Climatological Rainfall Analyses for Southeast South Australia

by

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Contents:

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1. Summary

This report describes the analysis of climatological mean rainfall in southeast South Australia, on monthly, seasonal and annual time scales. It represents the results of a project commissioned by the South Australian Department of Water, Land and Biodiversity Conservation (DWLBC) in collaboration with the Australian Bureau of Meteorology. For the region of concern, it updates the national climatological analysis undertaken by the National Climate Centre in the *Climatic Atlas of Australia – Rainfall* project (Bureau of Meteorology 2000). In this respect, it uses an updated climatology period (1971 – 2000), a finer resolution analysis scale, an improved digital elevation model, and a greater range of available rainfall data.

The region chosen for analysis was the 6°×6° region from 33°S to 39°S and 136°E to 142°E. This included a buffer zone of 0.5° on all four sides, so that the final analyses are provided on the 5°×5° region from 33.5°S to 38.5°S and 136.5°E to 141.5°E. After consideration of a range of possible analysis resolutions, a resolution of 0.01° (approximately 1 km in the north/south direction and 0.8 km in the east/west direction) was adopted. The analyses use a combination of actual and estimated station data. The estimated station data, arising from rainfall data outside the climatology period (1971 – 2000), comprise around 20 to 25% of the combined network, and provide a useful filling of gaps in the primary network of directly observed station data.

Cross-validation experiments on the annual analysis indicate an uncertainty of approximately 5%. Investigations into model biases indicate that the biases do not appear to be significant. There does appear, however, to be a tendency for the model to slightly underestimate (overestimate) rainfall on the wetter western (drier eastern) slopes of the Mt Lofty Ranges. This indicates that the analysis is slightly smoother in the region of the ridge top than the limited observational data might suggest.

The project outputs are

- a final report (this document),
- 13 (annual and monthly) directly analysed 0.01°×0.01° grids in ASCII format, supplemented by 6 seasonal grids obtained by summation of the monthly grids;
- maps for these 19 periods, with an addition version of the annual map featuring an expanded contour set.

2. Analysis Region

The region specified by DWLBC for consideration consists of three spatial tiles.

- Kangaroo Island.
- Fleurieu Peninsula and adjacent areas west of 139°40′26″E between 34°07′51″S and 35°40′36″S.
- The Southeast and adjacent areas between 138°51′50″E and 140°58′36″E and south of 35°20′11″S. This tile overlaps to some extent the Fleurieu Peninsula tile.

Preliminary analyses at 0.025°×0.025° resolution indicated that it was feasible to analyse these three regions as a single combined region. Therefore an *analysis region* of 33°S to 39°S and 136°E to 142°E was chosen. This represents the smallest rectangular latitude/longitude box surrounding the three spatial tiles, with a buffer of approximately 1° on the eastern and northern sides and slightly more than 0.5° on the southern and western sides. The inclusion of these buffers was to avoid any potential edge effects that might have arisen in the analysis process. Under the terms of the project, analysis grids covering the 5°×5° region 33.5°S to 38.5°S and 136.5°E to 141.5°E are supplied in the project outputs.

3. Analysis Periods

Thirteen climatological periods were analysed directly. These are annual, and the twelve calendar months (January, February, …, December). Climatological averages for six additional periods have been generated by summation of the climatological monthly grids. These six additional periods are the seasons

- summer (December to February),
- autumn (March to May),
- winter (June to July),
- spring (September to November),
- wet season (May to November), and
- dry season (December to April).

The monthly and annual averages described in this report are calculated over the 30-year period 1971 to 2000, contrasting with the World Meteorological Organization (WMO) standard period of 1961 to 1990 (WMO 1989), used in the *Climatic Atlas of Australia – Rainfall* project (Bureau of Meteorology 2000).

The annual analysis was performed directly on annual data. It was not obtained by summation of the monthly grids (unlike the six seasons referred to above), and comparison between the annual analysis and the summation of the monthly analyses formed an important aspect of the quality control. The authors believe that the analysis of annual totals gives a better representation of the climatological annual rainfall than would be obtained from the summation of the corresponding monthly analyses.

4. Data and methods

The analysis technique used in the project is a three-dimensional thin-plate smoothing spline method (Hutchinson 1995), using code developed by Professor Michael Hutchinson (presently at ANU CRES), subsequently modified by the National Climate Centre (NCC). Prof. Hutchinson's code is called *ANUsplin*. This analysis technique is the same one that was used in the revision of the *Climatic Atlas of Australia – Rainfall* (Bureau of Meteorology 2000). It uses latitude, longitude and elevation as explanatory variables. Paraphrasing from the *ANUsplin* documentation, the spline technique is a least squared error minimisation technique, where the minimisation is subject to a penalty constraint on the smoothness of the fitted model. [Smoother (rougher) models fit the data less well (better).] The coefficient on the smoothness penalty function is determined by minimising a measure of predictive error of the fitted surface given by the generalised cross validation (GCV). The GCV is calculated for each value of the smoothing coefficient by implicitly removing each data point and calculating the residual from the omitted data point of a surface fitted to all other data points using the same value of the smoothness coefficient. The GCV is then a suitably weighted sum of the squares of these residuals.

Monthly rainfall data was extracted from the Australian Data Archive for Meteorology (ADAM) for all Bureau of Meteorology rainfall districts contained entirely or partially within the analysis region.

Primary data sets

This extraction comprised rainfall districts 18-26 (SA), 47 (NSW), 76-79 and 90 (Victoria) shown in Figure 1, and all monthly rainfall records from 1800 to the present (effectively 2004). Following the WMO standard, an initial criterion of at least 25 years in the 30 years of 1971-2000 was used to construct climate averages (*i.e.*, monthly and annual rainfall averages) for the 13 analysis periods. This resulted in *primary data sets* of around 700 stations (701 for the annual data, with the monthly data sets ranging from 709 to 714 stations). On restriction to the analysis region (something performed automatically by the *ANUsplin* analysis code), there were 444 stations in the annual data set, with the monthly data sets ranging from 444 to 446 stations. Any station where the record was sufficient to generate at least one climate average (out of the possible 13) was sufficient to ensure membership of the primary network.

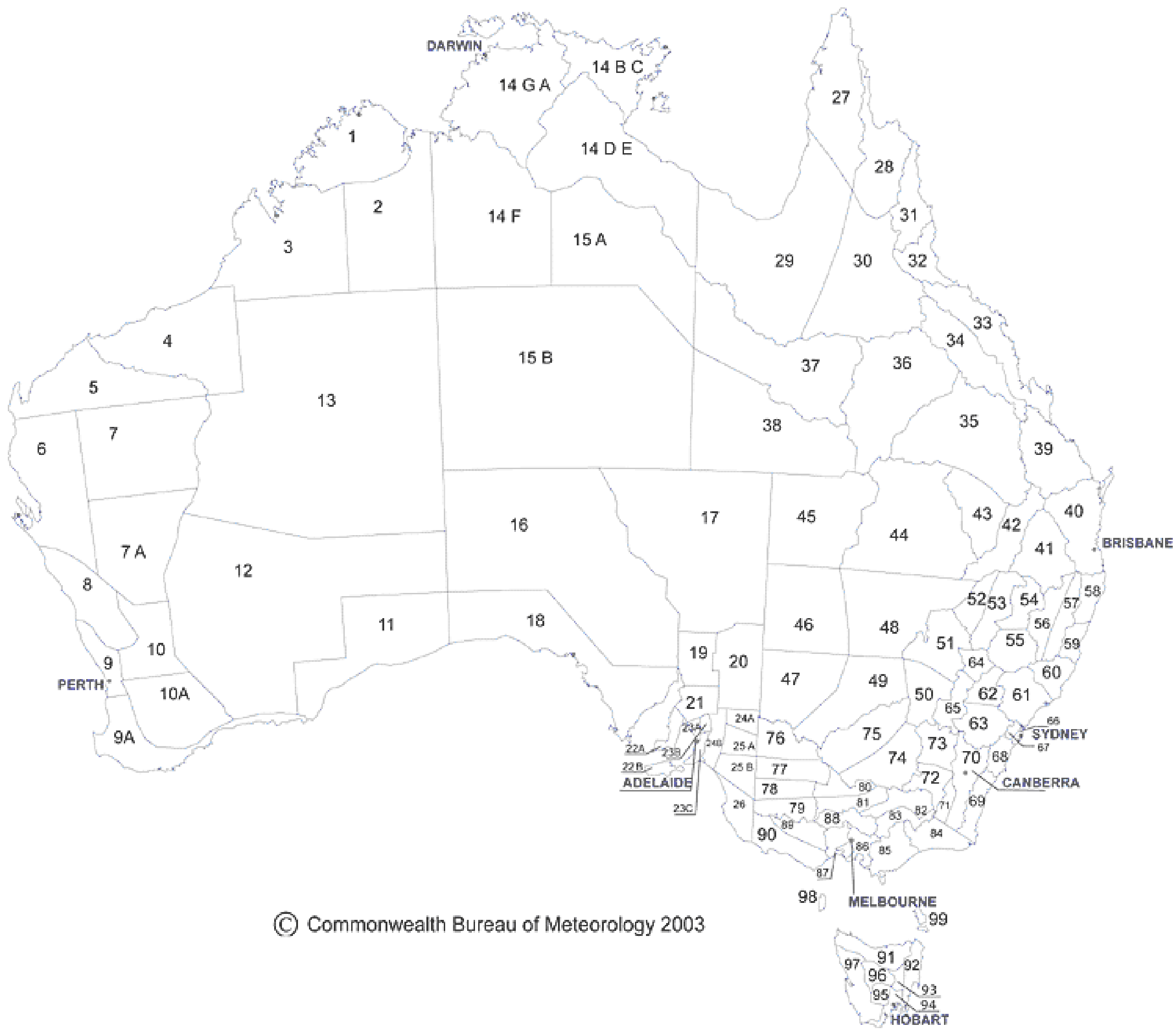


Figure 1: Map of Bureau of Meteorology Rainfall Districts

Not all stations in the primary data set have complete sets of averages (*i.e.*, 13 averages). To maintain quality of the input data, single missing averages were not inferred by addition (in the case of a missing annual averages) or subtraction (in the case of a missing monthly average), nor were missing average infilled from neighbouring stations, except in a very limited set of circumstances (discussed subsequently).

Secondary data sets

To supplement the primary network, all other stations within the analysis region were considered as potential members of a secondary network. The criteria for membership of the secondary network were as follows.

- The station could not be a member of the primary network.
- It had to be open (*i.e.*, measuring monthly rainfall) and reporting (those observations to the Bureau) for at least one month in the period 1971 to 2000.
- It had to have been open and reporting for at least 25 years (although not necessarily consecutively so) in its history.
- Searches were made amongst the nearest six stations from the primary network as suitable candidates for a regression-based approach for infilling of missing data.

For each secondary station, only one primary station (of the six nearest) was used as a regression predictor, the same primary station being used for all analysis periods. Although searches were made from amongst the nearest six neighbouring primary network stations, in the majority of cases, the chosen candidate was one of the nearest three such stations.

