of missing data on the day when observations resume. WMO (1989) recommends more strict criteria, with the limits being more than 5 missing days, or more than 3 consecutively, respectively.

WMO (1989) states that climatological standard normals for a calendar month should only be calculated if there are values available for at least 25 of the 30 years, with no more than 2 consecutive missing years.

No formal guidance exists for the maximum number of missing years in the calculation of normals or period averages other than climatological standard normals.

10.2 Accumulated data and climatological normals

In some cases, the first observation following a period of missing data will be an accumulated value over two or more days. This is most commonly true of daily precipitation and evaporation (where the first measurement after a break will often be the total precipitation or evaporation since the last observation), but can also be true of maximum and minimum temperatures, especially if these are measured using manually-read maximum and minimum thermometers rather than by an automated system.

For additive elements such as precipitation, a period of missing data will not cause a bias in the monthly record, as long as:

- Accumulated values encompass the full period of missing data (e.g. if 3 consecutive days are missing, the next observation is known to be accumulated over 4 days).
- There is an observation on the last day of the month.
- The instrumentation is such that there is not a risk to interference to the record between observations (e.g. evaporation, seepage or animals/birds drinking).

As an extreme case, whilst higher-frequency observations are desirable, a rain gauge that is consistently read on the last day of the month (possibly one in a remote area) can still provide useful information for a long-term monthly climatology.

Errors in individual monthly totals can arise, even if accumulated values encompass the full period of missing data, if either the last day of a month is missing, or the first observation of a month includes values carried over from the previous month. Depending on the nature of the missing data, these errors may cancel out each other. As an example, if a station regularly misses Saturday and Sunday observations and reports a 3-day accumulation on Monday (a common scenario in Australia), monthly totals will be an overestimate in months when the 1st or 2nd is a Monday, and an underestimate in months when the 31st is a Saturday or Sunday. As these two events occur equally frequently over the long term there would be no expected bias in a long-term average. Such data should not necessarily be discounted in the calculation of climatological normals but great care should be taken in their use. The use of data sets with missing weekend observations is discussed further by Revfeim (1990).

Accumulated daily maximum and minimum temperatures will show a bias, as the maximum temperature over a multi-day period will be the highest temperature recorded in that period (and conversely the minimum temperature will show a negative bias). Trewin (2001a) found that, if one day of observations per week was consistently missed and the following day's value was accumulated over two days, this resulted in a typical bias of 0.1 to 0.3°C in Australian maximum and minimum temperatures (positive for maxima, negative for minima), exceeding 0.4°C in a few cases. Where two days per week were missed, these biases increased to a typical range of 0.2 to 0.6°C. These biases are a function of the variance of daily maximum and minimum temperatures and will be higher in some extra-tropical continental climates where daily temperatures are more variable than is the case at any Australian location.

It is recommended that, for daily maximum and minimum temperatures, any accumulated data not be included in the calculation of mean monthly values, and that days with accumulated data be considered as missing for the purpose of determining the number of missing days in the month. However, accumulated data are still useful in measuring extreme monthly values. If documentation of which observations are accumulated is incomplete or non-existent, it is recommended that all observations made with manual maximum-minimum thermometers which follow a period of missing data be assumed to be accumulated over the period of missing data.

10.3 An evaluation of the impact of missing data on climatological normals

As defined in section 2 above, climatological normals and averages are defined as the mean of a time series of monthly values. In the context of the calculation of normals and averages, two types of missing data must be considered:

(a) Missing daily data that contributes to a monthly value for a specific month/year.
(b) Missing monthly values (including values not calculated because of the presence of insufficient daily values) during the time period over which averages/normals are being calculated.

The impact of missing data, in both cases, was evaluated by estimating the uncertainty in a period average that would arise from randomly deleting a given number of observations, as described below. The 'time series of interest' was defined, in case (a), as the set of values for a given station for a given month/year, and in case (b) as the set of 30 values for a given station for a given month over the 1961-1990 period.

The parameters evaluated were mean daily maximum and minimum temperature, mean sea level pressure, mean vapour pressure and mean daily sunshine duration, at the same stations as were used for the analysis in section 6. In case (a), the data set used was that of all months at the given stations in the 1961-1990 period that had no missing observations. (In case (b) there are no missing monthly values, by definition from the choice of stations as described in section 6.)

- For each time series of interest, 100 modified time series were generated. These were modified by deleting *m* observations which were randomly chosen, subject to the condition that at least *n* of the *m* observations must be consecutive. (The case $n = 1$ equates to a totally random choice of *m* observations).
- The mean of each of the 100 modified time series was calculated, and a 95% confidence interval calculated for the mean using these modified series.
- For each *m* and *n*, the width of the 95% confidence interval was divided by the standard deviation of the data set. These values were then averaged across all stations, months and, in case (a), years. The standard deviation of the data set is defined as the standard deviation of all daily values (across all years from 1961-1990) for that month in case (a), or all monthly values for that month in case (b).

The reason for dividing by the standard deviation is that the width of the confidence interval will scale linearly with the standard deviation of the data set (this can be demonstrated by replacing the raw values X with $X = \mu + z\sigma$, where μ and σ are the mean and standard deviation of the data set). This procedure will therefore show the expected width of the confidence interval per unit standard deviation.

The procedure was carried out for all values of *m* from 1 to 15, and for each *m*, for all values of *n* from 1 to *m*. The separate evaluation for data sets with a certain number of consecutive values deleted was carried out to assess the extent to which the imposition of a condition on the maximum allowable number of consecutive missing values reduced the uncertainty in estimated mean values. Such a condition only has effect if the time series under examination is positively autocorrelated (as most meteorological time series are), as in a positively autocorrelated time series, a data set consisting of means of randomly selected groups of *n* consecutive values will have a greater variance than one consisting of means of groups of *n* randomly selected observations (not necessarily consecutive).

The results for $n = 1$ (no constraint on consecutive values) are shown in Figure 16, whilst results for various values of *n* for selected values of *m* are shown in Figure 17.

Where there is no constraint on consecutive values, the different parameters show similar behaviour, as would be expected. There are, however, differences between the parameters when a constraint on consecutive values is imposed, reflecting the differing autocorrelation structures of the different parameters.

