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Verification of Australian monthly district rainfall totals using high resolution gridded analyses

David A. Jones and Grant Beard
Bureau of Meteorology, Australia

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The use of district rainfall totals for the description of Australian rainfall on monthly and longer time-scales has been investigated using a gridded rainfall dataset generated using an objective analysis technique. It has been verified that the operational district totals, generated within the Bureau of Meteorology for rainfall monitoring and prediction purposes, provide a reasonable indication of rainfall on the whole, both in the mean and in individual months. Some deficiencies have been found in the district totals in certain parts of the country, most notably in the subtropical parts of Western Australia, southern half of the Northern Territory, tropical Queensland, and western Tasmania. In each of these areas districts encompass geographical regions with large spatial variation in rainfall, and the distribution of stations available for the calculation of district average rainfall is not sufficient. The appropriateness of the district boundaries and the variability of rainfall within districts is also investigated.

Introduction

The description of the spatial and temporal distribution of rainfall presents a major challenge to the atmospheric sciences. Rainfall is discontinuous in both time and space, and shows structure across a wide range of time and length scales (Lovejoy 1982; Manton 1993). The distribution of accumulated rainfall over some time period reflects the combined effect of discrete rainfall systems ranging from individual showers and storms to organised synoptic-scale systems such as tropical-extratropical cloudbands and cyclones (Sumner 1988). Each of these may produce rainfall with differing temporal and spatial distributions and be sampled to differing degrees by the observing network.

Despite the difficulty in analysing and observing rainfall, its primary role in the atmospheric general circulation through latent heat processes (Sumner 1988, Peixóto and Oort 1992), and basic role in agricultural production and human activity in general, means that the study of rainfall and rainfall analysis has been performed over many years (Manton 1993). The role of rainfall in the general circulation and human activity has resulted in numerous studies of the climatology of rainfall (e.g., Jaeger 1983; Legates and Willmott 1990; Drosdowsky 1993c), rainfall variability (e.g., Pittock 1975; Srikanthan and Stewart 1991; Zhang and Casey 1992), and change (e.g., Nicholson 1989; Nicholls and Lavery 1992; Climate Change 1995; Watanabe and Shinoda 1996), and served as an impetus for the Global Precipitation Climatology Project (WCRP 1986).

The social and economic importance of rainfall and rainfall variability is perhaps no more pronounced than in Australia. Lying in the subtropics on the edge of the Pacific Basin, Australia experiences a largely arid climate with often marginal rainfall for agriculture and land-use in general (Gentilli 1971; NATMAP 1986). Serving to exacerbate the impact of low rainfall in the mean, Australian rainfall is more variable than would be expected when compared to global patterns of variability (Conrad 1941; Nicholls et al. 1997). This increased temporal variability of rainfall is largely due to the quasi-periodic El Niño - Southern Oscillation phenomenon which strongly modulates rainfall on seasonal to interannual time-scales across the Australian continent (e.g., Pittock 1975; McBride and Nicholls 1983; Drosdowsky and Williams 1991; Zhang and Casey 1992).

Corresponding author address: Dr David Jones, Bureau of Meteorology Research Centre, GPO Box 1289K, Melbourne, Vic. 3001, Australia.

Given the importance of rainfall and rainfall variability in Australia, the observation, analysis, and prediction of rainfall has been a primary focus of the Australian Bureau of Meteorology. In support of these activities, the Bureau has developed an extensive network of rainfall observing stations with typically 5000 or more rain gauge sites maintained for the observation of rainfall during the twentieth century (Jones and Weymouth 1997). These raw rainfall data have in turn provided the basis for a systematic and comprehensive review of the Australian rainfall climate and mechanism of its variability in the scientific literature. For recent studies on Australian rainfall and rainfall variability and a historical survey of the pertinent literature, the reader is referred to Srikanthan and Stewart (1991), Lavery et al. (1992, 1997), Nicholls and Lavery (1992), Allan and Haylock (1993), and Drosdowsky (1993a,b).

In addition to providing for the scientific needs for rainfall data, a primary requirement of the rainfall observing network is the accrual of data in near real time, for the monitoring of recent rainfall trends and patterns. These data and the subsequent analyses are then widely used in such fields as water storage, primary production and resource management. It is against this operational background that the historical use of district average rainfall arose, a technique which forms an integral part of the Bureau's rainfall monitoring program, and which is the primary focus of this study.

The use of district totals within the Bureau developed from a desire to economically portray rainfall information in regions which have common seasonal rainfall regimes, and in doing so provide a clearer picture of the rainfall and rainfall variability than that offered by individual stations. The use of district totals for rainfall analysis is introduced in Hunt (1910), while Watt (1938) and Lee and Gaffney (1986) provide updates. The district rainfall is taken to be the arithmetic mean across a sample of stations which lie within a district, where stations are chosen using local knowledge of their reliability and representativeness (Chappel 1995). This provides a simply calculated robust measure of the meso to synoptic-scale rainfall patterns. District totals calculated in this fashion date back to 1913 and have found wide use both operationally and in research studies including Treloar and Grant (1953), Pittock (1975), Zhang and Casey (1992), Allan and Haylock (1993), Drosdowsky (1993a,b) and Chappel (1995).

Regional meteorological offices in each State have in the past been responsible for the development of district totals and the documentation of the techniques and stations used has often been *ad hoc*. Furthermore, it has been known by operational meteorologists that there have been slightly differing policies between States when generating district averages, and an uneasiness about their accuracy and usefulness. District totals have for many years been tabulated in monthly Bureau publications such as the centrally produced *Monthly Rainfall Review*, and the regional *Monthly Weather Reviews*. Also, they are ideally suited to the *Seasonal Climate Outlook*, and three-monthly district totals have historically formed the backbone for this seasonal forecast publication. District rainfall data have been promulgated widely in yearbooks and numerous publications aimed at the primary sector.

Despite their wide use, the procedures applied to generating district totals, and particularly, the accuracy of derived totals have received little attention in the scientific literature. It is the purpose of this study to address this shortcoming. We aim to document the reliability of the district rainfall totals in defining the mean rainfall climate and temporal variability about the mean using independent and reliable digital rainfall analyses. Further, it will be shown that the use of objective analysis schemes to derive a rainfall surface from which a district average can be computed allows for an accurate and economical estimation of area-averaged rainfall over meteorological districts.

Data and methodology

The data used in this study comprise numerical gridded rainfall analyses and district rainfall totals for each month in the period 1913 to 1995, inclusive. These data are available from the National Climate Centre, Australian Bureau of Meteorology, and currently form the basis for the operational monitoring and prediction of rainfall in the Australian region.