Missing monthly/annual values in the various time series of the secondary station were infilled on the basis of a linear regression against this neighbouring primary station. A standard two-parameter linear regression was used for the annual values, and one-parameter regressions with fixed zero intercepts were used for the monthly values (see appendix 1 for further details on linear regression). This has the effect of preserving regions of zero monthly rainfall for individual calendar months, and avoids potential negative estimates for such months. A minimum coefficient of determination of 0.75 was required (likewise, see appendix 1 for further details), arising from at least 25 years worth of overlapping data (between the secondary station and neighbouring primary station). When two or more suitable neighbouring primary stations were available, a subjective choice was made based on a trade-off between nearness of the neighbouring stations, strengths of the various correlations and completeness of the estimated averages. A minimum of 25 years' worth of combined original and infilled or synthetic data within the 1971-2000 period was used to generate the secondary station estimates. This minimum was chosen for consistency with the WMO standard applied to the primary network. The linear regression approach described here has the effect of preserving the interannual variability of the 1971-2000 period. The approach yielded 138 extra annual stations, with the monthlies ranging from 130 to 156 extra stations. As with the primary data set, missing averages were generally not inferred by addition/subtraction.

Period	Total Stations	Primary Stations	Secondary Stations
Annual	839	701	138
January	842	712	130
February	857	713	144
March	851	711	140
April	862	712	150
May	862	714	148
June	865	713	152
July	853	711	142
August	851	710	141
September	865	710	155
October	867	711	156
November	850	711	139
December	832	709	123

Table 1: The breakdown of numbers of primary, secondary and total stations in the initial data extraction from ADAM.

Preliminary discussions about the project raised the possibility of using additional data records from 'hydrological' networks maintained by the Bureau and/or DWLBC. Data sets from these networks were considered, but all records were shorter than the required 25 years and could not be integrated into either the primary or secondary data sets covering the 1971-2000 period. The longest extractable series from these data was 16 years, with the rest typically being quite a bit shorter.

Even though the initial data extraction covered all stations in the listed districts, the analysis procedure automatically excluded all stations outside the analysis region. In the case of stations co-located to two decimal places in degrees latitude and longitude all but one station are deleted from consideration. Some stations in ADAM do not have elevations recorded. These were also excluded from consideration, as the analysis procedure makes direct use of the station elevations. The resulting network had 571 stations for the annual data set, with the monthly networks ranging from 561 to 589 stations. This represents monthly enhancements of 26% to 33%, and a 29% enhancement for the annual data set.

Period	Combined	Primary	Secondary	Enhancement
Annual	571	444	127	29%
January	564	444	120	27%
February	579	445	134	30%
March	576	445	131	29%
April	584	445	139	31%
May	581	445	136	31%
June	586	445	141	32%
July	577	445	132	30%
August	576	444	132	30%
September	586	444	142	32%
October	589	444	145	33%
November	573	444	129	29%
December	561	444	117	26%

Table2: Numbers of stations in the various combined data sets actually used in the analysis process are listed in the table. Percentage enhancements of the network from the primary stations to the combined stations are rounded to the nearest integer.

The generation of the synthetic data was quite useful in filling gaps in some parts of the analysis region (see Figure 2). Nevertheless there remain some data gaps for which there simply weren't available data. These gaps include the Ngarkat and Mount Rescue Conservation Parks in SA, the Murray-Sunset and Wyperfeld National Parks and the Big Desert Wilderness Park of Victoria.

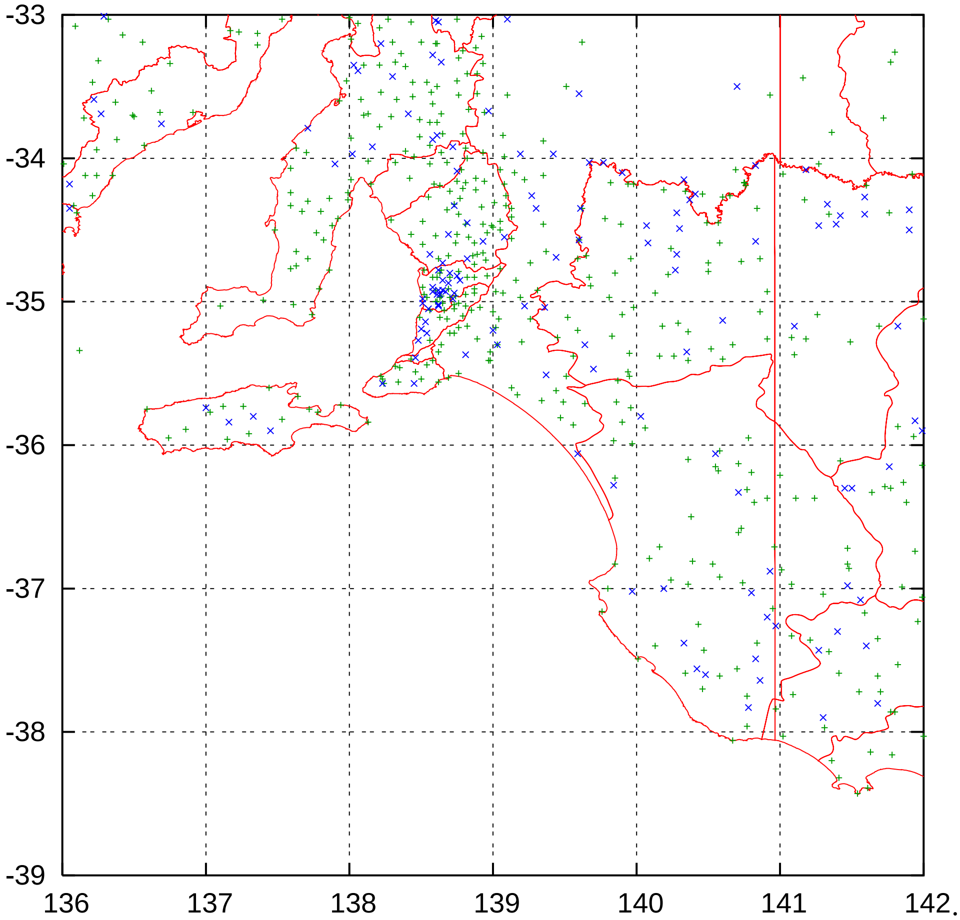


Figure 2: The annual data set with primary stations in green crosses (+) and the secondary stations in blue (×). The red lines indicate coastal boundaries and river basin boundaries (data from Geoscience Australia). Large gaps in the network coincide with National, Conservation and Wilderness Parks.

5. Analyses

Preliminary analyses were performed on the combined data sets, using a 0.025° digital elevation model (DEM) from the Australian National University (ANU), the same one used in the *Climatic Atlas of Australia – Rainfall* project (Bureau of Meteorology 2000).

Subsequently, a newer 0.01° DEM was derived from 0.0025° (250 m) digital elevation model obtained from the ANU's Centre for Resource and Environmental Studies (ANU-CRES). The 0.0025° DEM was sub-sampled to 0.01° for ease of handling. The 0.01° sub-sampling feeds directly in the analysis process. It is mapped in Figure 3 (at 0.02°) for illustrative purposes.

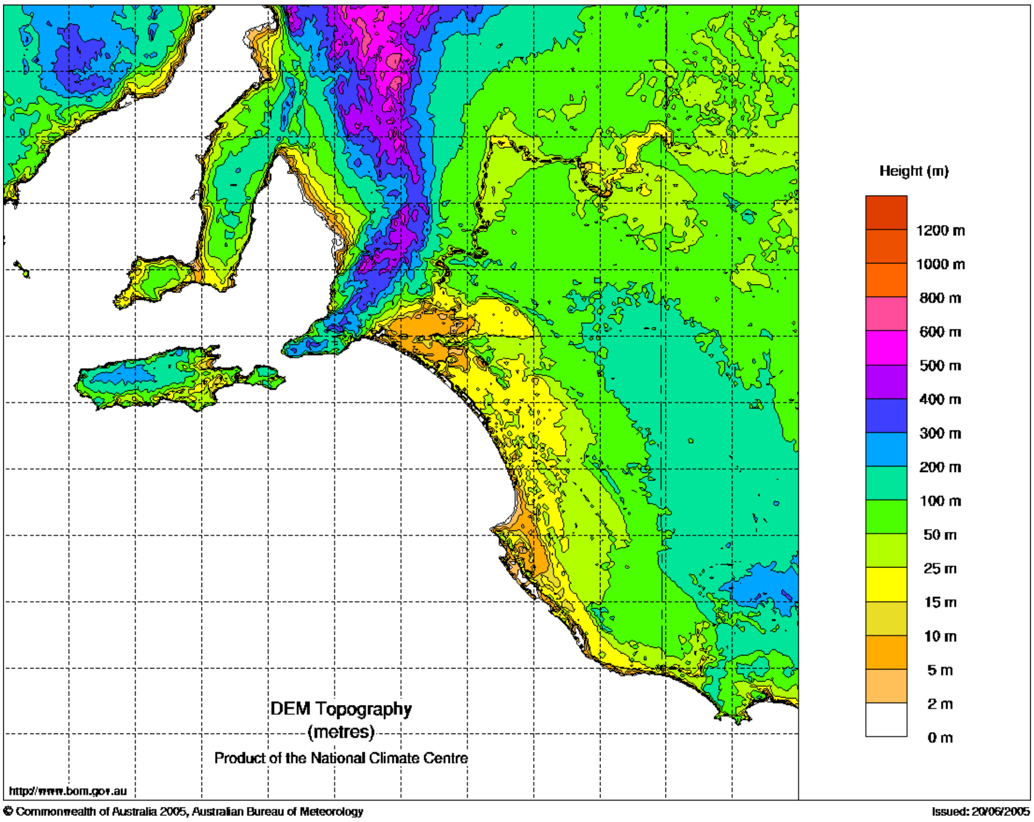


Figure 3: A mapping of the elevation of the analysis region. Topography has been sub-sampled to 0.02° for display purposes. Units are m.

An investigation at multiple resolutions (resolutions of 0.01°, 0.02°, 0.03°, 0.04°, 0.05°, 0.06°, 0.08°, *etc.*) suggested that 0.02° was the optimal resolution, although there was evidence of a secondary minimum in the mean absolute error (MAE) at 0.04°.

Cross-validation

The cross-validation experiments involve leaving out approximately 1% of the network at a time, analysing the remaining stations, interpolating the grids to the outsorted station locations (using a bi-cubic polynomial interpolation process), and accumulating error statistics on the discrepancies. [The selection of each 1% (five or six) to be left out was not done on a random basis, instead being uniformly spaced though the data list. This ensured that the omitted stations were widely separated. The cross-validation process therefore involved slightly less than 100 re-analyses.] For the coarser resolutions, the DEM was sub-sampled to the resolutions required rather than being averaged.

Given the small impact on the analysis accuracy (see the discussion on the MAE and RMSE statistics below) and after consultation with the Bureau's South Australian Regional Office (SARO) and DWLBC representatives attending the March 2005 meeting, it was agreed that analyses at the requested 0.01° resolution would be provided, as this involves only a slight degrading of the overall analysis accuracy. The results that would be obtained by analysing at 0.02° resolution can be obtained from the 0.01° resolution analyses simply by sub-sampling every second grid point in both directions.