In Australia, typical standard deviations of daily values are around 3°C for maximum and minimum temperature, 3 hPa for vapour pressure, 3 hours for daily sunshine duration and 6 hPa for mean sea level pressure (although individual stations can have standard deviations of up to double these values in some months). Applying these to the results in Figure 17, as an example, for the case of 5 missing values with at least 3 consecutive, the width of the 95% confidence interval is typically similar to, or less than, the mean absolute error in using the 1961-1990 normal to predict 1991-2000 values (as described in section 6.4) – for example, for maximum temperature, the typical width of the 95% confidence interval is 0.35 to 0.40°C, compared with the mean absolute predictive error of the 30-year normal of 0.39°C.

The uncertainty arising from missing monthly values in a period average (Figure 18) is even less than that arising from missing daily values in a monthly value, reflecting the lower standard deviation of monthly values (typically, around 1.2°C for maximum and minimum temperature, 1.2 hPa for vapour pressure, 2.0 hPa for mean sea level pressure and 1.0 hours for mean daily sunshine hours. This result is consistent with the results of section 6.4 – given the limited impact that the use of an averaging period as short as 10 years has on the predictive value of period averages, it is not surprising that randomly deleting a small number of years from a 30-year average has little impact on the confidence interval of that period average.

Figure 17 shows that, in general, daily data sets with a specified number of consecutive values do show slightly greater uncertainty in their means than those without. Typically, an additional 1-

2 consecutive missing values (with the total number of missing values fixed) has a similar impact to an additional 1 missing value, reflecting the autocorrelation of most of the data sets.

On the other hand, for monthly time series (Figure 19), the number of consecutive missing values has little impact on the uncertainty of the mean value for a given fixed number of missing values, except that where the missing values are all or almost all consecutive, the uncertainty in the mean actually declines, possibly because of the limited number of possible sets of consecutive values that can be chosen (for example, if *n* consecutive values are deleted from a set of 30 values, there are only (31-*n*) ways in which this can be done). For smaller values, the lack of effect of the number of consecutive missing values reflects the fact that, except for parameters which show a very strong trend over time, meteorological time series with annual intervals are not as strongly auto correlated as daily time series are.

11. Data homogeneity

11.1 Data homogeneity and its impact on climatological normals

The homogeneity of the data needs to be taken into account in consideration of any meteorological time series. A data set can be considered to be homogeneous if any changes in the data reflect a change in meteorological conditions, rather than a change in the conditions under which the observations were made.

Inhomogeneities in a meteorological time series can arise for a large number of reasons. These may include:

- A change in the location of an observation site
- A change in the instrumentation used to make an observation
- A change in procedures used to make observations or process data
- A change in the local environment around an observation site

Well-known specific examples in the Australian context include the change in radiosondes used for upper-air observations referred to in section 6.5.2, the effect of increasing urbanization on temperatures and winds in some urban locations, and the introduction of the Stevenson screen as a standard shelter for thermometers in the early part of the 20th century.

Data inhomogeneities have been discussed by many authors. Karl et al. (1995) discuss problems of data inhomogeneity in existing and future observation systems, whilst Torok and Nicholls (1996) and Lavery et al. (1992) consider specific issues relating to Australian temperatures and precipitation respectively.

In the context of the calculation of climatological normals, the significance of data homogeneity is that, if an inhomogeneous data set is used in calculating normals, then some or all of the data from which the normals are calculated will not be fully representative of current observations at that location. This reduces the predictive value of the normals at that location, as well as reducing the appropriateness of the normals as a benchmark against which current conditions at that location can be compared.

11.2 Adjustment of inhomogeneous data for use in climatological normals

A common practice in data sets which are used for the analysis of long-term climate change is to make adjustments to some of the data, in order to create a time series which is homogeneous. This is most commonly done by applying a fixed offset (which may be adding or subtracting an amount, or multiplying by an amount) to all data observed prior to an identified inhomogeneity. An example of a data set produced using such a method is the homogenized set of mean annual temperatures for Australia since 1910 described by Torok and Nicholls (1996) and Della-Marta et al. (2004). The issues involved in the identification and adjustment of inhomogeneities, as well as a review of methods then documented, are described by Peterson et al. (1998).

The two steps in adjusting inhomogeneous data are:

- Identifying the existence of an inhomogeneity and the time at which it took place;
- Determining appropriate adjustments to make to the inhomogeneous data to produce a homogeneous time series.

An inhomogeneity may be identified through metadata, visual examination, or through statistical methods (e.g. comparison with neighbouring locations). The advantage of using metadata is that documented changes at an observation site provides some *a priori* knowledge of the potential existence and dates of possible inhomogenities. However, in many cases metadata are incomplete or incorrect, requiring the use of statistical methods. Such methods often depend on the existence of a suitable time series against which the data set can be compared. Some inhomogenities are too small to be detectable by statistical methods, and the exact timing of an inhomogeneity may be difficult to determine in this manner.

The adjustment of inhomogeneous data also requires careful consideration. In many cases data are adjusted by applying a uniform correction to mean values, but whilst this may result in a data set whose mean values are homogeneous, it does not necessarily follow that other statistical properties of the data set are also homogeneous. Trewin and Trevitt (1996) and Trewin (2005) found that the temperature differences between pairs of neighbouring, but topographically contrasting, sites differed greatly between the warmest and coldest nights. Various approaches to producing daily temperature data sets with homogeneous higher-order statistical properties are described by Allen and DeGaetano (2000), Trewin (2001a) and Della-Marta (2005).

Furthermore, as different methods exist for identifying, and adjusting for, inhomogeneities, the results of an adjustment procedure may be method-dependent. It can also be difficult to detect inhomogeneities which occur near the start or end of a record. This is particularly relevant when an inhomogeneity (e.g. a station move) has taken place recently and current data are being compared with a set of climatological normals which may not be representative of the current observation site and conditions.

Factors that need to be considered before deciding whether or not to use adjusted data in the calculation of climatological normals include:

- Is it better to use a short period of homogeneous data or a longer period of adjusted data? This will depend on the applications for which the data are being used, as well as the amount of homogeneous data available. Any adjustment to data has a level of uncertainty associated with it (in the size of the adjustment, and usually in the timing of any inhomogeneities), and this additional uncertainty may outweigh the benefits of using a longer data set, depending on the time periods involved.
- Is the inhomogeneity too small to have a meaningful impact on the normals? This may depend on the application to which the data are put.
- Adjusted data may be more difficult to explain to data users, many of whom will be unfamiliar with the concept of climate data homogeneity, than a set based on raw observed data.