The monthly district totals which we have used are those which are operationally generated and stored within the Bureau of Meteorology. The distribution of the 107 districts covering the Australian continent is shown in Fig. 1. District totals are available from 1913 to the present for each district except districts 14F and 14DE for which totals commenced in 1923 and 1925, respectively. Reflecting the realities of operational analysis, the stations used for computing district totals vary in time through the record due to variations in those stations which are open, and also in response to the availability and veracity of reported data. Very little consistent documentation exists on the stations used to construct the historical district totals, though in recent times typically 10 to 50 per cent of the stations in each district have been used, depending on the State, size and nature of the district.

The conventional district totals are calculated as the mean of the rainfall at a set of stations within a given district, where stations are selected so as to provide the 'most reliable' and representative estimate of the rainfall across the district (Chappel 1995; Lee, personal com-

Fig. 1 The distribution of the 107 meteorological districts.

munication 1997). This process requires the local knowledge and skills of the human analyst to determine those stations which are to be used, and does not allow the analyst to vary the weighting a station has in a district total beyond that of including or excluding its rainfall value in the district total summation. The inability to accurately weight the contribution of stations to the district totals in accordance to their representativeness within districts casts doubt on the veracity and usefulness of the conventional district totals. This concern is compounded by the large variations in the spatial density of stations across Australia (Jones and Weymouth 1997), and the bias of stations towards population centres, transport routes, and the wetter coastal regions, all of which complicate the calculation of area means through unweighted summations.

The monthly rainfall analyses which we have used in this study are a subset of the archive documented in Jones and Weymouth (1997). These data are analysed on a regular 0.25° by 0.25° latitude-longitude grid covering the Australian continent, and have been shown to be reliable in the estimation of local area-averaged rainfall by Jones and Weymouth. This historical gridded rainfall archive was generated using the Barnes successive correction technique. The analysis parameters used in the development of this dataset were chosen on the basis of classical sampling theory applied to the observational station density (Koch et al. 1983), and are thoroughly documented in Jones and Weymouth (1997).

The Barnes technique belongs to the general class of inverse distance weighting schemes which have been widely adopted for meteorological analysis (Willmott et al. 1996), and the characteristics of this analysis procedure are documented in Koch et al. (1983), Barnes (1994a,b), Jones and Weymouth (1997), and Mills et al. (1997). In the analysis procedure, an analysis is derived in which the grid-point values are chiefly based on data at nearby observation points. In this process an observation's influence on a grid-point is determined by a weighting function whose value depends on the distance separating data and grid-points. The analysis technique is similar to the widely used Cressman objective analysis procedure (Cressman 1959), with the major difference being that the Barnes technique uses a Gaussian weighting function which asymptotes to zero as the distance between data and grid-points increases. This contrasts with the Cressman technique which abruptly changes to zero at the radius of influence. This abrupt change of the Cressman weighting function to zero can lead to artificial structures in the analysis, particularly for irregularly spaced data, due to changes in the observations influencing grid-points across the analysis grid. It is important to note that the Barnes technique is purely two-dimensional, and does not explicitly incorporate variations in rainfall due to topography in the generation of rainfall surfaces (analyses), which may be tenuous on short (monthly) timescales. The reasons for using this analysis technique include its computational simplicity and efficiency, well-documented analysis characteristics, and its relative accuracy and robustness.

The digital rainfall analyses have been used to generate a new set of district average rainfall for each month in the study period. Digitised polygon boundaries for each of the 107 districts were used to define those points on a 0.125° grid which lie within each district. The gridded rainfall was then averaged across these points, with intermediate point values interpolated using the Lagrangian cubic technique, which forms the basis for the backwards interpolation used in the Barnes analysis algorithm. The additional interpolation of the gridded rainfall to the finer 0.125° grid was necessitated by the small size of a number of the districts in southeast Australia and has a negligible impact on the rainfall in most districts. These new district totals have the advantage over the traditional technique (meaning stations) in that the prominence of a station in the average is controlled by the local density of stations and hence the amount of independent information each might be expected to contain. Further, by first modelling the rainfall surface and then determining an areal average, the analysis procedure is better able to use all rainfall data and reconcile conflicting reports, and makes no *a priori* decisions about the representativeness of stations which may or may not be correct.

For a number of districts, additional analysis of mean rainfall has been performed using the thin plate spline technique (Hutchinson 1991, 1995) in a two-dimensional (horizontal) and three-dimensional (incorporating topography) mode. This analysis has been performed using long-term station means, for which relationships between rainfall and topography can be expected to be well-defined, and these high-quality climatological analyses have been used to aid in the interpretation of differences between the aforementioned district totals. This additional climate analysis has used only those stations with 30 years or more of records during the period 1913-1995, to confine the analysis to those stations which will have made a significant contribution to the conventional district totals and 'Barnes' gridded analyses. The use of local high resolution analyses allows the very accurate modelling of the rainfall climate and allows the further verification of the grid-derived district totals documented above.

In the following sections, we will refer to the district totals derived using the gridded rainfall as the new or grid district totals. The statistical comparisons which follow have been largely confined to the months of January and July, and the summer and winter seasons for brevity.

Difference between monthly and seasonal district totals – mean absolute difference

To gauge the typical difference between the district average rainfall totals calculated using the conventional technique and those obtained using the gridded rainfall analysis set, we have computed the mean absolute difference (MAD) between series of monthly and seasonal totals for each district. This measure gives the amount by which district rainfall totals generated by the two techniques differ on, average, for any given month or season.

The geographical distribution of the MAD of district rainfall for the months of January and July, respectively, for the period 1913 to 1995 is shown in Fig. 2. In both months (and in fact all months) there is a marked tendency for those districts with the largest MAD to be also those with the highest rainfall in the mean (Lee and Gaffney 1986). Notably, of the ten districts in both months with the highest MAD, seven of these also occur in the list of the ten 'wettest' districts in each month. This observation is confirmed by the correlation between the MAD and mean rainfall across districts which is 0.88 in January and 0.71 in July.

Quantitatively, the MAD for January and July averaged across districts is 13.2 and 7.9 mm respectively, comprising some 17 per cent of the mean district rainfall, on average. The relatively low magnitude of the differences and the fact that values are skewed towards a small number of poorly observed districts indicates that the conventional district totals provide a relatively accurate estimate of the district rainfall in individual months when compared to the grid-based totals.

Fig. 2 The geographical distribution of the mean absolute difference between monthly district totals in the gridded and conventional datasets. (a) January and (b) July.