The independent cross-validation experiment results are given in the table below for a range of resolutions. These resolutions are those multiples of the base resolution (0.01°) of the DEM which are also commensurate with the analysis region being a 6°×6° box. The two error statistics used were Mean Absolute Error (MAE) and Root Mean Square Error (RMSE). The cross-validation experiment was only performed on the annual data set.

Resolution	Count	MAE (mm)	RMSE (mm)
0.01°	570	23.397	32.859
0.02°	570	23.096	32.443
0.03°	570	23.695	33.346
0.04°	570	23.346	33.438
0.05°	570	23.373	33.633
0.06°	570	24.423	34.463
0.08°	570	25.057	35.910
0.10°	570	25.480	36.904
0.12°	570	27.839	42.150
0.15°	570	30.624	45.594
0.20°	570	32.241	52.805
0.25°	570	36.365	57.430

Table 3: Average mean absolute (MAE) and root mean square (RMSE) errors for the independent cross-validation of the annual analysis. The various analysis resolutions are commensurate with the underlying DEM resolution and the size of the analysis region.

6. Annual/Monthly Discrepancy Comparison

Since the analyses of the thirteen periods are statistically independent procedures, the difference between the annual analysis and the sum of the monthly analyses was investigated. The result is mapped in Figure 4 (sub-sampled to 0.02° from the 0.01° grid).

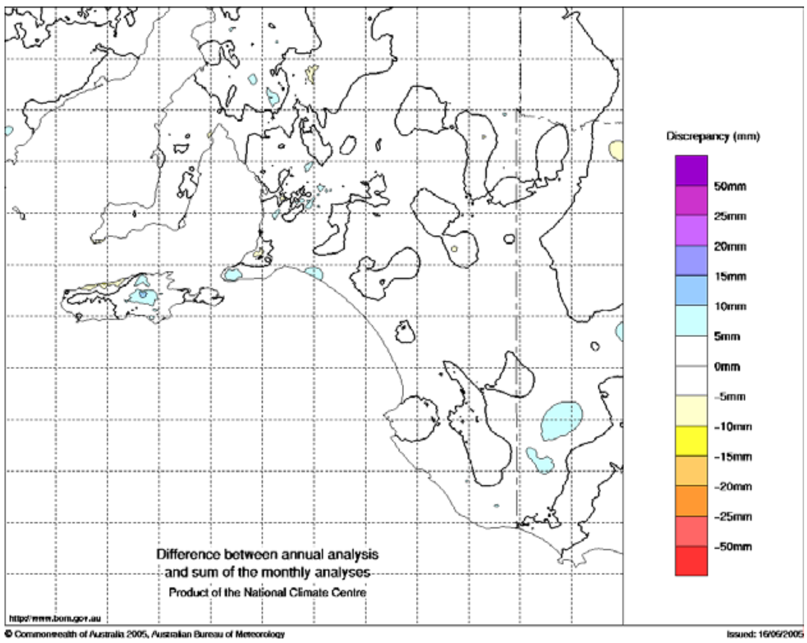


Figure 4: The difference between the annual analysis and the sum of the independently generated monthly grids. Units are mm.

The discrepancies arise mainly from the fact the data sets have not been restricted to stations with complete sets of averages. Rather than degrade the network considerably by removing all stations with incomplete sets of averages, a close inspection was made of all secondary stations in the vicinities of the major discrepancies. An iterative process led to the deletion of 12 secondary stations and the adjustment of 5 other stations – either by computing missing averages inferred by addition/subtraction, or using other primary stations in the regression process. The adjustment of these 5 stations represents the only infilling of missing climate averages attempted. The resulting discrepancies (less than 5 mm in magnitude over the vast majority of the analysis region) are thought to be sufficiently small to ignore. The statistics for the final data sets used in the analyses are given below.

Period	Combined	Primary	Secondary	Enhancement
Annual	570	444	126	28%
January	560	444	116	26%
February	574	445	129	29%
March	569	445	124	28%
April	578	445	133	30%
May	573	445	128	29%
June	580	445	135	30%
July	572	445	127	29%
August	572	444	128	29%
September	579	444	135	30%
October	582	444	138	31%
November	568	444	124	28%
December	558	444	114	26%

Table 4: Numbers of stations in the various combined data sets actually used in the analysis process. Percentage enhancements of the network from the primary stations to the combined stations are rounded to the nearest integer.

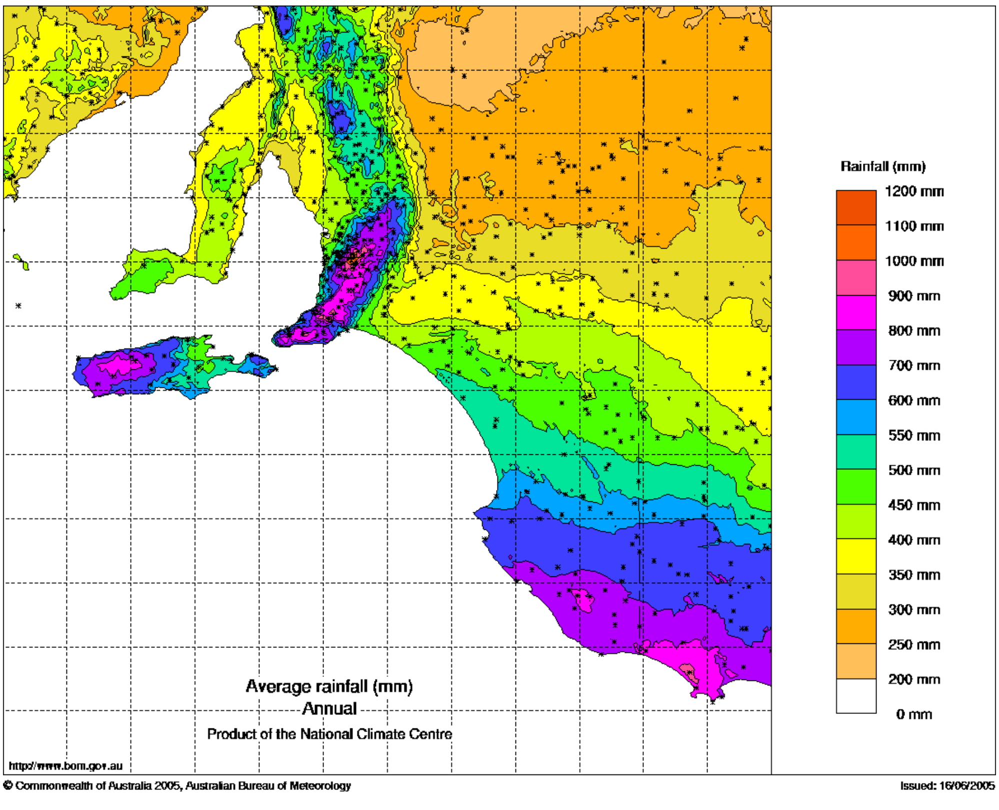
7. Analysis of Uncertainty and Bias

As part of the analysis procedure, biases were calculated across stations. These are the differences or discrepancies between the station rainfall (at station elevation) and the model rainfall at station elevation (note that the resulting analysis grid is model rainfall at model elevation). These biases may be either positive or negative. The absolute value of these biases (commonly called the "mean absolute error") gives the difference between observations and interpolated values as a positive number (an unsigned discrepancy).

The absolute values of the analysis biases are also analysed using the three-dimensional spline technique. These biases or discrepancies are not true cross-validated errors, only estimated errors, and as such are likely to be an underestimate of the true analysis error. The discrepancies or biases can arise from incorrect station metadata (*e.g.*, accuracy of station latitude and longitude to two decimal places; accuracy of the station elevation), from incorrect rainfall totals (arising from missing data, manual error in reading the rain-gauge, multi-day totals spanning the end of one month and the start of the next), errors of representativeness (station rainfall observations being atypical in a systematic way of the surrounding area), and the limitations of the statistical rainfall modelling process itself.

Figure 5 shows the annual analysis (top), with data locations superimposed, together with the analysed absolute biases (bottom). Documentation accompanying various implementations of *ANUsplin* indicate that the values mapped in Figure 5b can be interpreted as a prediction standard error, with 95% confidence intervals of the calculated spline values estimated by multiplying these analysed absolute biases by 1.96 (the relevant value from the standard normal distribution).

Investigations on the annual and June data in the present analyses suggest however that the absolute biases at the stations should be multiplied by 2 to yield an approximate 90% confidence interval. That is, approximately 90% of the station values lie within twice the calculated absolute biases of the model estimates at station elevation. This difference (from standard statistical theory) appears to arise from the fact that the biases are not exactly normally distributed.



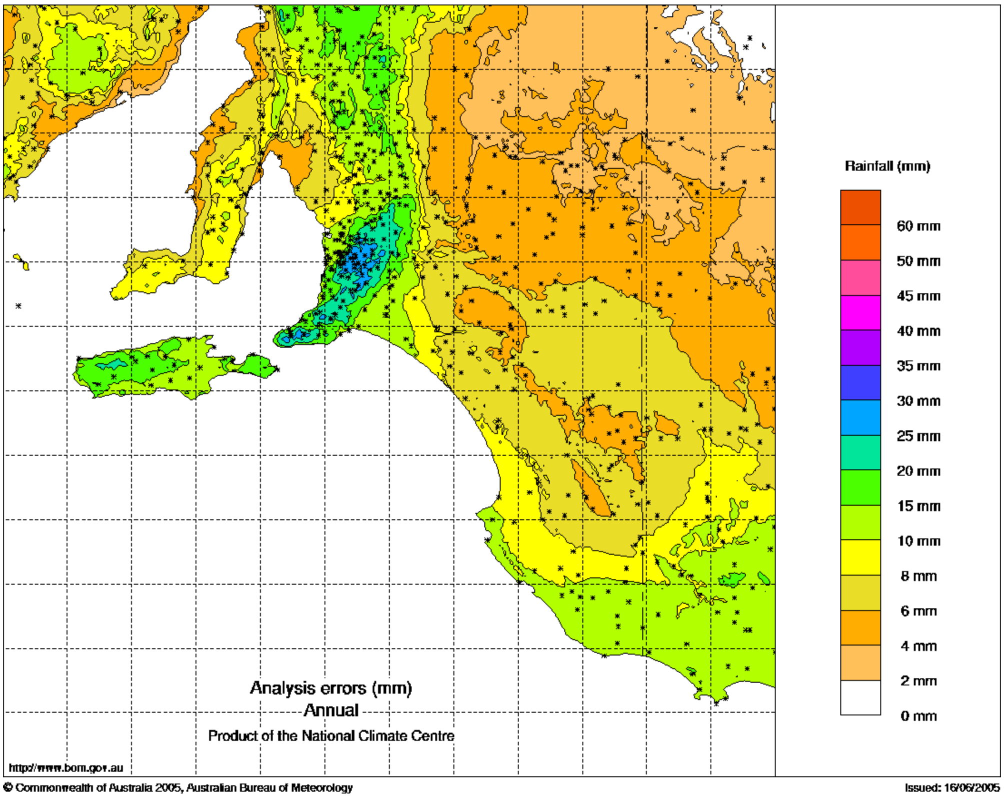


Figure 5: Analysis of average annual rainfall (top) and the mean absolute errors (absolute biases) (bottom). Observation locations are shown as stars. Units are mm.