These considerations do not automatically preclude the use of adjusted, homogenized data in the calculation of climatological normals. However, if adjustments are made, the timing of the adjustments and the methods used should be carefully documented.

12. Discussion and recommendations

Climatological normals, as discussed in the introduction, serve two principal purposes: as a reference against which observations at a particular time are compared, and as a prediction (implicit or explicit) of the conditions most likely to be experienced at a given location. These two purposes are not necessarily fully compatible. The earlier parts of this study have concentrated on the predictive aspect of climatological normals, as it is amenable to objective assessment.

Where climatological normals are used as a reference, there are no clear advantages in updating the normals frequently. Frequent updating carries the disadvantage that it requires recalculation of many data sets, not only the normals themselves but numerous data sets that use the normals as a reference. (As an example, global temperature data sets are currently calculated as anomalies from a reference period (usually 1961-1990)). Using a more recent averaging period, such as 1971-2000, results in a slight improvement in predictive accuracy (as described in section 6.5.1(c)) for parameters which show a secular trend, and 1971-2000 normals would be viewed by many users as more 'current' than 1961-1990, but the disadvantages of frequent updating could be considered to offset this advantage when the normals are being used for reference purposes.

Whilst a fixed 30-year period may be appropriate as a reference period, when normals are used for predictive purposes, the results described above suggest that shorter averaging periods (10 years or more for most parameters) perform as adequately as 30-year averaging periods, whilst allowing normals to be calculated for a much wider range of stations than is usually possible for a 1961-1990 reference period. Furthermore, the judicious use of data from neighbouring stations to modify short-period averages can allow estimated normals to be calculated from as little as 4-5 years of data with comparable predictive accuracy to that obtainable from longer periods, and useful information can be obtained from a single year of data. For parameters which show a substantial underlying trend (such as mean temperature), predictive accuracy is also improved by updating the normals frequently.

As a number of authors have noted, the arithmetic mean of a climate variable is only a partial description of its behaviour, and a full description of the climate requires specification of the full frequency distribution, as well as other statistical properties such as autocorrelation. This raises the question of how to maximize the amount of information that can be provided about the statistical properties of a variable using a finite number of numerical parameters. The standard deviation has sometimes been used for this purpose, but this only defines the frequency distribution if a variable follows a Gaussian distribution, something which is not the case for many climate variables. Other options include the definition of quantiles (such as quintiles) or the number of occasions on which thresholds are exceeded. Fitting idealized distributions to a data set is an option, but it is apparent from the results above that this should be done with great care, as the potential exists for the creation of systematic biases (such as the systematic under-estimation of the probability of extreme dry months when the gamma distribution is fitted to monthly precipitation values, as described above). At present the only quantile information that is routinely provided as part of data sets of climatological normals is quintile boundaries for monthly precipitation.

Whilst 10 years of data is adequate in most cases for the calculation of arithmetic means, more data are required for higher-order statistical properties such as quantile boundaries. A minimum of 30 years of data is recommended for the calculation of quantile boundaries with a reasonable level of confidence. Extreme high and low values of a variable are a special case, as many applications of such data require information about the highest and lowest values on record at a location, using all the available data. The results in section 8 suggest that, on average, a data set of 10-15 years will provide useful overall information about the likely long-term extremes at that location, but such short data sets may provide highly unrepresentative results for individual parameters and months.

The results obtained above also suggest that missing data, as long as it involves non-additive parameters and does not occur in a systematic way, only adds a modest amount of uncertainty in the estimation of a climatological normal. (An example of systematic missing data would occur, for example, if dew-point temperatures were not observed on any occasion when the wet-bulb temperature was below freezing). Furthermore, only a small amount of additional uncertainty occurs if a large number of the missing values are consecutive (and there is no additional uncertainty at all if the variable concerned is not auto correlated, as is the case for most annual time series). As such, there appears to be little justification for the stricter criteria for missing data used in WMO (1989) (relative to that used in the 1983 *Guide*), bearing in mind the number of additional stations for which normals can be calculated if more liberal criteria for data availability are used. There also appears to be little justification for having a 'consecutive years' criterion in the maximum number of missing years.

This leads on to the following recommendations:

1. A new form of climatological normals, 'operational normals', should be defined. These are intended to be normals defined in such a way as to maximize the predictive accuracy that can be obtained through their use.
2. Climatological standard normals should continue to be calculated for a 1961-1990 reference period, and this period should remain in use until 1991-2020 data are available. The principal purpose of climatological standard normals should be to be a reference against which observations (past, present or future) are compared. Climatological standard normals should only be calculated where values are available in at least 25 of the 30 years from 1961-1990 (but with no further limitation on consecutive missing years).
3. Operational normals may be calculated for any station with 10 years of more of data using that station's own data. The 10 years may be non-consecutive, subject to the homogeneity provisions in recommendation 7 below. They may also be estimated using a combination of the station's own data and data from neighbouring stations at stations with less than 10 years of data. Operational normals should be updated as frequently as practicable, and, at stations with 30 years or more of available data, may be calculated using either all available data or the most recent 30 years of data. In all cases the period used for the calculation of operational normals, and, where applicable, any estimation procedures used, should be documented.
4. Countries are encouraged to calculate both climatological standard normals and operational normals.
5. In addition to arithmetic means, countries are encouraged to calculate a wider range of statistical parameters for climatological variables, such as the standard deviation of daily and monthly values, quantile boundaries or the mean number of days on which thresholds are exceeded. Where quantile boundaries are calculated, the 'entire population' method described in section 9.1 should be used.
6. For non-additive parameters, a monthly value should not be calculated if more than 10 daily values are missing, or 5 or more consecutive daily values are missing.
7. Where a data set contains a major inhomogeneity, either normals should be calculated using only observations made after the inhomogeneity, or data prior to the inhomogeneity should be adjusted (where required) to be consistent with more recent observations. In the latter case the period of adjusted data, and the method used, should be documented.
8. Extreme high and low values of a variable, where calculated, should use all available data at a location, subject to the homogeneity provisions in recommendation 7 above.
9. All procedures described in WMO (1989) and the 1983 *Guide* which are not inconsistent with recommendations 1 to 8 above should continue to be followed.