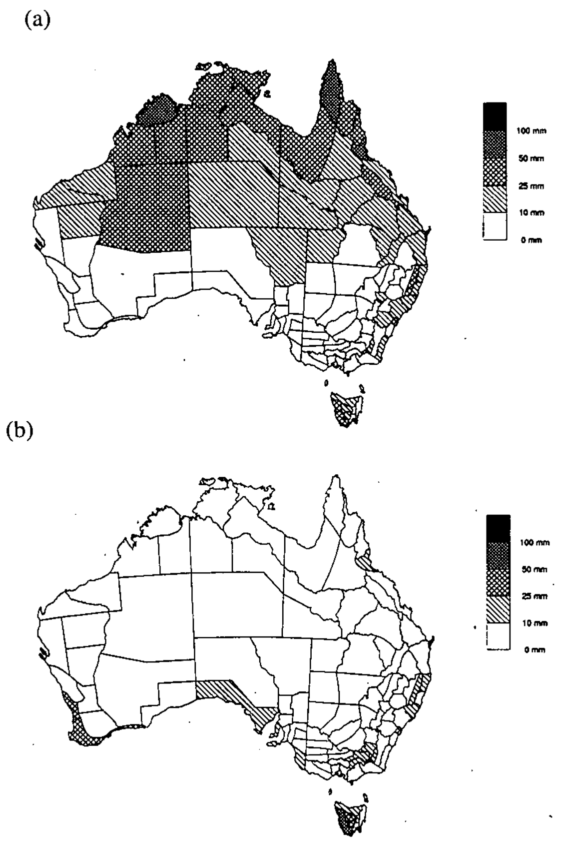
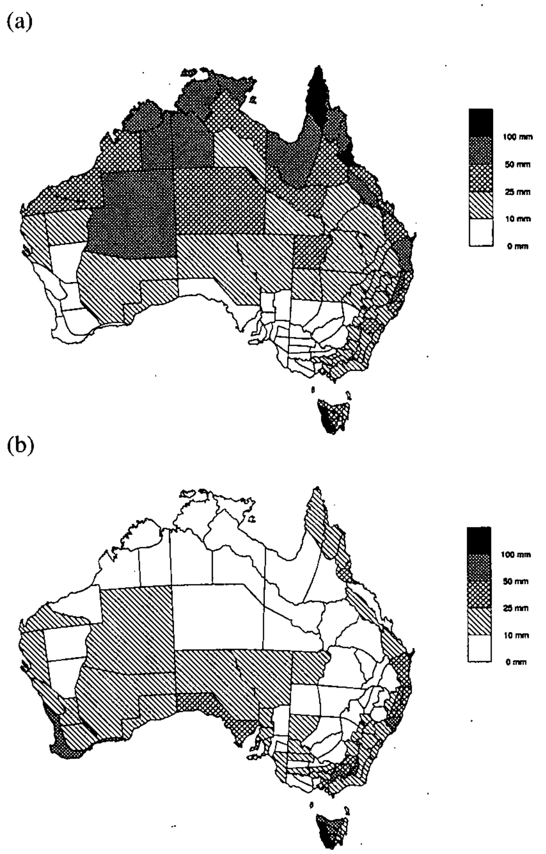


Fig. 3 The geographical distribution of the mean absolute difference between seasonal district totals in the gridded and conventional datasets. (a) Summer and (b) winter.



Regionally, the greatest values of the MAD during January occur in the poorly observed and high rainfall districts 1 and 27, and in the topographically diverse district 32. In each of these districts the MAD is greater than 50 mm, and amounts to some 20 to 30 per cent of the long-term mean rainfall. During July most districts have a MAD less than 10 mm, with the greatest values occurring in the southwest of Western Australia and western Tasmania where the mean rainfall is relatively high, and the MAD is largely a product of differing climatological mean rainfall in the two sets rather than due to differing temporal variations of rainfall.

The geographical distribution of the MAD of district rainfall totals for summer and winter is shown in Fig. 3. In agreement with the extreme months, the MAD is largely determined by the mean rainfall of districts, with the higher rainfall districts being those with the greatest MAD. As a percentage of the district mean rainfall, the MAD comprises some 12 per cent during summer and 14 per cent during winter, while the districts with the greatest differences are districts 27, 32, and 97.

Comparison of the rainfall climate in districts

Means

In this section we examine the reliability of the conventional district totals in defining the mean rainfall climate of districts. The mean rainfall in each district for January and July for the conventional set plotted against the equivalent values in the gridded set is shown in Fig. 4. An overview of these data is provided in Table 1. It should be noted that we have plotted the cube root of rainfall to compress the graph axes and hence allow for the four orders of magnitude over which monthly rainfall varies between districts.

During January and July, there is a good correspondence between the district average rainfall in the two sets, with most districts near the slope 1 line. The mean difference averaged across all districts is 5.8 mm in January and 5.5 mm in July. These values represent a percentage difference of the mean of seven and eleven

Fig. 4 **The monthly mean rainfall for each of the 107 districts for the gridded and conventional datasets. (a) January and (b) July.**

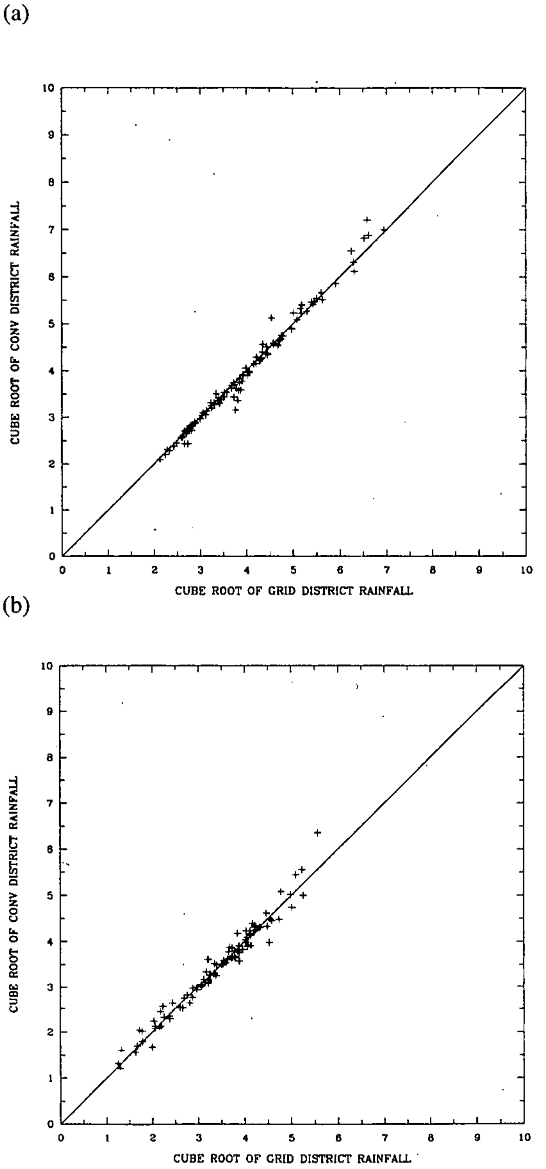
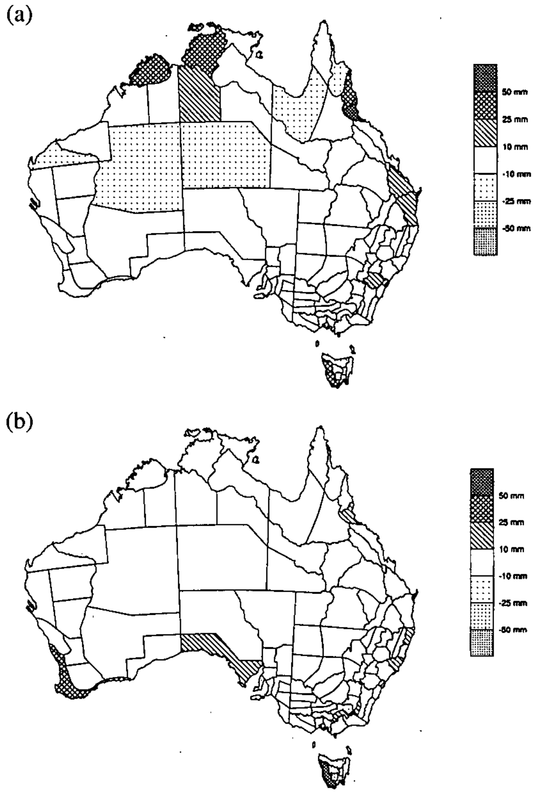