An upper bound on the analysis errors can be obtained through the process of cross-validation. We analyse the fully-cross-validated analysis (absolute or unsigned biases) incurred by leaving out each station in turn. The set of absolute biases are mapped with a two-dimensional spline (*i.e.*, the analysis method used in this project without the inclusion of topography).

These values are generally larger than those shown in the previous figures. The edge effects towards the western end of Kangaroo Island imply that the included stations there are having a considerable impact on the analysis – their deletion has a decidedly deleterious effect on the analysis. [This is also due to the tendency of the polynomial spline method to extrapolate beyond the spatial extent of the data, against which tendency the 0.5° buffer zone has been included in the analysis region.] In the denser parts of the network, the effects of individual stations on the resulting analysis are nearly always proportionally less. A Barnes analysis (the technique used in the Bureau's operational rainfall analysis procedures (Jones and Weymouth 1997)) of these absolute errors yields almost the same result as that given here, provided the characteristic length scale is not too small.

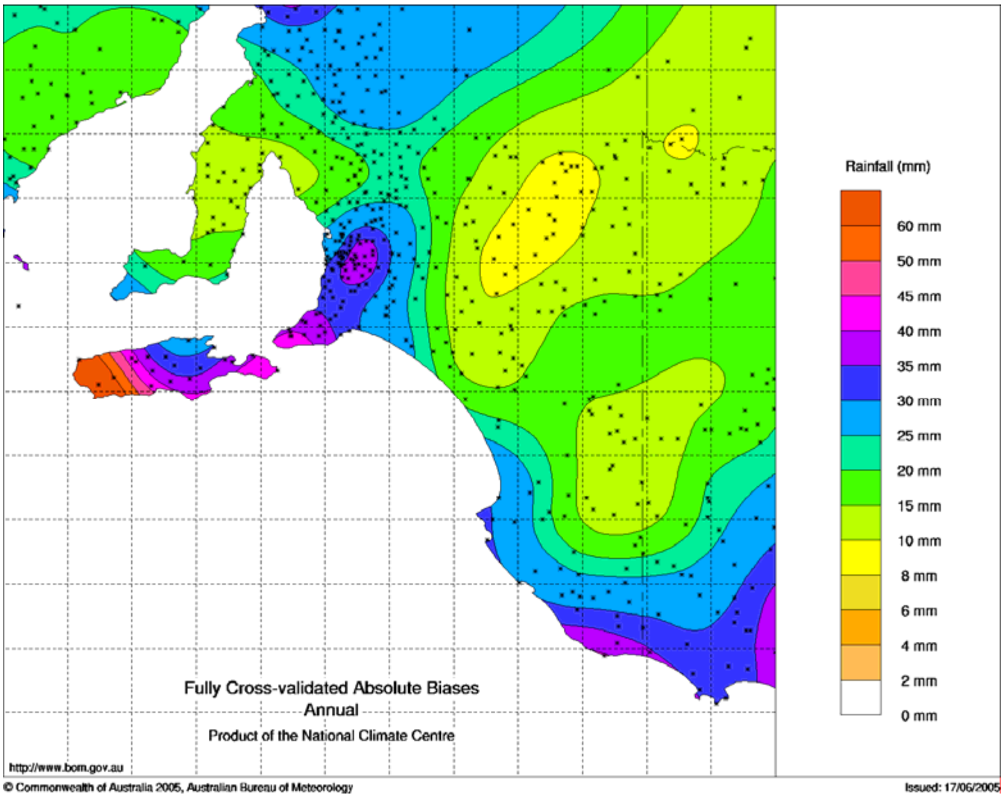


Figure 6: Analysis of the mean absolute errors (absolute biases). Observation locations are shown as stars. One station is removed at a time in the cross validation process. This can have a marked effect where observations are sparse or where edge effects become important (some coastal areas and western Kangaroo Island). Units are mm.

We now turn to the analysis of the signed un-cross-validated biases. [This is in contrast to the two maps of the absolute or unsigned biases already presented.] As previously indicated, the biases are the discrepancies between the station value and the 3d-spline's estimate of the rainfall at the station location and elevation. [Note that the grid-point value is the model's estimate of the rainfall at the model elevation rather than at station elevation.] A positive (negative) bias here occurs when the station rainfall is higher (lower) than the model rainfall estimate at the station elevation. These biases have been analysed for mapping purposes using a two-dimensional Barnes successive correction analysis scheme (Jones and Weymouth 1997), using an outer radius of 10 km, output onto a 0.02° grid.

The purpose of mapping the analysis of the signed bias is to determine if there are any sizeable regions where the model is consistently overestimating (negative bias) or underestimating (positive bias) the rainfall. Almost everywhere the biases are very small, typically in the range of 10 mm or less, being around 2% of the annual mean rainfall, and without large scale structure (see below). There does appear, however, to be a tendency for the model to slightly underestimate (overestimate) rainfall on the wetter western (drier eastern) slopes of the Mt Lofty Ranges. This indicates that the analysis is slightly smoother in the region of the ridge top than the limited data might suggest. Comparison against the mean rainfall field (Figure 5) reveals the biases as a percentage of the mean are small in this region, implying that the biases are climatologically insignificant.

To calculate the relative bias, the grid used to produce the bias map is divided by the analysis grid and mapped. The relative biases are generally less than 4%, although in some places they do rise above that.

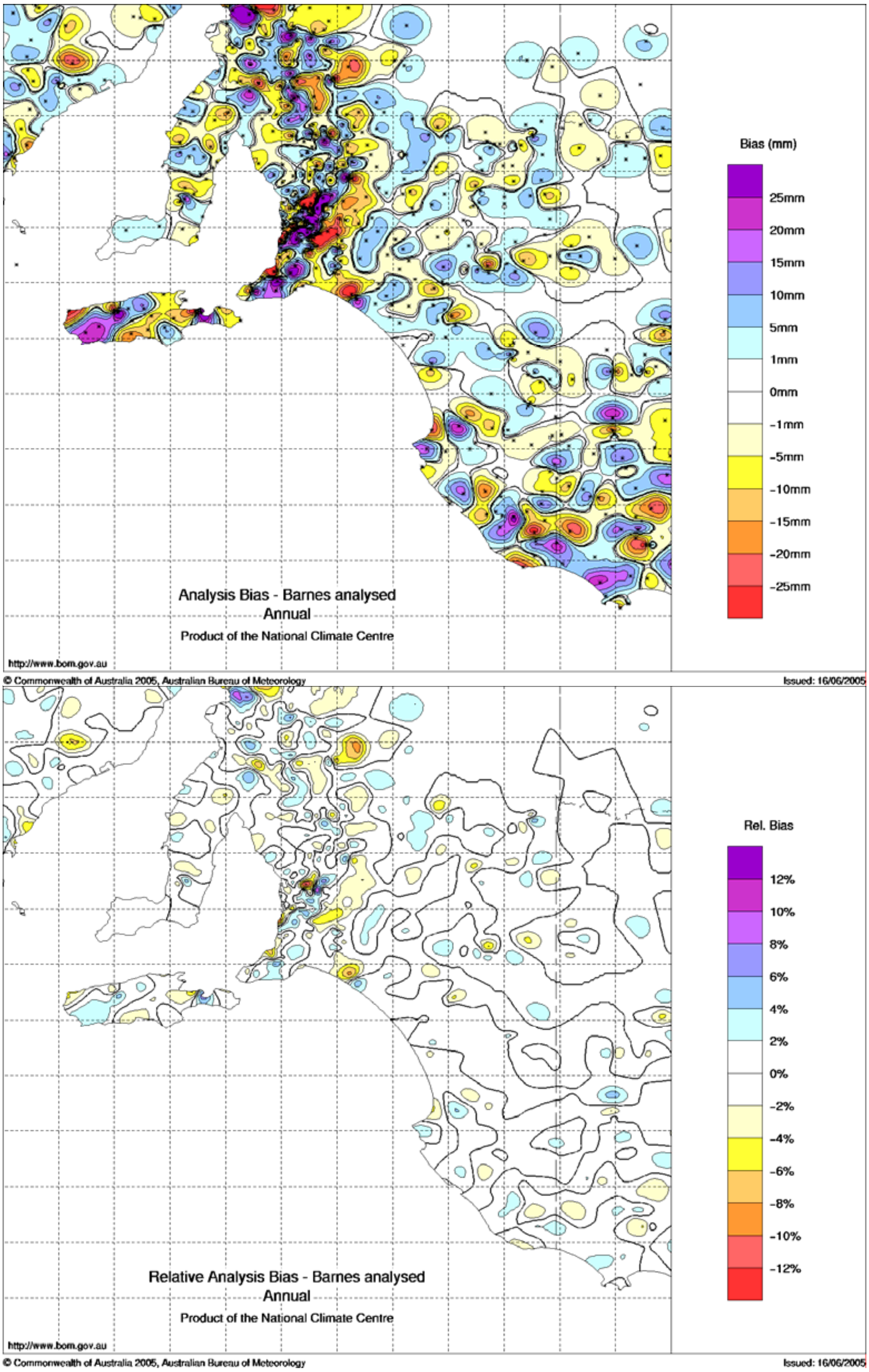
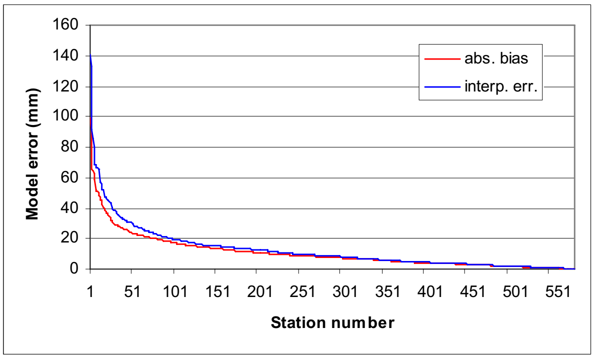


Figure 7: Analysis bias at stations (top) and relative bias (bottom). These are mapped at 0.02°, subsampled from the 0.01° grids. Units are mm and % respectively.

We can also look at the statistical distribution of absolute or unsigned biases (red curve), ranked from highest to lowest. The 90th (95th) percentile for the station absolute biases is about 23 mm (32 mm), meaning that 90% of the station absolute differences are less than 23 mm. The median absolute bias is 7.7 mm. Another way of looking at this is via the station (absolute or unsigned) interpolation errors. While the biases involve model estimates of station rainfall at station elevation, the output grids can be interpolated to station location to get a rainfall estimate. This is in effect a model estimate of station rainfall at model elevation rather than at station elevation, and is how the grids would be used once they are become available to the general public. Not surprisingly the absolute interpolation errors (blue curve) are larger than the absolute biases (red curve). Still, 90% (95%) of the station absolute interpolation errors are less than 28 mm (40 mm) for the annual analysis. The median (absolute or unsigned) interpolation error is 8.7 mm.

In terms of the relative (absolute) errors, the 90th (95th) percentile for the station relative biases is about 4.6% (5.5%), while the 90th (95th) percentile for the station relative interpolation errors is about 5.5% (7.0%). The median relative (absolute or unsigned) bias is 1.7%, while the median (absolute or unsigned) interpolation error is 1.9%.