13. Acknowledgements

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Figure captions

Figure 1. Location of stations used in analysis in section 6. (a) Temperature; (b) Mean sea level pressure; (c) Vapour pressure; (d) Precipitation; (e) Sunshine duration; (f) Upper-air observations.
Figure 2. RMS (solid line) and MAE (dashed) errors for averaging periods of surface data from 1 to 30 years ending in 1990: (a) Maximum temperature (ºC); (b) Minimum temperature (ºC); (c) Mean sea level pressure (hPa); (d) Mean daily sunshine duration (hrs); (e) Vapour pressure (hPa); (f) Precipitation (mm); (g) Number of days with precipitation ≥ 1.0 mm.
Figure 3. MAE for periods ending in 1990 (solid line) and random sub sample from 1961-1990 (dashed) for surface data: (a) Maximum temperature (ºC); (b) Minimum temperature (ºC); (c) Mean sea level pressure (hPa); (d) Mean daily sunshine duration (hrs); (e) Vapour pressure (hPa); (f) Precipitation (mm); (g) Number of days with precipitation ≥ 1.0 mm.
Figure 4. MAE for periods ending in 1990 (solid line) and 2000 (dashed) for surface data: (a) Maximum temperature (ºC); (b) Minimum temperature (ºC); (c) Mean sea level pressure (hPa); (d) Mean daily sunshine duration (hrs); (e) Vapour pressure (hPa); (f) Precipitation (mm); (g) Number of days with precipitation ≥ 1.0 mm.
Figure 5. RMS (solid line) and MAE (dashed) errors for averaging periods from 1 to 30 years ending in 1990 at 500 hPa level: (a) Geopotential height (m); (b) Temperature (ºC); (c) *u*-wind component (m/s); (d) *v*-wind component (m/s); (e) wind steadiness ratio (%).
Figure 6. RMS (solid line) and MAE (dashed) errors for averaging periods from 1 to 30 years ending in 1990 at 200 hPa level: (a) Geopotential height (m); (b) Temperature (ºC); (c) *u*-wind component (m/s); (d) *v*-wind component (m/s); (e) wind steadiness ratio (%).
Figure 7. MAE for periods ending in 1990 (solid line) and random sub sample from 1961-1990 (dashed) at 500 hPa level: (a) Geopotential height (m); (b) Temperature (ºC); (c) *u*-wind component (m/s); (d) *v*-wind component (m/s); (e) wind steadiness ratio (%).
Figure 8. MAE for periods ending in 1990 (solid line) and random sub sample from 1961-1990 (dashed) at 200 hPa level: (a) Geopotential height (m); (b) Temperature (ºC); (c) *u*-wind component (m/s); (d) *v*-wind component (m/s); (e) wind steadiness ratio (%).
Figure 9. MAE for periods ending in 1990 (solid line) and 2000 (dashed) at 500 hPa level: (a) Geopotential height (m); (b) Temperature (ºC); (c) *u*-wind component (m/s); (d) *v*-wind component (m/s); (e) wind steadiness ratio (%).
Figure 10. MAE for periods ending in 1990 (solid line) and 2000 (dashed) at 200 hPa level: (a) Geopotential height (m); (b) Temperature (ºC); (c) *u*-wind component (m/s); (d) *v*-wind component (m/s); (e) wind steadiness ratio (%).
Figure 11. MAE for unadjusted (solid line) and adjusted (dashed) surface data: (a) Maximum temperature (ºC); (b) Minimum temperature (ºC); (c) Mean sea level pressure (hPa); (d) Precipitation (mm).
Figure 12. Comparison of expected extreme value for given period and 30-year extreme: (a) Maximum (solid line) and minimum (dashed) temperature difference (ºC); (b) Daily precipitation ratio.
Figure 13. Location of rainfall stations used in analysis in section 9.
Figure 14. Width of 95% confidence intervals for upper boundaries of quantiles of mean monthly precipitation (mm), using observed data (solid line) and fitted gamma distribution (dashed): (a) 0^{th} quintile; (b) 1^{st} quintile; (c) 2^{nd} quintile; (d) 3^{rd} quintile; (e) 4^{th} quintile; (f) 5^{th} quintile.
Figure 15. Comparison of monthly precipitation quantiles (mm) using fitted gamma distribution (30 year sub samples) and raw data (full 100 years): (a) upper boundary of 1^{st} quintile; (b) lower boundary of 5^{th} quintile.
Figure 16. Width of 95% confidence interval (as multiple of standard deviation) of means with given number of days of missing data for daily maximum temperature (Tmax), minimum temperature (Tmin), vapour pressure (Vp), mean sea level pressure (MSLP) and sunshine duration (Sun).
Figure 17. Width of 95% confidence interval (as multiple of standard deviation) of means with maximum given number of consecutive missing values, for set total numbers of missing values: 15 (solid line); 10 (dashed line); 5 (alternating dashes); monthly means of daily values; (a) Mean

maximum temperature; (b) Mean minimum temperature; (c) Mean sea level pressure; (d) Vapour pressure; (e) Sunshine duration.

Figure 18. Width of 95% confidence interval (as multiple of standard deviation) of means with given number of years of missing data for mean monthly maximum temperature (Tmax), minimum temperature (Tmin), vapour pressure (Vp), mean sea level pressure (MSLP) and sunshine duration (Sun).

Figure 19. Width of 95% confidence interval (as multiple of standard deviation) of means with maximum given number of consecutive missing values, for set total numbers of missing values: 15 (solid line); 10 (dashed line); 5 (alternating dashes); mean monthly values; (a) Mean maximum temperature; (b) Mean minimum temperature; (c) Mean sea level pressure; (d) Vapour pressure; (e) Sunshine duration.

Table captions

Table 1. Number of Australian stations with specified amounts of data available (as of August 2005)

Table 2. Mean values (mm) of quintile boundaries from monthly precipitation, from 100 years of observed data and fitting gamma distributions from 30 years of data.

Table 3. Frequency of monthly precipitation observations in quintile bands 1991-2000, using quintile boundaries calculated from 1961-1990 data using listed methods.

Table 1. Number of Australian stations with specified amounts of data available (as of August 2005)

Number of stations with data available	Element		
	Max. temperature	Min. temperature	Precipitation
Meets current WMO normals requirements for 1961-1990	283	284	5581
25 or more years in 1961-1990 period, not necessarily meeting WMO requirements	344	349	6417
20 or more years (at any time)	576	586	8297
10 or more years (at any time)	1006	1009	12165
5 or more years (at any time)	1317	1333	14474
1 or more years (at any time)	1768	1770	17232

Table 2. Mean values (mm) of quintile boundaries from monthly precipitation, from 100 years of observed data and fitting gamma distributions from 30 years of data.