Fig. 5 **The geographical distribution of the difference between the mean district rainfall in the gridded and conventional datasets. (a) January and (b) July (conventional minus grid).**



per cent in January and July, respectively. The average differences are a little larger in summer and winter (not shown), but, like the months, also comprise percentage errors of seven and eleven per cent, respectively.

The geographical distribution of the difference in mean rainfall between the grid and conventional district totals for January and July is shown in Fig. 5 (conventional minus grid). The equivalent maps for the summer and winter seasons are shown in Fig. 6. There is a clear tendency for the districts which have the greatest difference in mean rainfall to be high rainfall districts (in which the size of differences is clearly mitigated by the background climatology), and/or remote and poorly observed districts where the distribution of stations is insufficient or unrepresentative of the district at large.

Across the 107 districts, the difference in the monthly mean rainfall between the two sets of data is significant at the 95 per cent level for seven districts in January and 21 districts in July. During summer, some 12 districts have average rainfall in the two sets which are significantly different while this value is 28 in winter. Geographically, there is a tendency for the statistically significant differences to occur in Tasmania, in the central subtropics, and on the north Queensland coast.

Fig. 6 **The geographical distribution of the difference between the mean district rainfall in the gridded and conventional datasets. (a) Summer and (b) winter (conventional minus grid).**

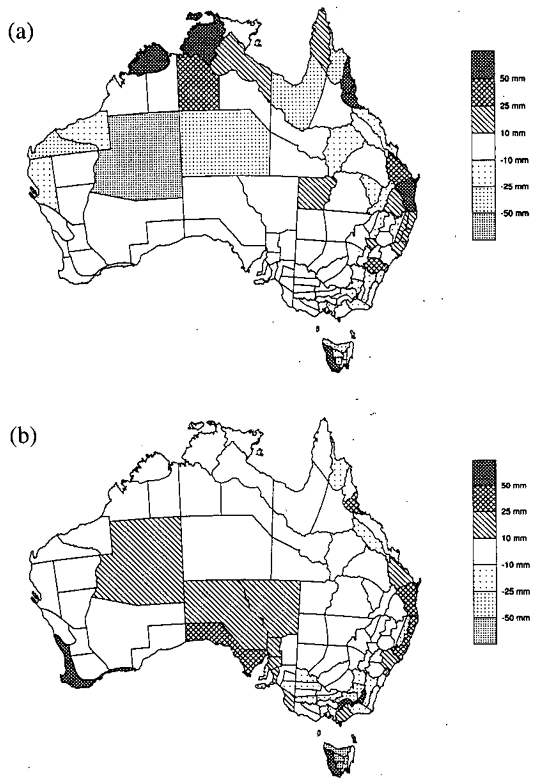


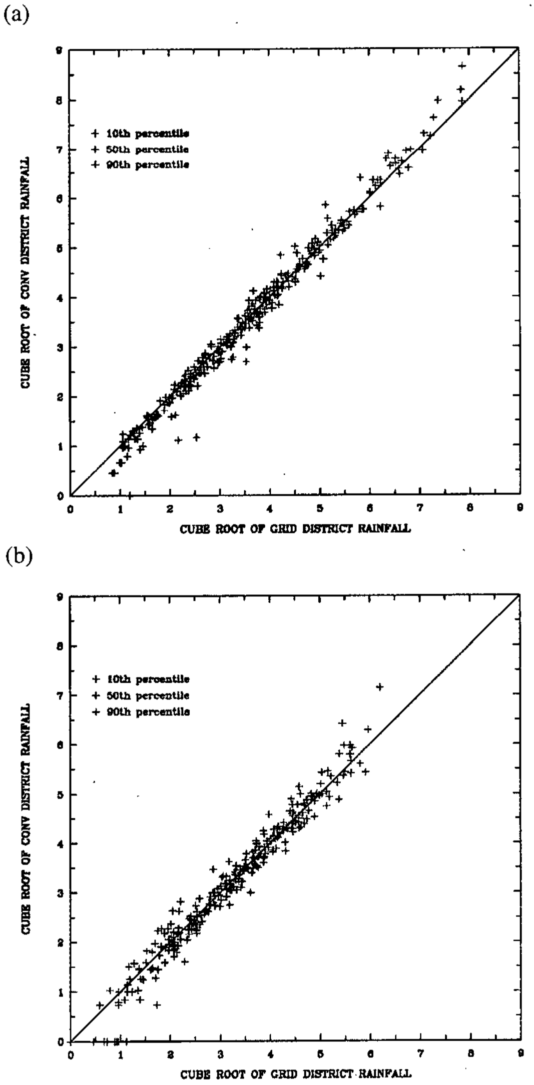
Table 1. **Statistics from the comparison of district totals for January, July, summer, winter, and annual.**