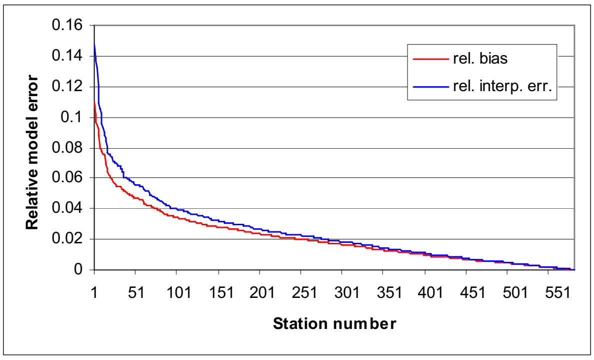


Figure 8: Distribution of the absolute (left) and relative (right) biases (red) and interpolation errors (blue).

8. Maps

The analysis and derived grids were converted to ASCII format and imported into ESRI ArcInfo™. The data were manipulated and mapped using the Grid and ArcPlot modules within ArcInfo™. To generate the mapped contours, the 0.01° base grids were lightly smoothed with a 3×3 binomial smoother (see appendix 1 for details), then resampled to 0.001°, using a standard 16-term cubic polynomial interpolation (also see appendix 1 for details). This was implemented outside the ESRI software. Initially the cubic-convolution method (as implemented within ArcInfo™) was investigated for the resampling process, but the results obtained proved to be inferior to those of the standard cubic polynomial interpolation process. The contours thus obtained are simply stepped around the resulting 0.001° grid. These maps are reproduced in the Appendix. The 0.01° base grids are equivalent to a resolution of about 1 square kilometre or 100 hectares. *It is not possible to discern detail below this scale in the analyses.*

Edge effects normally inherent in the resampling process were excluded by clipping the outer 0.5° of the analysis grids after the smoothing and resampling. The underlying 0.01° grids are also supplied in this clipped form. Given the uncertainties discussed in the previous section, the accuracy of the isohyets should be regarded as approximately 5%.

9. A Brief Description of the Rainfall Maps and Their Interpretation

The climatological rainfall maps (in the Appendix) show a complex rainfall pattern, dominated by higher rainfall in elevated regions and the far southeast, and a marked rain shadow to the east of the Mount Lofty Ranges. Rainfall varies from around 200 mm in the far north and north east of the analysis region to more than 1000 mm near Mount Lofty. Secondary maxima are evident over the western interior of Kangaroo Island, the foot and other elevated parts of the Yorke Peninsula, and around Mount Burr in the southeast.

Comparison with the *Climatic Atlas of Australia – Rainfall* reveals good general agreement in most areas, through the Atlas is considerably less detailed owing to the smaller number of stations used in the study region and the post analysis smoothing that was necessary for the national product.

The monthly analyses reveal a strong seasonal cycle of rainfall in most parts with February being the driest month overall. Rainfall tends to peak during the months of July and August. Autumn and spring are transition periods between the wet winter and dry summer, the overall rainfall pattern being of a Mediterranean type. The northeast corner of the analysis region is unique. March is the driest month and October is the wettest. Median rainfalls, especially in this northeast area and across much of the region in summer, may be slightly different from (and generally lower than) average analyses.

In interpreting the rainfall analyses it is important to keep in mind that rainfall can vary significantly from decade to decade, as well as show possible long term trends. South Australian rainfall (see Figure 9) has shown considerable variation over the past century with drier decades around 1930 and the 1960. In contrast the 1970s were wet, particularly in inland parts, while 1992 was the wettest year overall in much of coastal South Australia between Ceduna and Meningie, including the Mt Lofty Ranges (although in area-averaged terms for the entire State, 1974 was the wettest year by some distance). Despite these variations, we note that the south and east of South Australia has seen little annual trend in rainfall since 1900 (see Figure 10), although there has been some seasonal shift at least since 1950. It remains to be seen whether larger trends will emerge in the future as a result of anthropogenic climate change. To monitor possible trends, these analyses should be updated at ten year intervals.

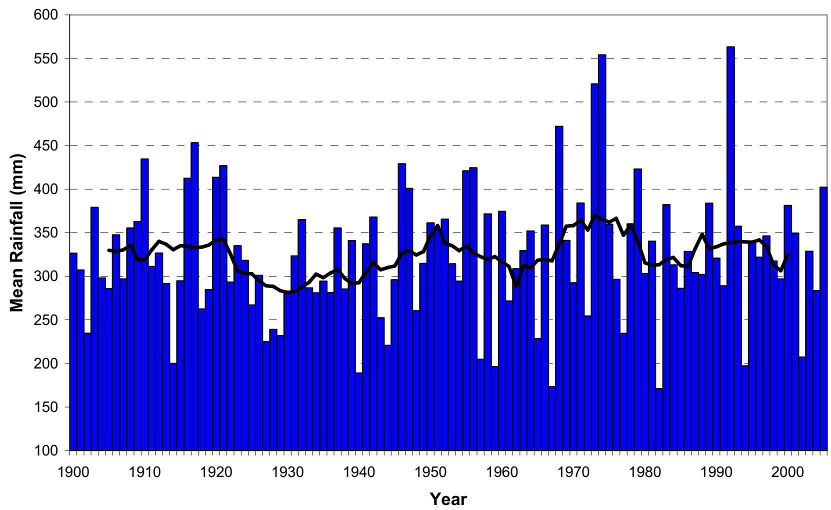


Figure 9: Time series of areally-averaged annual rainfall (1900 to 2005) for those parts of South Australia between 129°E and 141°E and south of 31.5°S. These data are obtained from the Bureau's operational monthly rainfall analyses. The analysis technique is the Barnes successive correction method. Units are mm.

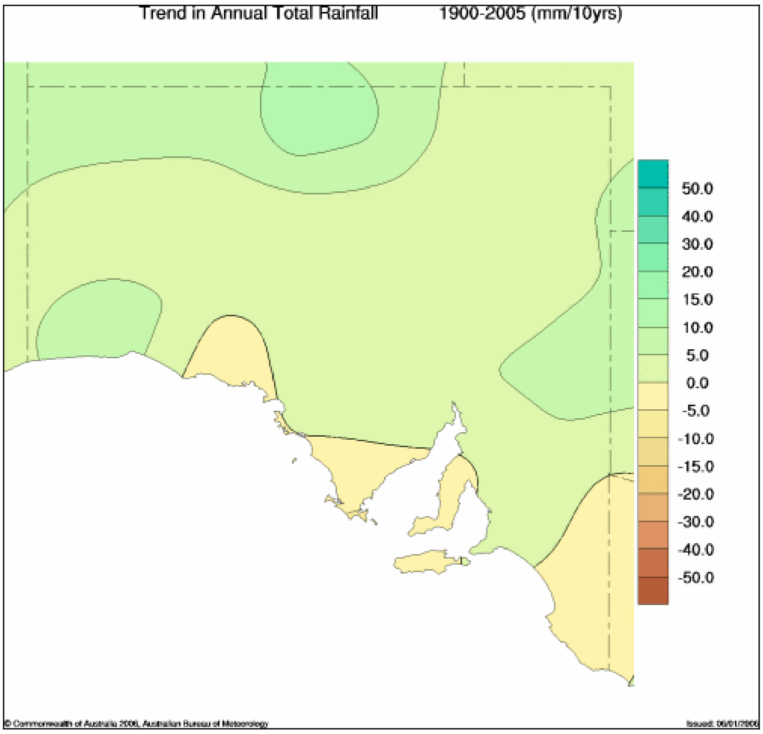


Figure 10: Trend in annual South Australian rainfall from 1900 to 2005. This map is based on an analysis of trends in a high-quality rainfall network. Units are mm/decade.

References

Bureau of Meteorology, 2000. Climatic Atlas of Australia – Rainfall.

Hutchinson, M F, 1995. Interpolating mean rainfall using thin plate smoothing splines. *International Journal of Geographical Information Systems*, **9**, 385-403.

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Press, W H, Flannery, B P, Teukolsky S A and Vetterling W T, 1989. Numerical Recipes: The Art of Scientific Computing (Cambridge University Press). See also www.nr.com .

World Meteorological Organization 1989. Calculation of monthly and annual 30-year standard normals. *W.M.O. Tech. Disc. No.*, **341**, 11pp.

Appendix 1: Technical details

3×3 Binomial smoothing

If x_{ij} ($i = 1,\ldots,n$ and $j = 1,\ldots,n$) are grid points on an n-dimensional square grid, then the 3×3 binomially smoothed value y_{ij} is

$$y_{ij} = (x_{i-1j-1} + x_{i+1j-1} + x_{i-1j+1} + x_{i+1j+1} + 2(x_{ij-1} + x_{ij+1} + x_{i-1j} + x_{i+1j}) + 4x_{ij})/16.$$

Appropriate adjustments are made for grid edges and corners, but these in any case have been excluded in the grid clipping process.

Cubic polynomial interpolation

In one dimension, the Lagrange interpolating polynomial $P(x)$ of degree $n-1$ which passes through the n points $\{(x_1,y_1),\ldots,(x_n,y_n)\}$ is

$$P(x) = \sum_{j-1}^{n} y_j \prod_{k=1;k\neq j}^{n} \frac{x - x_k}{x_j - x_k}.$$

The specific reduction of this to the cubic case of 4 points $(-1,y_{-1})$, $(0,y_0)$, $(1,y_1)$ and $(2,y_2)$ is

$$P(u) = -\frac{y_{-1}}{6}u(u-1)(u-2) + \frac{y_0}{2}(u+1)(u-1)(u-2) - \frac{y_1}{2}(u+1)u(u-2) + \frac{y_2}{6}(u+1)u(u-1).$$

A similar result obtains in two dimensions, using points (u,v,y_{uv}) for $u = -1, 0, 1, 2$ and $v = -1, 0, 1, 2$. It contains 16 terms. See Press *et al.* (1989) (page 89) for further details.