Quintile (upper boundary of)	Observed data	Fitted gamma distribution
1st	19.2	21.3
2nd	33.3	33.6
3rd	50.3	49.0
4th	76.8	72.7

Table 3. Frequency of monthly precipitation observations in quintile bands 1991-2000, using quintile boundaries calculated from 1961-1990 data using listed methods.

Method	Frequency (%) of months with precipitation in quintile:				
	1	2	3	4	5
CLIMAT method	17.1	18.9	19.8	19.4	17.9
‘Entire population’ method	18.0	18.4	19.0	18.9	18.8
1983 *Guide* method	16.2	19.5	20.4	20.0	17.0

Appendix A. Stations used for analysis of predictive skill of climatological normals.

Australian station number	WMO station number	Station name	Lat (deg S)	Lon (deg E)	Element					
					T	MSLP	Rain	VP	Sun	Upper
3003	94203	Broome	17.95	122.23	Y	Y	Y	N	N	N
5026	94313	Wittenoom	22.24	118.34	Y	N	N	N	N	N
6011	94300	Carnarvon	24.89	113.67	Y	Y	Y	Y	N	N
7045	94430	Meekatharra	26.61	118.54	Y	Y	N	N	N	N
8051	94403	Geraldton	28.80	114.70	Y	Y	Y	Y	N	N
9021	94610	Perth Airport	31.93	115.98	Y	Y	Y	Y	N	Y
9518	94601	Cape Leeuwin	34.37	115.14	Y	Y	Y	N	N	N
10035	94626	Cunderdin	31.66	117.25	Y	N	Y	N	N	N
12038	94637	Kalgoorlie	30.78	121.45	Y	Y	Y	N	N	Y
13017	94461	Giles	25.03	128.30	Y	N	N	N	Y	Y
14015	94120	Darwin	12.42	130.89	N	N	N	N	Y	Y
15590	94326	Alice Springs	23.80	133.89	Y	Y	Y	N	Y	Y
16001	94659	Woomera	31.16	136.81	Y	Y	Y	N	N	N
18012	94653	Ceduna	32.13	133.70	Y	Y	Y	Y	Y	N
23034	94672	Adelaide Airport	34.95	138.52	N	N	N	N	N	Y
26021	94821	Mount Gambier	37.75	140.77	Y	Y	Y	Y	N	N
31011	94287	Cairns	16.87	145.75	Y	Y	Y	Y	N	N
32040	94294	Townsville	19.25	146.77	Y	Y	Y	Y	Y	Y
33119	94367	Mackay	21.11	149.22	Y	Y	Y	Y	N	N
39039	94543	Gayndah	25.63	151.61	Y	Y	Y	Y	N	N
39083	94374	Rockhampton	23.38	150.48	Y	Y	Y	Y	N	N
40004	94568	Amberley	27.63	152.71	Y	Y	Y	Y	N	N
44021	94510	Charleville	26.42	146.25	N	N	N	N	N	Y
59040	94791	Coffs Harbour	30.31	153.12	Y	Y	Y	Y	N	N
61078	94776	Williamtown	32.79	151.84	N	Y	Y	Y	Y	N
66062	94768	Sydney	33.86	151.20	Y	Y	Y	Y	N	N
70014	94926	Canberra	35.30	149.20	Y	Y	Y	Y	N	N
72150	94910	Wagga Wagga	35.16	147.46	Y	N	N	N	N	N
76031	94963	Mildura	34.23	142.08	Y	Y	Y	Y	N	N
85072	94907	East Sale	38.12	147.13	Y	Y	Y	N	Y	N
86071	94868	Melbourne	37.81	144.97	Y	Y	Y	Y	N	N
87031	94865	Laverton	37.86	144.76	Y	Y	N	N	N	N
94008	94975	Hobart Airport	42.84	147.50	N	N	N	N	N	Y
94029	94970	Hobart	42.89	147.33	Y	Y	Y	Y	N	N
94069	95971	Grove	42.98	147.08	Y	N	N	N	N	N

(Y – station is used for this element; N – station not used for this element).

WMO station numbers are correct as of 18 October 2005.

Appendix B. Stations used in precipitation quintile analysis

Australian station number	WMO station number	Station name	Latitude (deg S)	Longitude (deg E)
2016		Lissadell	16.67	128.55
5008	94306	Mardie	21.19	115.98
5015		Mulga Downs	22.10	118.47
5020		Ningaloo	22.70	113.67
5032		Yarraloola	21.57	115.88
5052		Karratha Station	20.88	116.68
6019		Doorawarrah	24.81	114.43
6029		Lyndon	23.64	115.25
6052		Williambury	23.86	115.15
7027		Gabyon	28.25	116.34
7197		Challa	28.28	118.31
9018		Gingin	31.35	115.90
9500	94801	Albany	35.03	117.88
9507		Bannister	32.68	116.52
9510	94616	Bridgetown	33.96	116.14
9515		Busselton Shire	33.66	115.35
9518	94601	Cape Leeuwin	34.37	115.14
9552		Greenbushes	33.84	116.06
9561		Kendenup	34.49	117.63
9575		Marradong	32.86	116.45
9619		Wilgarrup	34.15	116.20
9628		Collie	33.36	116.15
10041		Doongin Peak	31.62	117.44
10073	95603	Kellerberrin	31.62	117.72
10515	95615	Beverley	32.11	116.92
10525		Broomehill	33.85	117.64
10579	94629	Katanning	33.69	117.56
10582		Kojonup	33.84	117.15
10614	94627	Narrogin	32.93	117.18
10626	95616	Pingelly	32.53	117.08
10647	95618	Wagin	33.31	117.34
10648		Wandering	32.68	116.68
12018		Coolgardie	30.95	121.17
12046	94448	Leonora	28.88	121.33
12065	94639	Norseman	32.20	121.78
12074	94634	Southern Cross	31.23	119.33
12093		Yundamindra	29.25	122.10
13012	94439	Wiluna	26.59	120.22
16005		Carriewerloo	32.40	137.22
16043		Woomera (South Gap	31.63	137.62
16055		Station)	32.38	135.52
17031	94480	Yardea	29.65	138.06
17055		Marree	30.02	138.04
17056		Marree (Witchelina)	30.41	139.42
18002		Wooltana	31.83	132.63
18014	94661	Penong (Pennalumba)	33.70	136.49
18043		Cleve	34.41	135.82
18069	94656	Koppio	33.65	134.89
18070		Elliston	34.72	135.86
18079	94654	Port Lincoln	32.80	134.21
19001		Streaky Bay	33.05	138.43
19006		Appila	32.88	138.35
19009		Booleroo Centre	32.42	138.53
19018		Carrieton	31.88	138.84
19024		Hawker (Holowilena)	32.83	138.19
		Melrose		