Measure	*January*	*July*	*Summer*	*Winter*	*Annual*
MAD (mm)	13.2	7.9	26.8	20.5	72.8
MAD mean (mm)	5.8	5.5	14.2	16.0	57.2
MAD 10th percentile (mm)	3.9	3.2	12.9	11.3	48.9
MAD 50th percentile (mm)	7.0	5.7	17.0	16.6	60.1
MAD 90th percentile (mm)	12.1	10.1	25.7	22.9	71.7
MAD standard deviation (mm)	4.8	3.0	7.7	6.0	14.9
Mean district rainfall grid (mm)	77.8	47.8	216.7	141.8	657.2
Mean district rainfall conventional (mm)	79.0	48.8	219.8	144.3	670.1
correlation	0.95	0.95	0.95	0.95	0.94

Percentiles

To gauge the relative frequency distribution of rainfall, the 10, 50, and 90th percentiles of the conventional district average rainfall plotted against the equivalent values for the gridded data for January and July are shown in Fig. 7 . With few exceptions the new and conventional district rainfall totals are in close agreement with most totals lying near the slope 1 line. The mean differences between the totals during January for the 10, 50, and 90th percentiles are 3.9, 7.0, and 12.1 mm, being some

Fig. 7 **The monthly rainfall for each of the 107 districts for the gridded and conventional datasets for the 10th, 50th, and 90th percentiles. (a) January and (b) July.**



14, 11, and 9 per cent of the average district rainfall for each percentile (Table 1). The equivalent values for July are 3.2, 5.7, and 10.1 mm, and 17, 14, and 12 per cent, respectively. This suggests that the rainfall climate of most districts is not highly sensitive to which of the two techniques is used to generate district totals. Given that the gridded data provide an accurate estimate of the district rainfall, these values indicate that the conventional technique of defining district rainfall to be the arithmetic mean of a list of stations provides a mostly satisfactory estimate of the rainfall across districts.

On a quantitative level, the comparison of the data highlights a number of systematic differences. At the upper end of district rainfall totals and particularly for the 90th percentile, there is a general tendency for the conventional totals to be higher than those generated using the gridded analyses. This is evidenced by the clustering of the rainfall totals above the slope 1 line at the high end of both graphs. In contrast, for low rainfall, the reverse tends to be the case, with a tendency for the 10th percentile, in particular, to be a little higher in the new district totals.

The equivalent figures for the 10, 50, and 90th percentiles for summer and winter (not shown) broadly confirm the earlier observations, with the district rainfall generally similar. Again, there is a tendency for the tails in the distributions for districts to be a little longer in the conventional district totals, with the conventional data having a tendency for lower and higher rainfall totals matching the 10 and 90th percentile values, in particular. This is largely due to the slightly greater variability which the conventional data possess, when compared to the new grid-derived set, as we will see later.

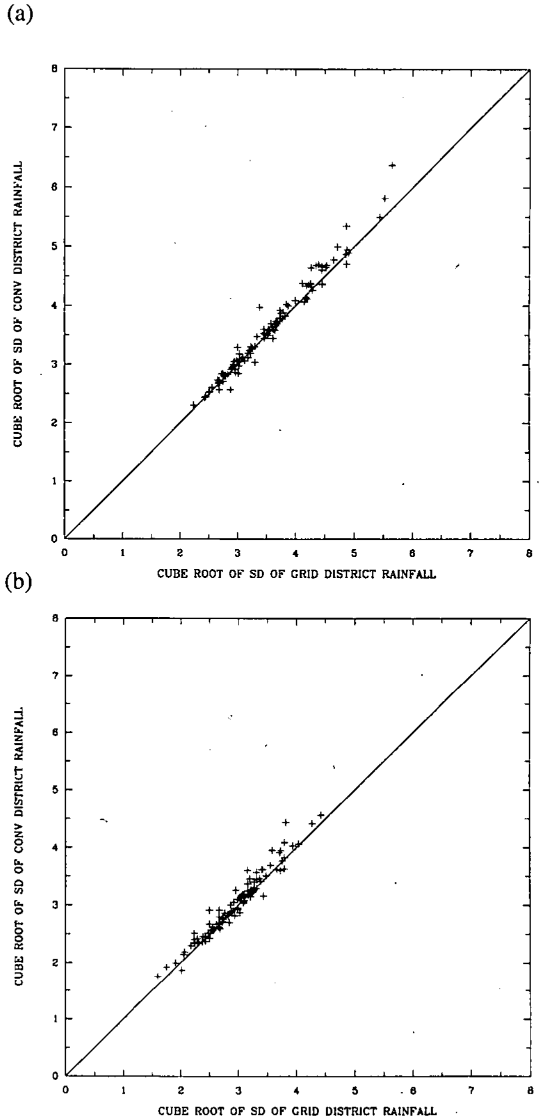
Comparison of the temporal variability of district rainfall

Standard deviations

To compare the variability of district totals about their long-term means the temporal standard deviation of the monthly district totals about their long-term means for January and July for the two datasets is shown in Fig. 8. Supporting the earlier findings, the temporal standard deviations of the monthly totals are broadly similar, differing by an average of 5 mm during January and 3 mm in July. These values indicate that in the mean the monthly standard deviation of rainfall for the two sets differ by just ten per cent of the average standard deviation.

A notable feature of this comparison is a general bias of the populations, with the standard deviations being mostly less in the gridded data. The mean bias during January is 4 mm, while that during July is near 2 mm, with the standard deviation being nearly ten per cent less in the grid district data. The tendency is similar in summer and winter, with the standard deviation being about seven per cent greater in the conventional data. These observations suggest that a large component of the difference in standard deviations is systematic in nature, and due to slightly greater variability in the conventional data. This in turn is reflected in the tails of the rainfall distributions (as measured by the 10th and 90th percentiles; Fig. 7) which tend to be a little longer in the conventional district data.