One-parameter linear regression

For a sample $\{(x_1,y_1),\ldots,(x_n,y_n)\}$, the least-squares line of best fit of the form $y = \beta x$ is estimated via

$$\hat{\beta} = \frac{\sum_{i=1}^{n} x_i y_i}{\sum_{i=1}^{n} x_i^2}.$$

The coefficient of determination is estimated as

$$R^2 = \frac{n\left[\sum_{i=1}^{n} x_i y_i\right]^2 - \left[\sum_{i=1}^{n} x_i^2\right]\left[\sum_{i=1}^{n} y_i\right]^2}{\sum_{i=1}^{n} x_i^2\left[n\sum_{i=1}^{n} y_i^2 - \left(\sum_{i=1}^{n} y_i\right)^2\right]}.$$

Two-parameter linear regression

For a sample $\{(x_1,y_1),\ldots,(x_n,y_n)\}$, the least-squares line of best fit of the form $y = \beta_0 + \beta_1 x$ is estimated via

$$\hat{\beta}_1 = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2},$$

$$\hat{\beta}_0 = \bar{y} - \hat{\beta}_1 \bar{x}.$$

Here, $\bar{x}$ and $\bar{y}$ denote the sample means. The coefficient of determination is estimated as

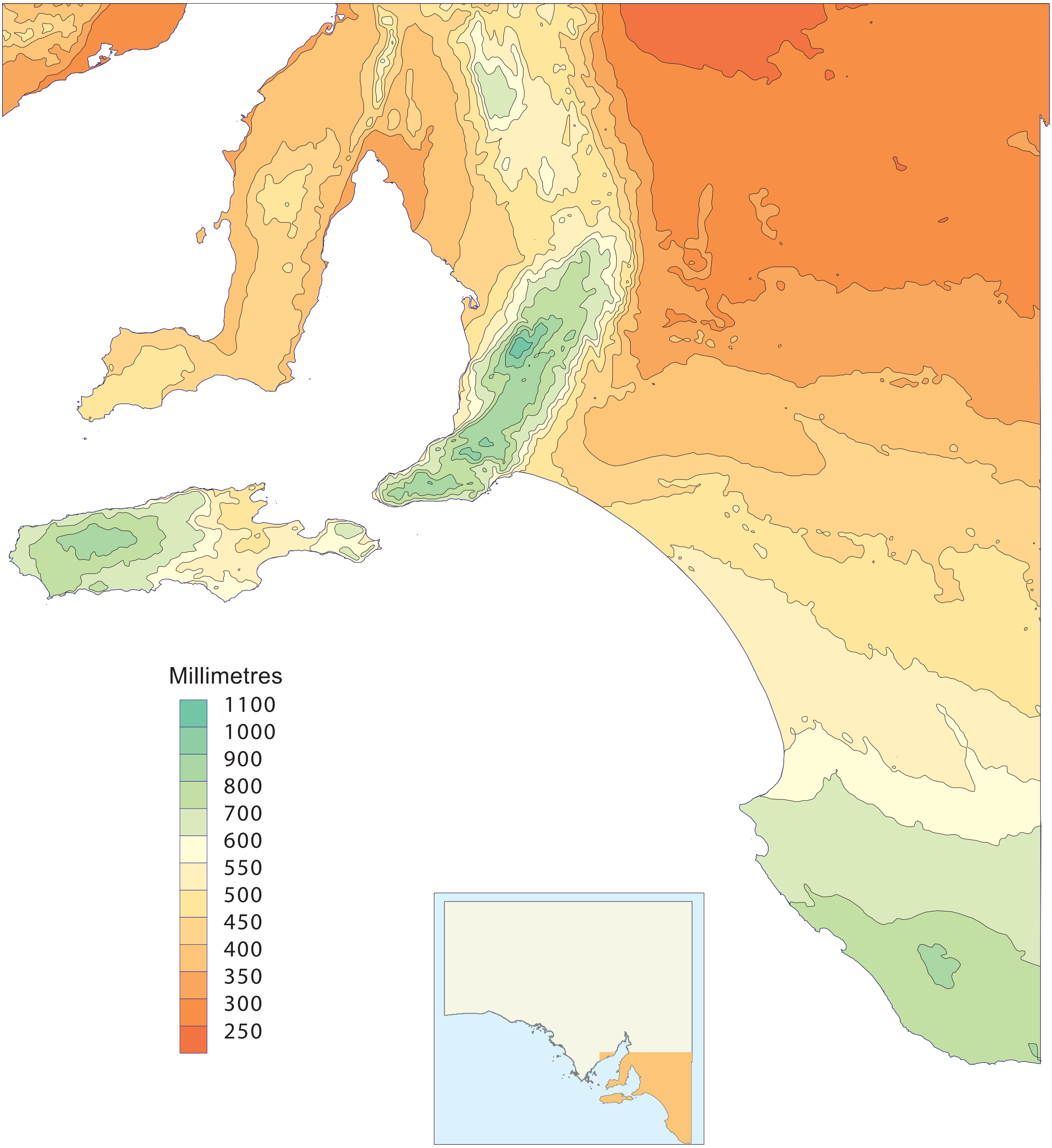
$$R^2 = \frac{\left[\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})\right]^2}{\left[\sum_{i=1}^{n}(x_i - \bar{x})^2\right]\left[\sum_{i=1}^{n}(y_i - \bar{y})^2\right]}.$$

In both the one-parameter and two-parameter regression cases, the predictor value of the estimated rainfall is substituted into the linear equation to obtain the estimated value.

Appendix 2: Rainfall climatology maps

This appendix presents the rainfall climatology maps in a format suitable for separate publication. There are two versions of the annual map. The second version has an expanded range of contours, giving more detail in the lower end of the scale. The annual maps are followed by the monthly maps, the maps of the standard seasons, and lastly the wet (May to November) and dry (December to April) seasonal maps.

Average rainfall - Annual



Australian Government
Bureau of Meteorology

Government of South Australia
Department of Water, Land and Biodiversity Conservation

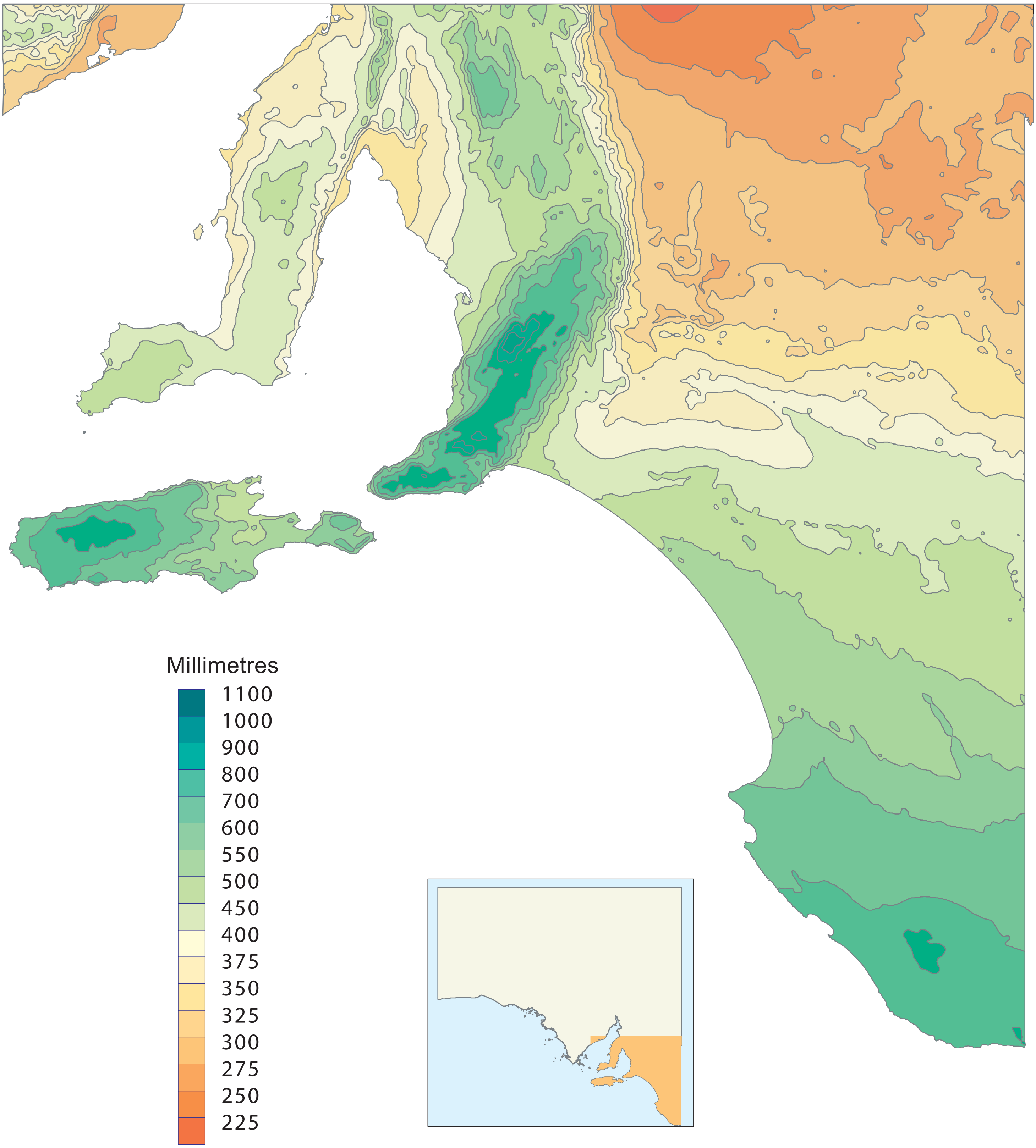
0 40 80 120 160 km

Scale 1 : 2,600,000

Projection: Lambert conformal with standard parallels 10°S, 40°S.
Based on a 30-year climatology (1971 - 2000).

Produced by the Bureau of Meteorology, National Climate Centre.

Average rainfall - Annual



Australian Government
Bureau of Meteorology

Government of South Australia
Department of Water, Land and Biodiversity Conservation