Appendix B (cont.). Stations used in precipitation quintile analysis

Australian station number	WMO station number	Station name	Latitude (deg S)	Longitude (deg E)
19032		Orroroo	32.74	138.61
19034		Peterborough	32.98	138.84
19037		Port Germein	33.02	138.00
19038		Quorn	32.36	138.04
19048		Wilmington	32.65	138.10
19062	94679	Yongala	33.03	138.75
20010		Koonamore	32.06	139.38
20012		Lilydale	32.96	139.97
20021		Yunta (Paratoo)	32.73	139.40
20024		Yunta (Winnininnie)	32.47	139.71
21002		Balaklava	34.14	138.42
21003		Blyth	33.84	138.49
21009		Spalding (Bundaleer	33.47	138.54
21010		Reservoir)	33.75	138.56
21015		Brinkworth (Bungaree)	33.71	138.29
21019		Snowtown (Condowie)	33.83	138.79
21023		Farrell Flat	33.41	138.89
21027		Hallett	33.20	138.61
21029		Jamestown	33.59	138.33
21031		Koolunga	33.19	138.30
21034		Laura	33.55	138.89
21041		Mount Bryan	33.56	139.10
21043	94669	Burra (Poonunda)	33.17	138.01
21044		Port Pirie	34.18	138.15
21045		Port Wakefield	33.54	138.22
21046		Redhill	33.78	138.21
21050		Snowtown	33.15	138.92
21054		Terowie	33.96	138.64
21057		Watervale	33.57	138.44
21086		Yacka	33.84	139.07
22003		Burra (Worlds End)	34.70	137.71
22006		Curramulka	33.96	137.70
22008	94665	Kadina	34.37	137.67
22009		Maitland	34.77	137.59
22017		Minlaton	34.91	137.80
22020		Stansbury	33.93	137.63
22021		Wallaroo	34.28	137.86
22801	94805	Ardrossan (Winulta)	35.75	136.59
22807		Cape Borda	35.66	137.64
23011		Kingscote	34.92	138.60
23021		North Adelaide	34.53	138.75
23025		Roseworthy	34.68	138.69
23305		Smithfield	34.46	138.93
23310		Greenock	34.00	138.81
23314		Manoora	34.16	138.75
23315		Riverton	34.08	138.78
23319		Saddleworth	34.28	138.77
23707		Tarlee	35.01	138.76
23724		Bridgewater	35.07	139.00
23733	94806	Kanmantoo	35.06	138.85
23739		Mount Barker	35.04	138.91
23751		Nairne	35.55	138.62
23754		Victor Harbor	35.46	138.35
24013		Yankalilla	34.44	140.49
		Loxton (Pyap)		

Appendix B (cont.). Stations used in precipitation quintile analysis

Australian station number	WMO station number	Station name	Latitude (deg S)	Longitude (deg E)
24016		Renmark	34.17	140.75
24501		Australia Plains	34.10	139.15
24508		Callington	35.12	139.04
24511	94680	Eudunda	34.18	139.08
24515		Langhorne Creek	35.30	139.03
24517		Mannum	34.91	139.30
24518	95814	Meningie	35.69	139.34
24519		Milang	35.41	138.97
24521	95812	Murray Bridge	35.12	139.26
24523		Blanchetown (Wyn-Moor)	34.42	139.78
24530		Sedan (Sandleton)	34.46	139.35
24535		Swan Reach	34.57	139.60
24573		Truro	34.41	139.13
25502		Cooke Plains	35.38	139.56
25509	94688	Lameroo	35.33	140.52
26005		Cape Northumberland	38.06	140.67
26012		Kingston SE	36.83	139.85
26018		Millicent	37.59	140.34
26023		Naracoorte	36.96	140.74
26026	94812	Robe	37.16	139.76
29041		Normanton	17.67	141.07
30018	94275	Georgetown	18.29	143.55
30024		Hughenden	20.84	144.20
30040		Pentland	20.52	145.40
31036		Kuranda	16.82	145.64
31037	94285	Low Isles	16.38	145.56
32004	94292	Cardwell	18.26	146.02
32032		Macknade	18.59	146.25
32044		Valley of Lagoons	18.66	145.10
33012		Collaroy Station	22.03	149.18
33047	95366	Te Kowai	21.16	149.12
33062		Ravenswood	20.10	146.89
33065	94369	St. Lawrence	22.35	149.54
33073		Woodhouse	19.83	147.13
33076		Yaamba	23.13	150.37
35002		Arcturus Downs	24.03	148.41
35019	94359	Clermont	22.82	147.64
35026		Duaringa	23.71	149.67
35056		Rainworth	24.12	147.93
35069	94355	Tambo	24.88	146.26
35070	94525	Taroom	25.64	149.80
36007	94350	Barcaldine	23.55	145.29
36013		Camoola Park	23.04	144.52
36016		Coreena	23.28	145.40
36026	94345	Isisford	24.26	144.44
36037		Muttaburra	22.59	144.55
36143		Blackall	24.42	145.47
36144		Terrick Terrick	24.74	145.07
37025		Katandra	21.55	143.80
37043	94329	Urandangi	21.61	138.31
37051	94339	Winton	22.39	143.04
38003	94333	Boulia	22.91	139.90
39022		Camboon	25.03	150.44
39036		Eidsvold	25.37	151.12