Fig. 8 **The temporal standard deviation of the monthly mean rainfall for each of the 107 districts for the gridded and conventional datasets. (a) January and (b) July.**



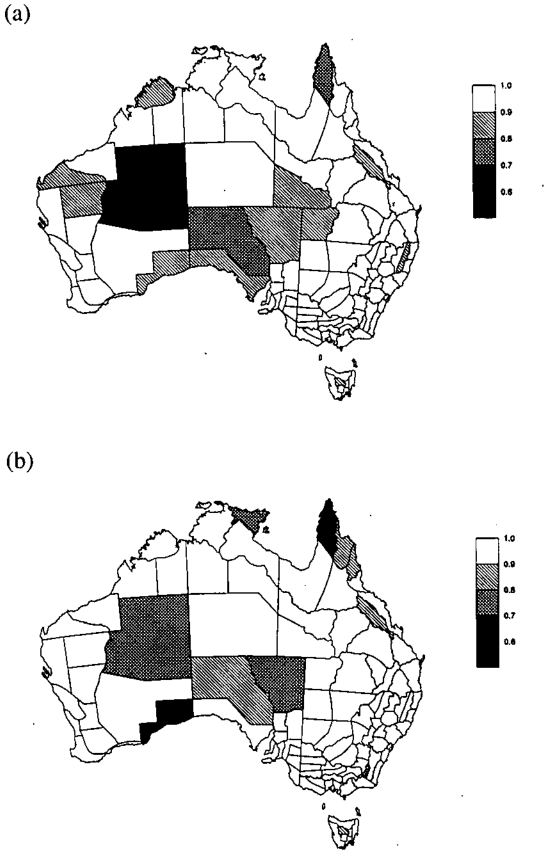
One obvious reason for this systematic difference is the use of more observations in the grid-derived data, and thus a reduction in the time variance due to local variations at stations. Another possible influence is the filtering effect of spatial analysis on small-scale structures. It is noteworthy that the Barnes analysis procedure filters those components of the field which are undersampled by the observational network (Koch et al. 1983), and which could be expected to be largely cancelled in an area average if sufficient stations were available. The conventional district totals do not possess such a filter and might be expected to over-estimate the temporal variability of the spatial (district) averages due to the lower spatial sampling and hence a greater amount of noise due to local non-representative variability (noise) at stations. It is not possible to unambiguously determine which of the standard deviation estimates is the more accurate, however, the small difference in most cases means this is not critical, while the superior physical basis to the digital analyses would seem to favour them as the more reliable data.

Correlations

To gauge the similarity of the temporal variations of district rainfall about the monthly mean the geographical distribution of the time-synchronous correlation coefficient of the conventional and district rainfall totals for January and July is shown in Fig. 9 . For most districts there is a very high similarity in time series of the monthly totals and this is indicated by correlations which are mostly greater than 0.9 and average 0.95 in both months. Stratifying the correlation coefficients by district, it is apparent that 92 and 96 of the 107 districts in January and July, respectively, have correlations greater than 0.9.

Geographically, districts with the lowest correlation coefficients mostly occur in the central subtropics. These districts tend to be large and poorly observed by the rain gauge network (*vide* Jones and Weymouth 1997). In addition, gauges tend to be clustered within these districts and frequently occur along major transport routes, meaning a representative district total is difficult to derive using the conventional technique. *A priori* one would expect the arithmetic mean approach applied to the generation of the conventional district totals to perform proportionally worse in the more poorly sampled districts. It is very likely that the new analyses, which are able to make use of neighbouring district observations and more appropriately weight station contributions to the district totals, provide a more accurate description of the true variability. Correlations less than 0.8 occur in districts 13, 16 and 27 during January, and 11, 13, 14BC, 17, 27 and 71 during July. Of these districts, the low correlations in districts 11 and 71 are largely due to anomalous trends in the conventional district totals during the first 30 years of this study, most likely due to the establishment of new stations. In the remaining districts the lower correlations are due to non-systematic differences in the time series for the two sets.

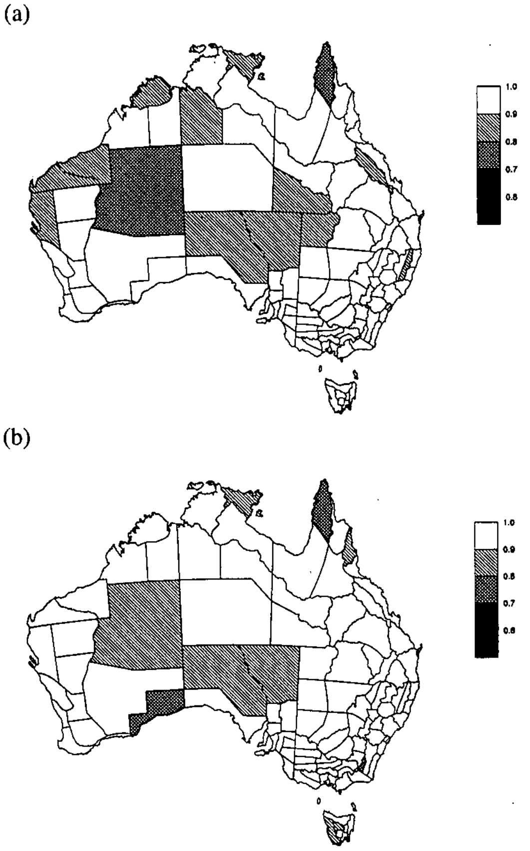
Fig. 9 **The geographical distribution of the correlation between monthly district totals in the gridded and conventional datasets. (a) January and (b) July.**



The equivalent correlation figures for the summer and winter seasons are shown in Fig. 10. With few exceptions, those districts with relatively low correlations in January and July correspond to those with relatively low correlations in winter and summer.

Correlations below 0.8 for the seasonal data are confined to districts 13 and 27 during summer, and 11, 27, and 71 during winter. In districts 11 and 71, the relatively poor correlations are again due to anomalously high rainfall during the early part of the conventional district record, which seems to be due to under-sampling of lower rainfall regions in the station network. In districts 13 and 27, the poor correlations are due to erratically varying differences between the respective time series.

Fig. 10 **The geographical distribution of the correlation between seasonal district totals in the gridded and conventional datasets. (a) Summer and (b) winter.**



Comparison of individual districts

The foregoing analysis has revealed that the conventional district totals provide a mostly satisfactory estimate of the mean rainfall and rainfall variability for districts. However, there have been a number of districts highlighted for which the rainfall climate and variability defined by the two sets differ appreciably. For the most part, the district totals agree best in those regions which are well sampled, or which possess relatively homogenous rainfall patterns. Among those districts where marked difference have been noted, we will examine more closely district 32 which is on the tropical Queensland coast, and districts 96 and 97 in Tasmania.

District 32

District 32 on the north Queensland coast is climatically one of the most varied of the rainfall districts with mean annual rainfall varying by an order of magnitude between the southwest and northeast. It is also the district where differences between the conventional and grid-derived district totals tend to be the largest, particularly during the summer (wet) season. This is evidenced by the MAD between the two sets of district rainfall which is 91 mm in January, a value nearly double the next greatest difference (57 mm in district 1). A large component of this difference is systematic in nature and reflects a marked difference in the mean climate, with the conventional data having a 1913 to 1995 mean of 374 mm compared to 285 mm in the grid-derived set.