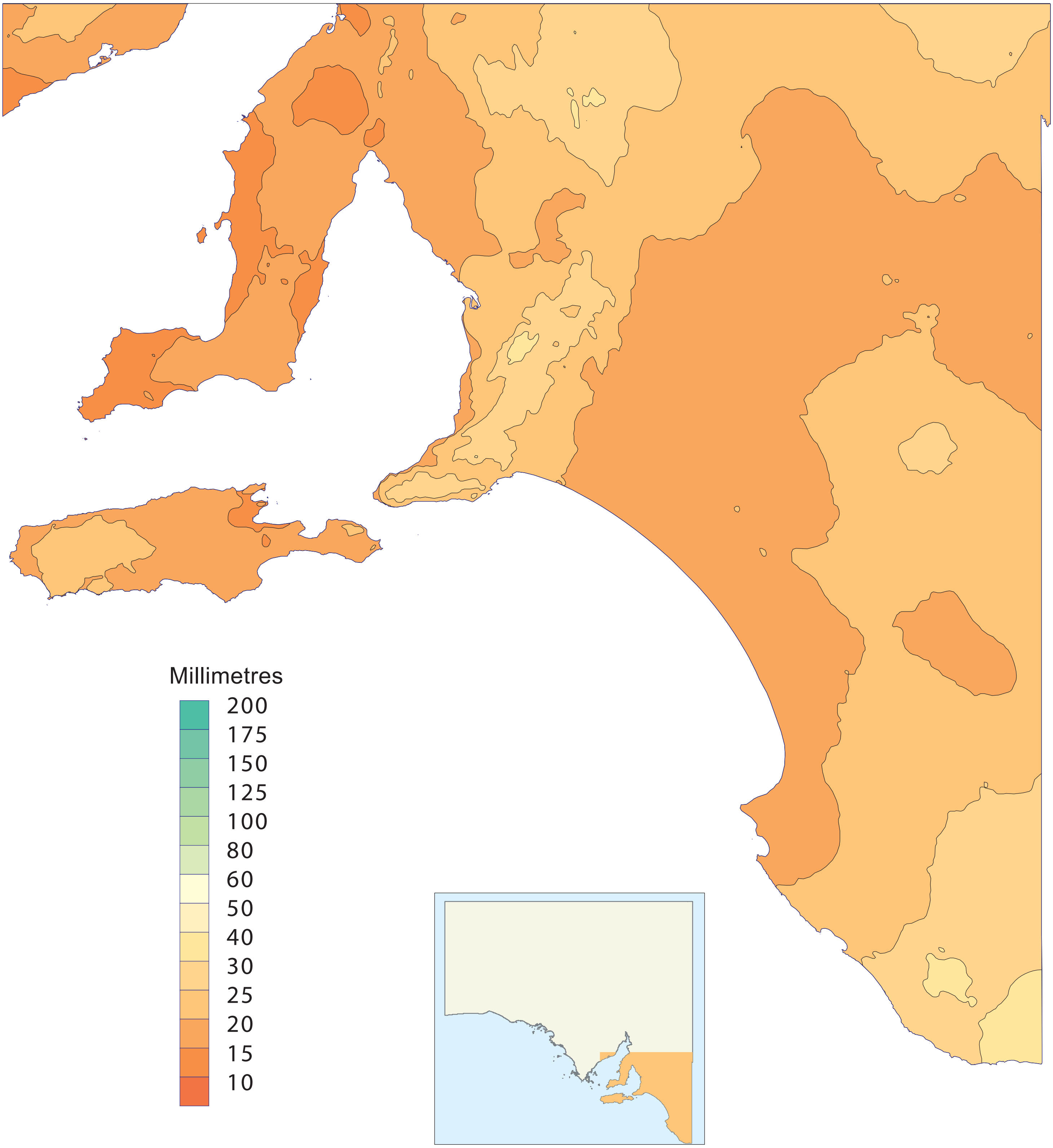
0 40 80 120 160 km

Scale 1 : 2,600,000

Projection: Lambert conformal with standard parallels 10°S, 40°S.
Based on a 30-year climatology (1971 - 2000).

Produced by the Bureau of Meteorology, National Climate Centre.

Average rainfall - January



Australian Government
Bureau of Meteorology

0 40 80 120 160 km

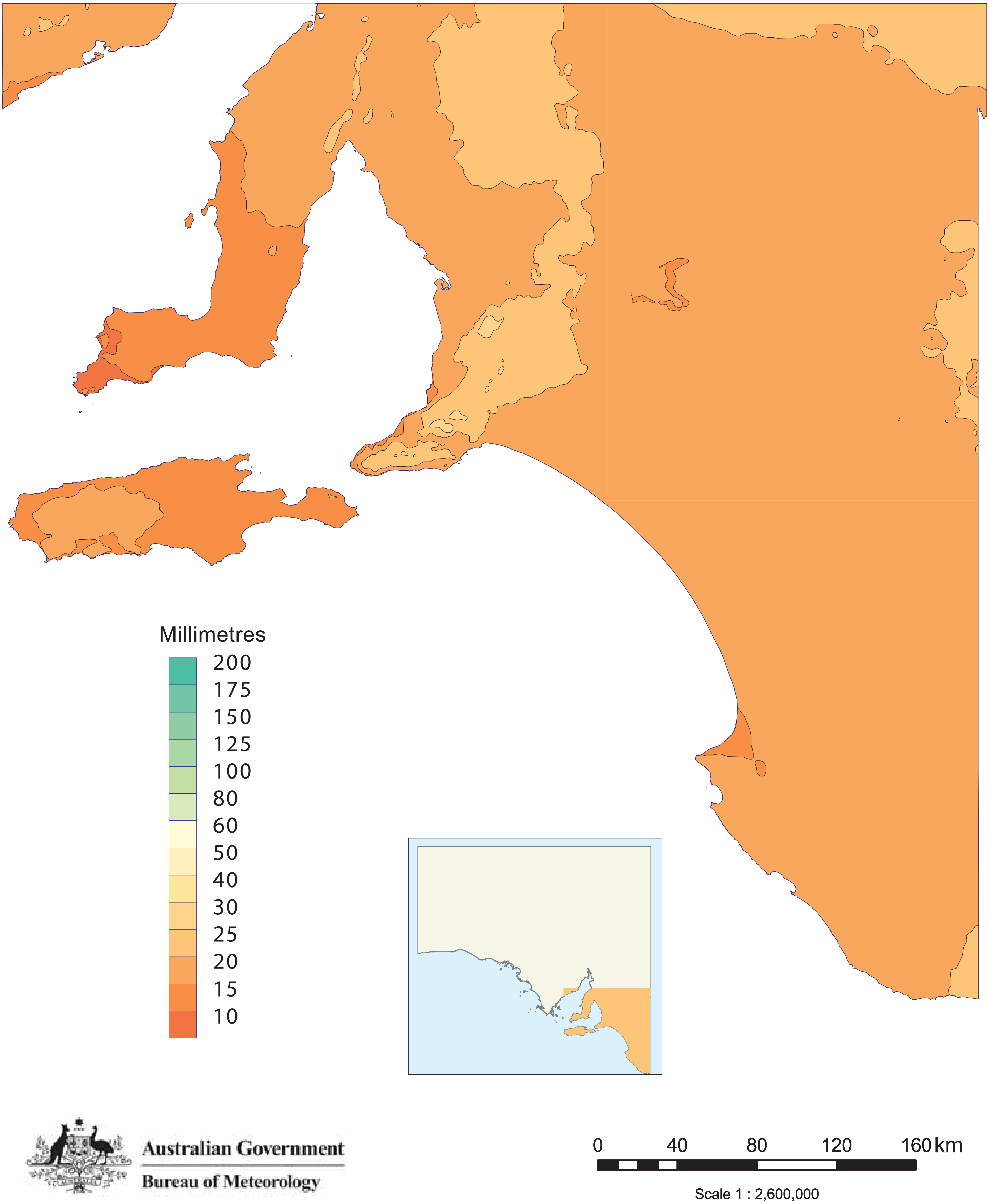
Scale 1 : 2,600,000

Government of South Australia
Department of Water, Land and Biodiversity Conservation

Projection: Lambert conformal with standard parallels 10^{o}S, 40^{o}S.
Based on a 30-year climatology (1971 - 2000).

Produced by the Bureau of Meteorology, National Climate Centre.

Average rainfall - February

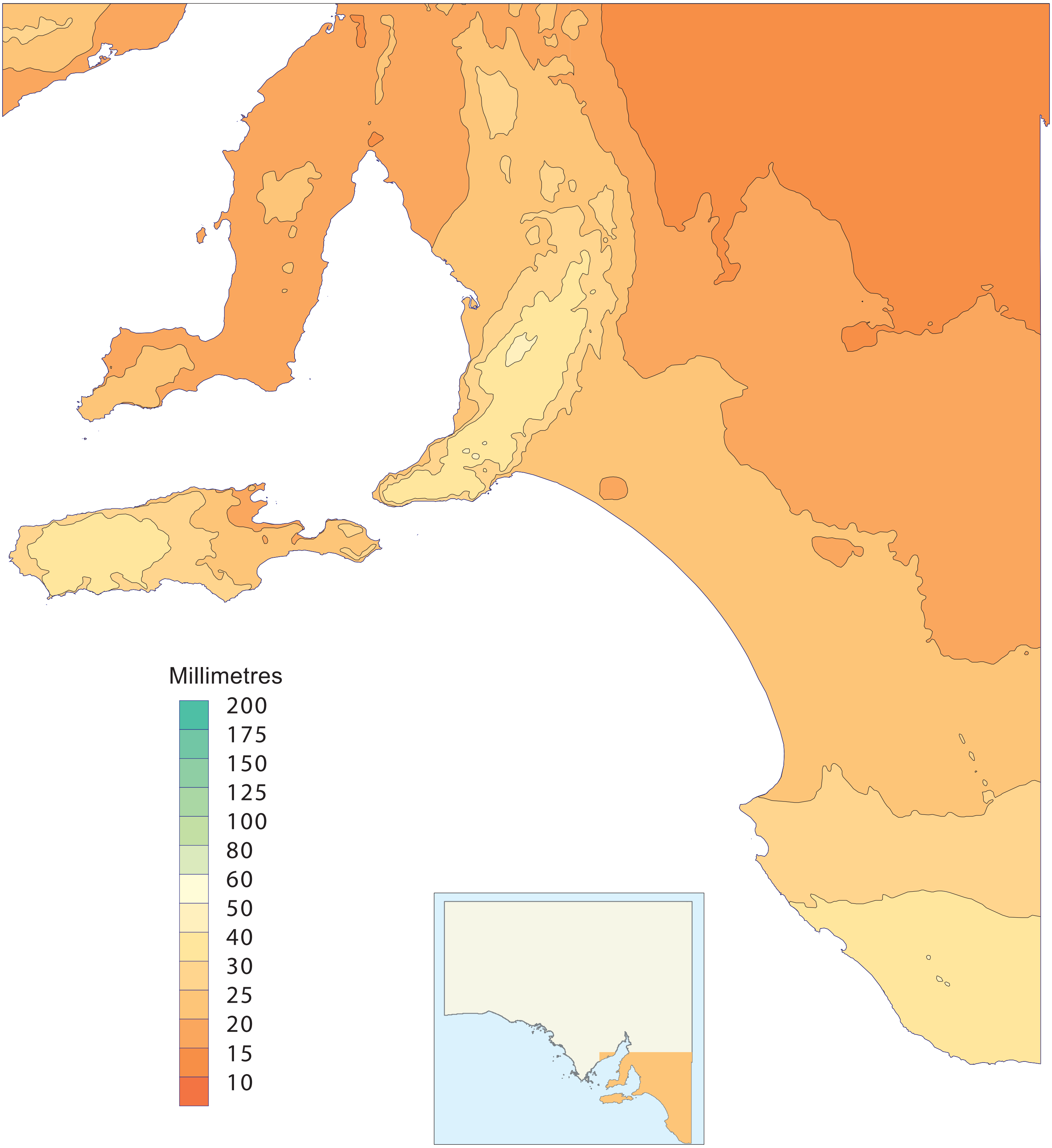


Australian Government
Bureau of Meteorology

Government of South Australia
Department of Water, Land and Biodiversity Conservation

Projection: Lambert conformal with standard parallels 10°S, 40°S.
Based on a 30-year climatology (1971 - 2000).