Appendix B (cont.). Stations used in precipitation quintile analysis

Australian	WMO station	Station name	Latitude	Longitude

station number	number		(deg S)	(deg E)
39037		Fairymead	24.79	152.36
39039	94543	Gayndah	25.63	151.61
39069		Walterhall	23.63	150.39
39070		Mt. Perry	25.17	151.64
39085	94390	Sandy Cape	24.73	153.21
40043	94594	Cape Moreton	27.03	153.47
40082	94562	Gatton (Uni of Queensland)	27.54	152.34
40083		Gatton (Allan Street)	27.54	152.30
40094		Harrisville	27.81	152.67
40098		Howard	25.32	152.56
40110		Kilcoy	26.94	152.56
40111		Kilkivan	26.09	152.24
40140		Mt Brisbane	27.15	152.58
40158		Nanango	26.68	151.99
40184		Rosewood	27.64	152.59
40374		Franklyn Vale	27.76	152.46
41018		Clifton	27.93	151.91
41034		Glenelg	28.40	151.47
41056		Killarney	28.33	152.30
41082		Pittsworth	27.72	151.63
41100	95533	Texas	28.85	151.17
41103		Toowoomba	27.58	151.93
42023		Miles	26.66	150.18
43020	94514	Mitchell	26.49	147.98
43035	94521	Surat	27.16	149.07
43043		Yuleba	26.61	149.39
44002		Augathella	25.80	146.59
44012		Boorara	28.66	144.38
44026	94500	Cunnamulla	28.07	145.68
44166		Yamburgan	28.51	148.40
45017		Thargomindah	28.00	143.82
46003		Yanco Glen	31.29	141.44
46043	94695	Wilcannia	31.56	143.37
47000		Gum Lake (Ablemarle)	32.53	143.37
47014		Broken Hill (Kars)	32.22	142.03
47019	94694	Menindee	32.39	142.42
47053		Wentworth	34.11	141.92
48014		Goodooga (Brenda)	29.03	147.31
48020		Mungindi (Burrenbah)	29.04	148.65
48036		Walgett (Dungalear)	29.66	148.12
48053		Cobar (Lerida)	31.70	145.70
48082		Weilmoringle	29.24	146.92
49002	94696	Balranald	34.64	143.56
49004		Euabalong (Booberoi)	33.08	146.57
49008		Hatfield (Clare)	33.40	143.94
50011		Tottenham (Burdenda)	32.13	147.41
50016		Goonumbla (Coradgery)	32.97	148.06
50018		Dandaloo (Kelvin)	32.29	147.67
50031	94721	Peak Hill	32.72	148.19
51010	94718	Coonamble	30.98	148.38
51022		Gulargambone	31.33	148.47
51025		Warren (Haddon Rig)	31.46	147.88
51031		Nyngan (Canonbar)	31.64	147.32
51034		Warren (Mumblebone)	31.50	147.69
51042		Quambone Station	30.93	147.87
51054		Warren	31.70	147.84

Appendix B (cont.). Stations used in precipitation quintile analysis

Australian station number	WMO station number	Station name	Latitude (deg S)	Longitude (deg E)
52008		Rowena (Bunna Bunna)	29.80	149.20

52020	94520	Mungindi	28.98	148.99
53004		Boggabilla	28.60	150.36
53034		Wee Waa (Pendennis)	30.12	149.32
54003	94761	Barraba	30.38	150.61
54004		Bingara	29.87	150.57
54035		Yetman	28.90	150.77
55002		Mullaley (Bando)	31.23	149.83
55007		Boggabri	30.71	150.05
55018		Mullaley (Garrawilla)	31.17	149.65
55031		Manilla	30.75	150.72
55049	95746	Quirindi	31.51	150.68
55057		Willow Tree (Valais)	31.77	150.29
55067		Goonoo Goonoo	31.30	150.91
56008		Deepwater	29.44	151.85
56009		Emma ville	29.45	151.60
56016		Guyra	30.22	151.67
56029		Emma ville (Strathbogie)	29.46	151.47
56032	94556	Tenterfield	29.05	152.02
57022		Wollomombi (Wallamumbi)	30.49	152.10
58012	94589	Yamba	29.43	153.36
58015		Coraki	28.99	153.29
58037		Lismore	28.81	153.26
58038		Maclean	29.45	153.20
58061		Woodburn	29.07	153.34
59001		Bellingen	30.45	152.90
59002		Bowraville	30.65	152.85
59017	94788	Kempsey	31.08	152.82
60020		Kendall	31.63	152.70
60030		Taree	31.90	152.48
61002		Blackville	31.84	150.34
61010		Clarence Town	32.59	151.78
61014		Branxton	32.64	151.42
61016		Denman	32.39	150.69
61031		Raymond Terrace	32.78	151.73
61055	94774	Newcastle (Nobbys Head)	32.92	151.80
61071		Stroud	32.40	151.97
62013	94732	Gulgong	32.36	149.53
62021		Mudgee	32.60	149.60
63009		Blackheath	33.62	150.30
63012		Running Stream (Brooklyn)	33.02	149.88
63032		Golspie	34.27	149.66
64008	94728	Coonabarabran	31.27	149.27
65000		Arthurville (Cramond)	32.50	148.75
65006		Canowindra	33.57	148.66
65022		Manildra (Hazeldale)	33.16	148.59
65030		Dubbo (Mentone)	32.52	148.52
65034	94723	Wellington	32.56	148.95
65036		Yeoval	32.75	148.65
66006		Sydney Botanic Gardens	33.87	151.22
66062	94768	Sydney (Observatory Hill)	33.86	151.20
67019	94736	Prospect Dam	33.82	150.91
68027		Gerringong	34.75	150.82
68048		Nowra Treatment Works	34.87	150.62
69006		Bettowynd	35.70	149.79

Appendix B (cont.). Stations used in precipitation quintile analysis

Australian station number	WMO station number	Station name	Latitude (deg S)	Longitude (deg E)
69010		Braidwood	35.45	149.80
69018	94937	Moruya Heads	35.91	150.15
69107		Kameruka	36.74	149.71