To investigate further the rainfall climate in this district, a series of regional analyses have been performed using the Barnes technique applied to station mean totals, and also using the thin plate spline technique of Hutchinson (1991) which has been found to be highly skilful in analysing rainfall in high-gradient topographically varying regions (Hutchinson 1995). The distribution of January mean rainfall for the region about district 32 is shown in Fig. 11, derived using the thin plate spline technique with a high resolution 0.1° x 0.1° topography grid applied to those stations with rainfall records of 30 years or more. This shows the large variability of rainfall across this district, with a marked southwest to northeast gradient. The distribution of the available climate stations (30 years or more of data) is overlayed on this figure, which demonstrates a marked bias of stations toward the high rainfall coastal strip.

The thin plate spline technique has been applied at a grid resolution of 0.1° x 0.1° and 0.25° x 0.25° with and without topography using long-term (30 years or more) stations means, while an additional analysis has been performed using the Barnes technique on a 0.25° x 0.25° grid with the climate station means. The results of this analysis (shown in Table 2) indicate that all estimates of the district average rainfall based on the gridded data are significantly less than the 374 mm mean of the conventional series. Notably, despite the known bias of stations towards the relatively wet coastal fringe, the mean of the 48 stations in district 32 with 30 years or more of records (1913 to 1995) is 364, some 10 mm less than the conventional district total. These results strongly suggest that the conventional total for district 32 is biased high by the over-sampling of the high-rainfall coastal region. These observations highlight the difficulty in generating district totals through the meaning of individual station reports in districts with great spatial variability.

It is noteworthy that while each of the digital analyses covering the district are credible and qualitatively similar, there is considerable variability between these estimates of the mean rainfall across the district, which can be largely attributed to the tightness of the rainfall gradient. This variability between each of the sophisticated estimates of area-averaged rainfall highlights the difficulty of analysing rainfall in regions of very high spatial variability and suggests that area averages should be treated with some caution.

Fig. 11 Long-term mean January rainfall for the region around district 32, calculated using trivariate thin plate splines on a 0.1° x 0.1° latitude longitude grid. Overlayed is the distribution of stations with 30 years or longer of records (1913-1995) which have been used to generate the analysis.

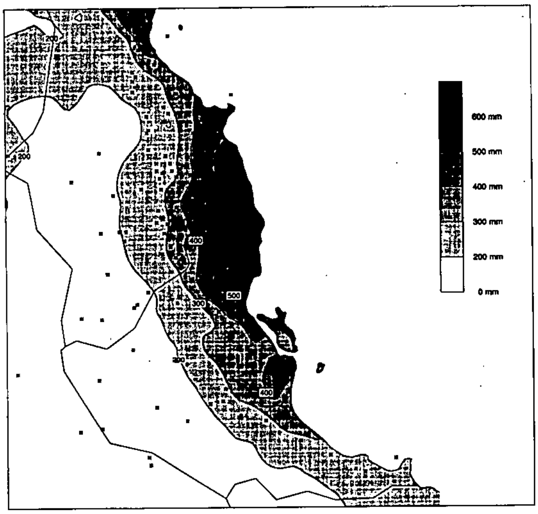
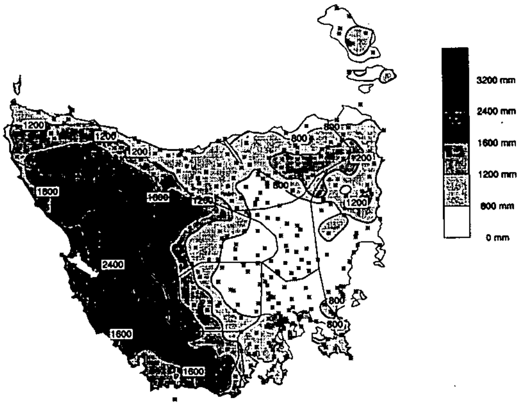


Table 2. Mean January rainfall for district 32.

District total	*January mean rainfall (mm)*
Conventional	374
Mean of stations	364
Grid	285
Barnes analysis of station means	289
Spline 0.25° x 0.25° no topography	301
Spline 0.25° x 0.25° with topography	270
Spline 0.1° x 0.1° no topography	300
Spline 0.1° x 0.1° with topography	269

Fig. 12 Long-term mean annual rainfall for western Tasmania, calculated using trivariate thin plate splines on a 0.1° x 0.1° latitude longitude grid. Overlayed is the distribution of stations with 30 years or longer of records (1913-1995) which have been used to generate the analysis.



District 96

District 96, comprising the central plateau of Tasmania, displays a marked east-west gradient in rainfall with annual mean rainfall varying from less than 800 mm near Waddamana to about 3000 mm in the west. This is demonstrated in Fig. 12 which shows the climatological mean annual rainfall for Tasmania generated using the thin plate spline incorporating topographical variations on a high resolution 0.1° x 0.1° grid. For reference the positions of all the stations with 30 years or more of rainfall records, which have been used to generate this analysis are overlayed.

Chappel (1995) has demonstrated that the conventional district 96 totals for the annual period display a marked upwards trend from 1913 to about 1950, which can be largely ascribed to changes in the station coverage across the district. To further investigate this rainfall increase, the ten-year mean annual rainfall for the conventional and gridded sets for the period 1913 to 1995 is shown in Fig. 13. This figure confirms the results of Chappel (1995), with a marked increase in the conventional district rainfall, particularly from 1930 to 1950. The district series generated using the gridded totals shows little evidence of this largely artificial trend (which has little support in station totals, Chappel 1995), indicating that the technique of first performing an analysis and then determining district total rainfall has acted to significantly reduce the impact of station variations on the district rainfall total. The results of this analysis clearly demonstrate the advantages of first modelling the rainfall field, in that the contributions of stations are weighted according to their density (and hence the amount of independent information they contain), as well as allowing the use of stations in neighbouring districts to diagnose the rainfall gradient across districts.

Fig. 13 Time series of the ten-year running mean of district 96 annual rainfall, for the conventional and grid district totals.

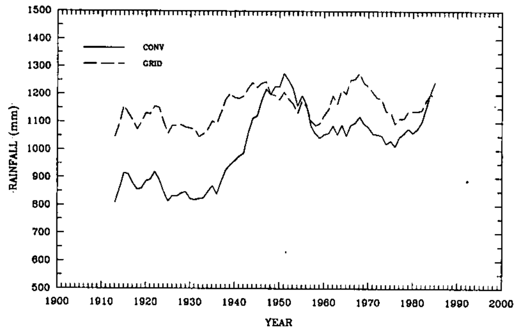
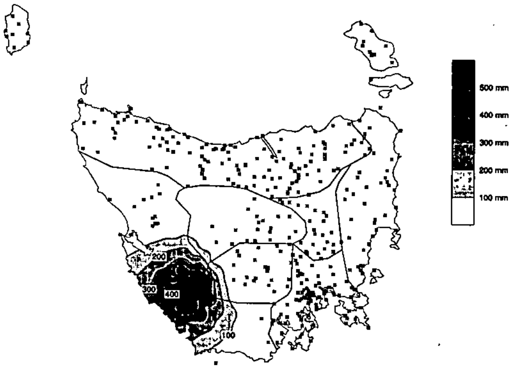


Fig. 14 The impact of Strathgordon on an analysis of the long-term mean annual rainfall in Tasmania using the thin plate spline on a 0.1° x 0.1° latitude-longitude grid.



District 97

The absence of long-term rainfall stations in the southwestern half of district 97 combined with the relatively low rainfall at Maatsuyker Island off the southwest coast makes modelling of the rainfall field in the southern half of district 97 problematic. Each of the analysis techniques which have been investigated, including the Barnes and thin plate spline technique (applied in either two or three dimensions), seriously underestimate the rainfall across the southern half of the district, when only those stations with long records (greater than 30 years) are used. The severity of this underestimation is highlighted by the mean annual district rainfall based on the conventional district series which is 2320 mm, compared to 1588 mm for the grid-derived series. The relatively high value of the conventional district mean rainfall reflects the clustering of long-term stations in the high rainfall area near Queenstown. The underestimation is mitigated when stations with relatively short-term records are included (such as Strathgordon with 27 years of records), however, such information is largely absent from the station lists used to generate the monthly historical series of grid-based district totals.

To demonstrate the severity of the problem of analysing in the southern half of district 97, a test has been made of the impact of including Strathgordon (with 27 years of records) on an analysis of the annual mean rainfall, where all other used stations have 30 years or more of station data. Figure 14 shows the impact of Strathgordon on the mean annual rainfall derived using the thin plate spline on a high resolution 0.1° x 0.1° grid. Regionally, differences are greater than 500 mm near Strathgordon, while differences greater than 100 mm extend across nearly half of the district. These differences indicate the severity of underestimating southwest Tasmanian rainfall based on the spatially limited climate stations. These results suggest that considerable caution should be exercised when using rainfall analyses in south west Tasmania, and particularly when using district totals.

Discussion and conclusions

In this study we have made use of high quality digital rainfall analyses to gauge the veracity of the conventional district totals in defining the climatology and variability of rainfall in districts. This analysis has shown the conventional district data generated in an operational environment to be, for the most part, reliable, despite the relatively simple nature of their generation.

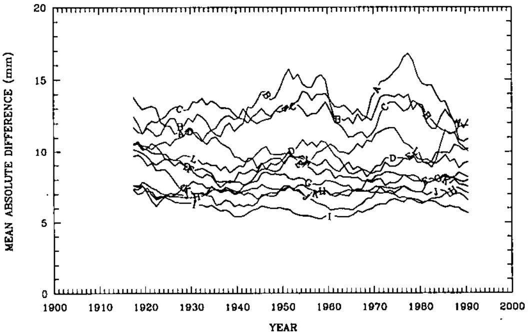
The MAD between the grid and conventional rainfall data has been shown to be near 13 mm during January and 8 mm during July, being some 17 per cent of the district mean rainfall on average. During summer and winter the equivalent values are 27 and 21 mm, and the percentage differences are 12 and 14 per cent, respectively.

The difference between the district totals for individual months and seasons has been shown to be due to differences in district mean rainfall climate, differences in the amount of time variance (standard deviations), and differences in the phase of temporal variations (correlations; *vide* Murphy 1995). To further aid in the interpretation of these results the relative contribution of differences in mean climate and differences in variations about the mean climate in determining the difference between the conventional and gridded district totals has been examined using the mean square difference. This measure allows the unique partitioning of differences in simultaneous district rainfall totals between the contribution due to differing time mean rainfall (i.e., mean climates) and that due to differences in the variations of the district rainfall series about their respective climate means (Murphy 1988). This has shown that for monthly and seasonal totals it is differences in the time variations about the respective district means, rather than differing time means which is most responsible for the difference between conventional and grid district totals. During January the difference in mean climates is the primary determinant of the total difference in only four of the 107 districts, namely, districts 14GA, 91, 95 and 97. During July the value is 16 districts, while during summer and winter the respective values are 12 and 31. The increased importance of the difference in means in determining the difference between district totals at longer times reflects the fact that the difference in means tends to be systematic in nature and is not significantly reduced through averaging, whereas a significant component of the difference due to non-similar variations about means is non-systematic and tends to be reduced through the time averaging. This is further evidenced by annual data for which differences in means is the primary factor in determining the difference between the annual district totals (as measured by the mean square difference) in 37 districts. Given the quality of the digital analyses, these findings reveal that the conventional district totals are generally less accurate in the description of the temporal variations of district rainfall than they are in the description of the mean rainfall climate of districts.

A question which arises from this study is whether the MAD values (representing the difference between the conventional and grid district totals) have changed during the period of study. Figure 15 shows the ten-year running mean of the MAD for each of the calendar months averaged across all districts. This figure suggests that there has been rather little variability in the MAD during most months, with a possible decrease during the winter half-year. In contrast, the MAD curves during January, February, and March are each suggestive of a slight increase in the MAD, however, this would appear to be largely an artifact of higher values during the 1950s and 1970s during which times the mean rainfall was also somewhat increased *(vide* Nicholls et al. 1997). This figure suggests that the overall quality of the conventional district totals has not changed significantly during the period of study.

A comprehensive analysis has been performed of the causes of differences between the grid-derived district totals and those of the conventional set on a district-by-district basis, and a subset of these results has been shown for districts 32, 96 and 97. This analysis has shown that the use of numerical analysis schemes to model the rainfall distribution across districts is advantageous compared to the conventional technique in that it can reduce biases which are due to the under-sampling of certain climate regimes in districts, and can reduce artificial trends in district rainfall totals due to the temporal variations in the distribution of stations. The results of this analysis are applicable across a wide number of districts which show large differences between the conventional and grid-determined district totals, including districts 11, 27, 71 and 91.

Fig. 15 **Time series of the ten-year running mean absolute difference between monthly district totals in the gridded and conventional datasets for each calendar month. A-January, B-February, etc.**



A general observation of this study has been that deficiencies in the conventional district totals are mainly due to insufficient sampling (stations) across districts, or biases in the distribution of stations in districts. These effects are generally reduced through the analysis of station totals to form rainfall grids from which district totals may then be computed. It is likely, however, that past and present shortcomings in the station network preclude the accurate estimation of district rainfall using either the conventional or gridded sets for a number of districts. This is particularly the case for the remote and poorly observed districts 13 and 97.

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