70005	94928	Bombala	36.91	149.24
70009		Bukalong	36.80	149.20
70025		Crookwell	34.46	149.47
70032		Fairlight	35.23	148.91
70035		Bungendore (Gidleigh)	35.31	149.47
70071		Goulburn (Pomeroy)	34.65	149.50
70072		Queanbeyan	35.36	149.22
70080	94735	Taralga	34.40	149.82
72000		Adelong	35.31	148.07
72024		Humula	35.50	147.77
72043	94918	Tumbarumba	35.78	148.01
72044		Tumut	35.32	148.23
73014	94725	Grenfell	33.90	148.17
73025		Old Junee (Millbank)	34.79	147.56
73041		Wombat (Tumbleton)	34.41	148.18
73127		Wagga Wagga Ag Institute	35.05	147.35
74008		Grong Grong	34.86	146.82
74009		Berrigan	35.66	145.81
74025		Burrumbuttock	35.85	146.78
74053		Henty	35.52	147.03
74056		Jindera (Wadilock)	35.95	146.90
74087		Urana (Nowranie)	35.33	146.03
74106	94877	Tocumwal	35.81	145.60
74110		Urana	35.33	146.27
74128		Deniliquin	35.53	144.95
74236		Bungowannah (Roseleigh)	36.02	146.76
75004		Wakool (Barratta)	35.28	144.53
75007		Booligal (Belmont)	33.84	144.91
75032	94700	Hillston	33.49	145.52
75034		Hillston (Hunthawang)	33.34	145.75
75039	95707	Lake Cargelligo	33.28	146.37
75046		Moulamein	35.09	144.03
75049		Maude (Nap Nap)	34.45	144.17
75062		Moulamein (Tchelery)	34.81	144.17
75067		Carrathool (Uardry)	34.47	145.30
75075		Conargo (Willurah)	35.00	145.09
77030		Narraport	36.00	143.03
77047		Tyrrell Downs	35.36	142.98
77051		Rainbow (Werrap)	35.94	141.93
78000		Warracknabeal (Ailsa)	36.36	142.33
78014		Glenlee	36.26	141.86
78041		Wooroonook	36.25	143.18
78043		Yanac North	36.11	141.42
79014		Eversley	37.19	143.17
79016		Warranooke (Glenorchy)	36.73	142.73
79017		Goroke	36.72	141.47
79019		Great Western	37.16	142.86
79023		Horsham (Polkemmet)	36.65	142.11
79035		Murtoa	36.62	142.47
79039		Redbank	36.91	143.34
80015	94861	Echuca	36.17	144.76

Appendix B (cont.). Stations used in precipitation quintile analysis

Australian station number	WMO station number	Station name	Latitude (deg S)	Longitude (deg E)
80023	94844	Kerang	35.72	143.92
80029		Lake Marmal	36.15	143.52
80039		Yarrawalla South	36.19	144.05
80042		Nathalia	36.06	145.20
80053		Tandarra	36.43	144.25
80065		Yarroweyah	35.88	145.55

81008		Colbinabbin	36.53	144.77
81026		Laanecoorie Weir	36.83	143.89
82002	94884	Benalla	36.55	145.97
82010		Chiltern	36.15	146.61
82011	94899	Corryong	36.20	147.90
82047		Tallangatta (Bullioh)	36.19	147.36
84016	94933	Gabo Island	37.57	149.92
85020		Clydebank	38.04	147.18
85049		Leongatha	38.49	145.93
86018		Caulfield	37.88	145.04
86070		Maroondah Weir	37.64	145.55
86071	94868	Melbourne	37.81	144.97
86085		Narre Warren North	37.99	145.34
86098		Red Hill South	38.37	145.03
86117		Toorourrong Reservoir	37.48	145.15
86121		Warburton	37.75	145.68
87006		Ballan	37.60	144.23
87007		Morrisons (Ballark)	37.74	144.14
87011		Beales Reservoir	37.54	144.03
87014		Bungaree (Kirks Reservoir)	37.55	143.93
87034		Lovely Banks Reservoir	38.07	144.33
87043		Meredith (Darra)	37.82	144.15
87046		Mount Buninyong	37.67	143.94
88011		Campbelltown	37.22	143.96
88015		Clunes	37.30	143.78
88042		Malmsbury Reservoir	37.20	144.37
88043	94849	Maryborough	37.06	143.73
89009		Cavendish	37.53	142.04
89030		Trawalla	37.48	143.46
89103		Derrinallum	37.97	143.22
90011		Camperdown	38.23	143.14
90015	94842	Cape Otway	38.86	143.51
90020		Casterton (Warrock)	37.44	141.34
90061		Pennyroyal Creek	38.42	143.83
90063		Penshurst	37.88	142.29
90067		Port Campbell	38.62	142.99
90085		Terang (Woorywyrite)	38.08	142.99
90167		Winchelsea	38.24	143.99
91057		Low Head	41.06	146.79
92029		Ormley	41.72	147.82
93014		Oatlands	42.30	147.37
94010	94967	Cape Bruny	43.49	147.14
94029	94970	Hobart	42.89	147.33
94041	94962	Maatsuyker Island	43.66	146.27
94061		Sandford	42.93	147.52

WMO station numbers are valid as of 18 October 2005.

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WCDMP-36 REPORT OF THE MEETING OF THE CCI TASK TEAM ON CLIMATE ASPECTS OF RESOLUTION 40, Geneva, Switzerland, 10-1 1 June 1998 - (WMO-TD No. 925)

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WCDMP-49 1. REPORT ON THE CLICOM-DARE WORKSHOP (San José, Costa Rica, 17-28 July 2000); 2. REPORT OF THE INTERNATIONAL DATA RESCUE MEETING (Geneva, 11-13 September 2001) (WMO-TD No. 1128)

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WCDMP-51 SUMMARY REPORT OF THE EXPERT MEETING FOR THE PREPARATION OF THE SEVENTH GLOBAL CLIMATE SYSTEM REVIEW (7GCSR) (Geneva, 16-19 September 2002) (WMO-TD No. 1131)

WCDMP-52 GUIDELINES ON CLIMATE OBSERVATION NETWORKS AND SYSTEMS (WMO-TD No. 1185)

WCDMP-53 GUIDELINES ON CLIMATE METADATA AND HOMOGENIZATION (WMO-TD No. 1186)

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WCDMP-56 FOURTH SEMINAR FOR HOMOGENIZATION AND QUALITY CONTROL IN CLIMATOLOGICAL DATABASES (Budapest, Hungary, 6-10 October 2003) (WMO-TD No. 1236)

WCDMP-57 REPORT OF THE RA V DATA MANAGEMENT WORKSHOP (Melbourne, Australia, 28 November-3 December 2004) (WMO-TD No. 1263)

WCDMP-58 GUIDELINES ON CLIMATE WATCHES (WMO-TD No. 1269)

WCDMP-59 REPORT OF THE MEETING OF THE RA I WORKING GROUP ON CLIMATE MATTERS (Dakar, Senegal, 22 – 24 February 2006) (WMO-TD No. 1351)

WCDMP-60 GUIDELINES ON CLIMATE DATA MANAGEMENT (WMO-TD No. 1376)

WCDMP-61 THE ROLE OF CLIMATOLOGICAL NORMALS IN A CHANGING CLIMATE (WMO-TD No. 1377)