Average rainfall - March



Australian Government
Bureau of Meteorology

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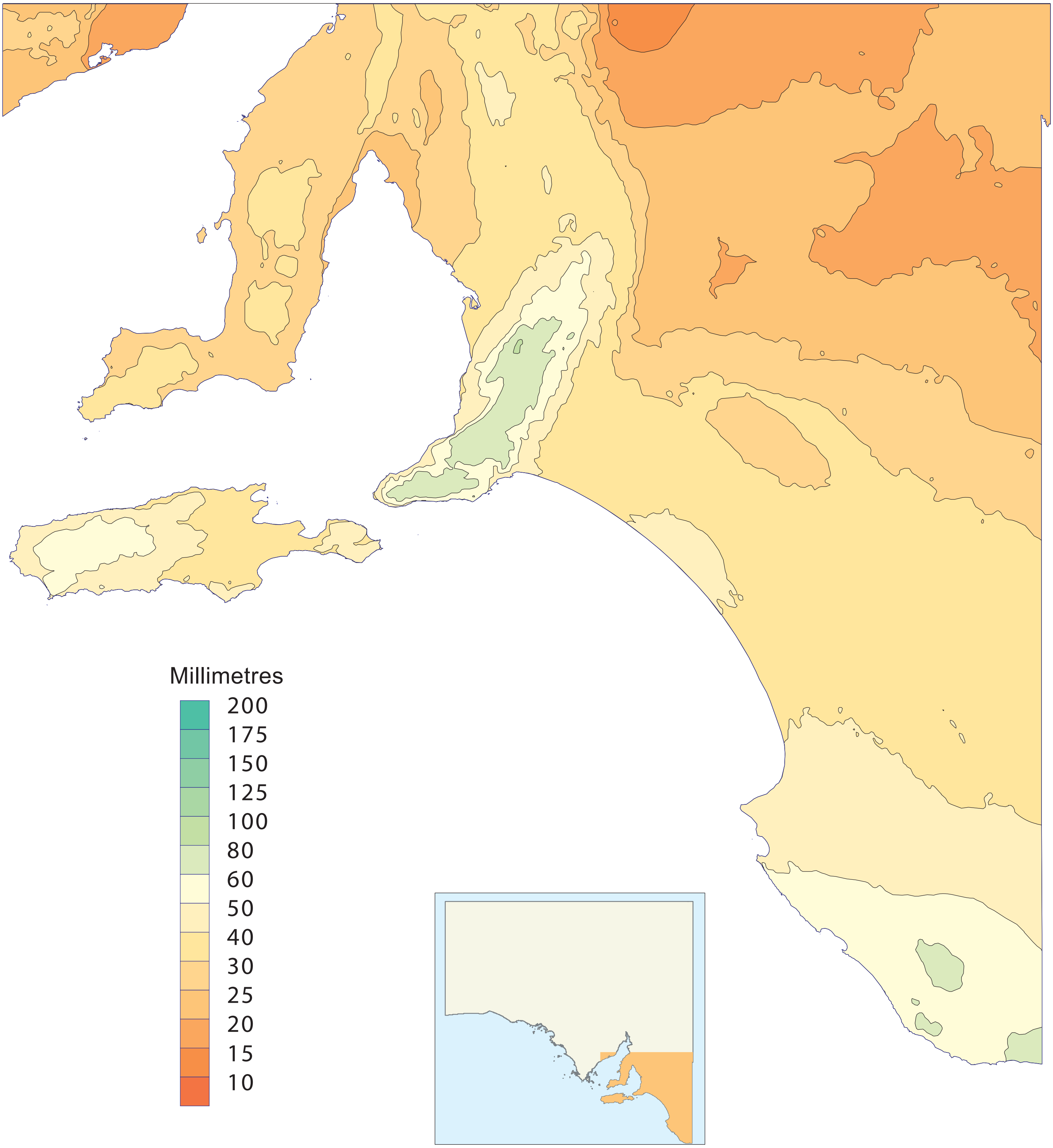
0 40 80 120 160 km

Scale 1 : 2,600,000

Projection: Lambert conformal with standard parallels 10^{o}S, 40^{o}S.
Based on a 30-year climatology (1971 - 2000).

Average rainfall - April



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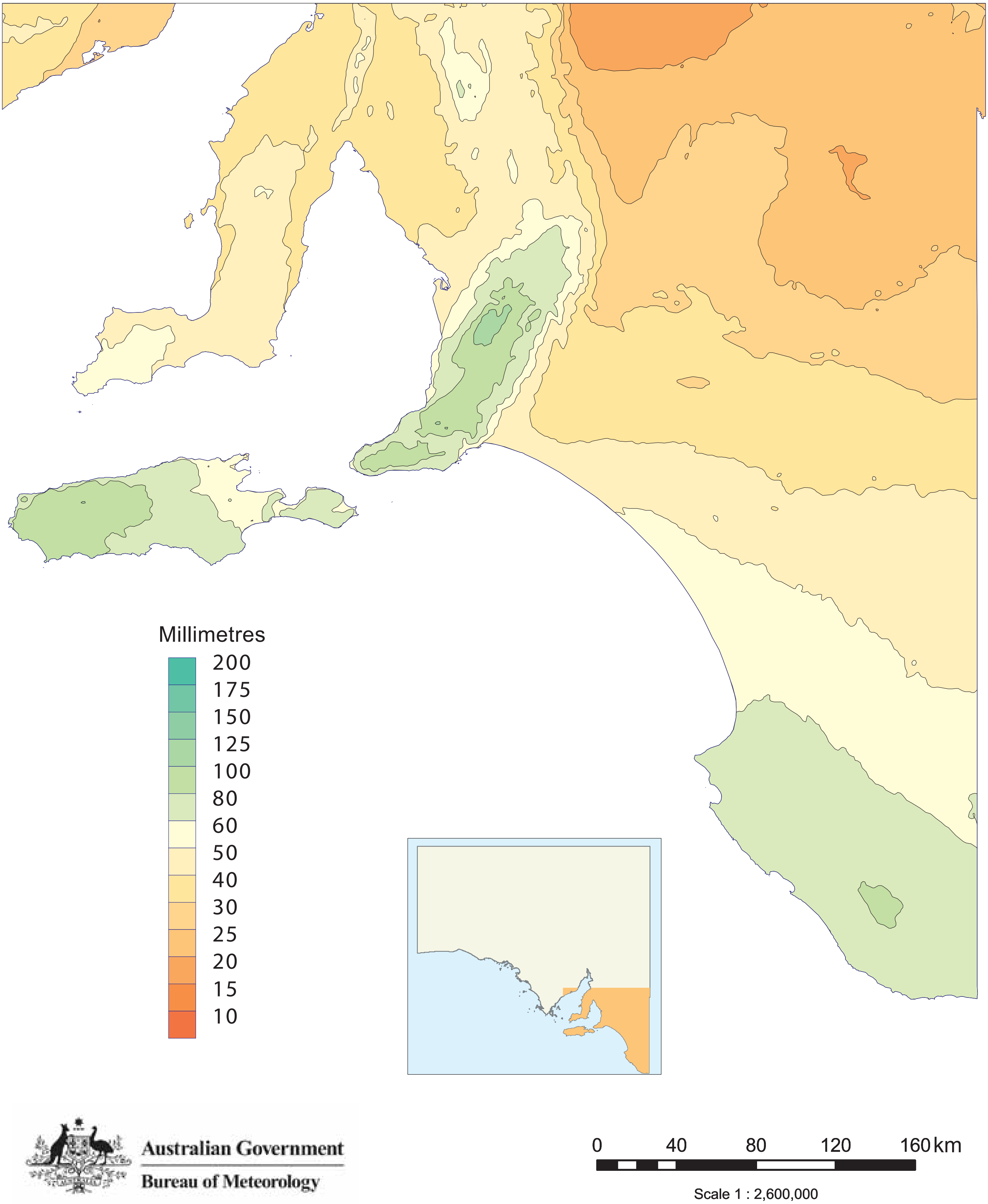
0 40 80 120 160 km

Scale 1 : 2,600,000

Projection: Lambert conformal with standard parallels 10°S, 40°S.
Based on a 30-year climatology (1971 - 2000).

Produced by the Bureau of Meteorology, National Climate Centre.

Average rainfall - May



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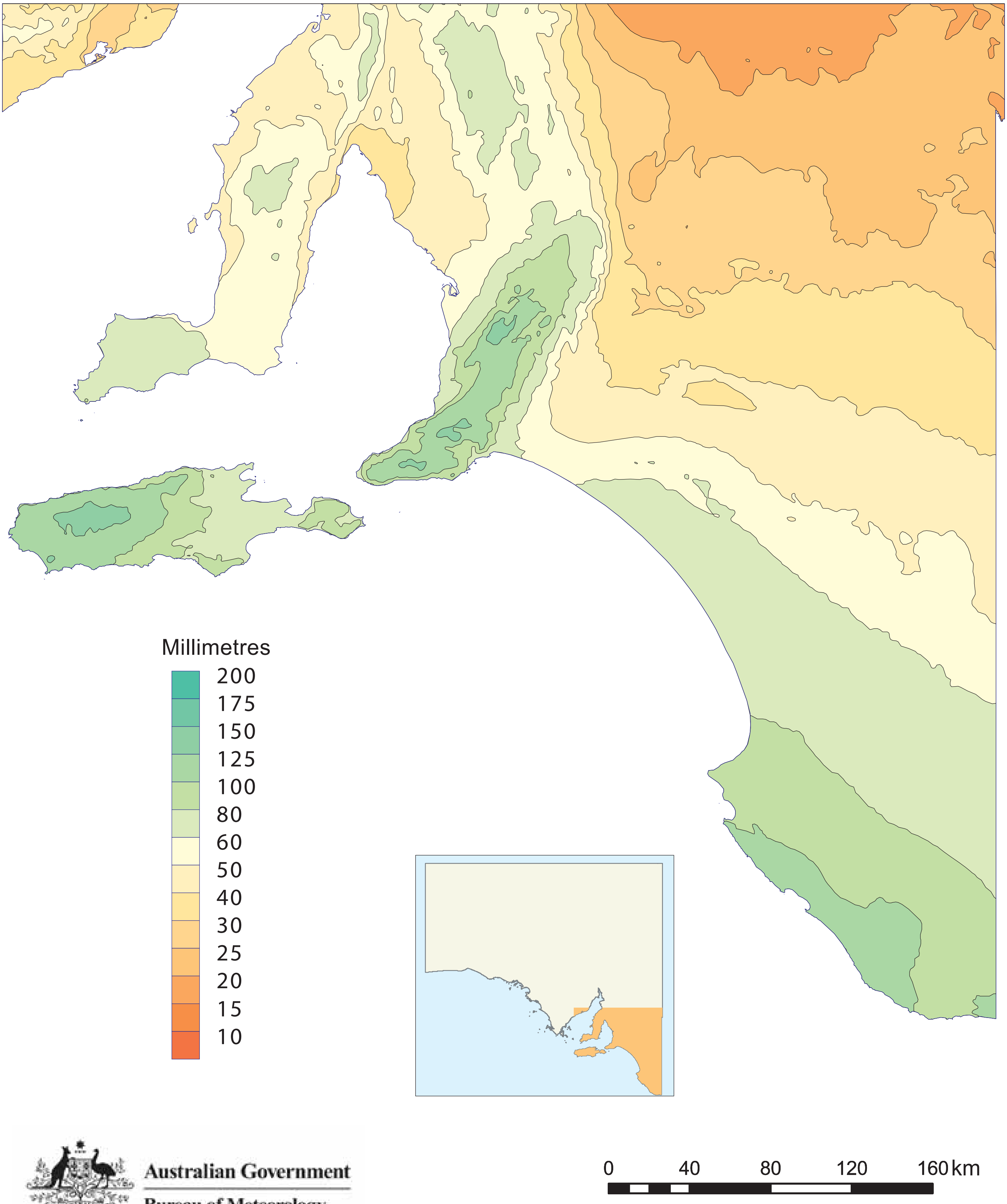
Projection: Lambert conformal with standard parallels 10^{o}S, 40^{o}S.
Based on a 30-year climatology (1971 - 2000).

Produced by the Bureau of Meteorology, National Climate Centre.

Average rainfall - June



Scale 1 : 2,600,000

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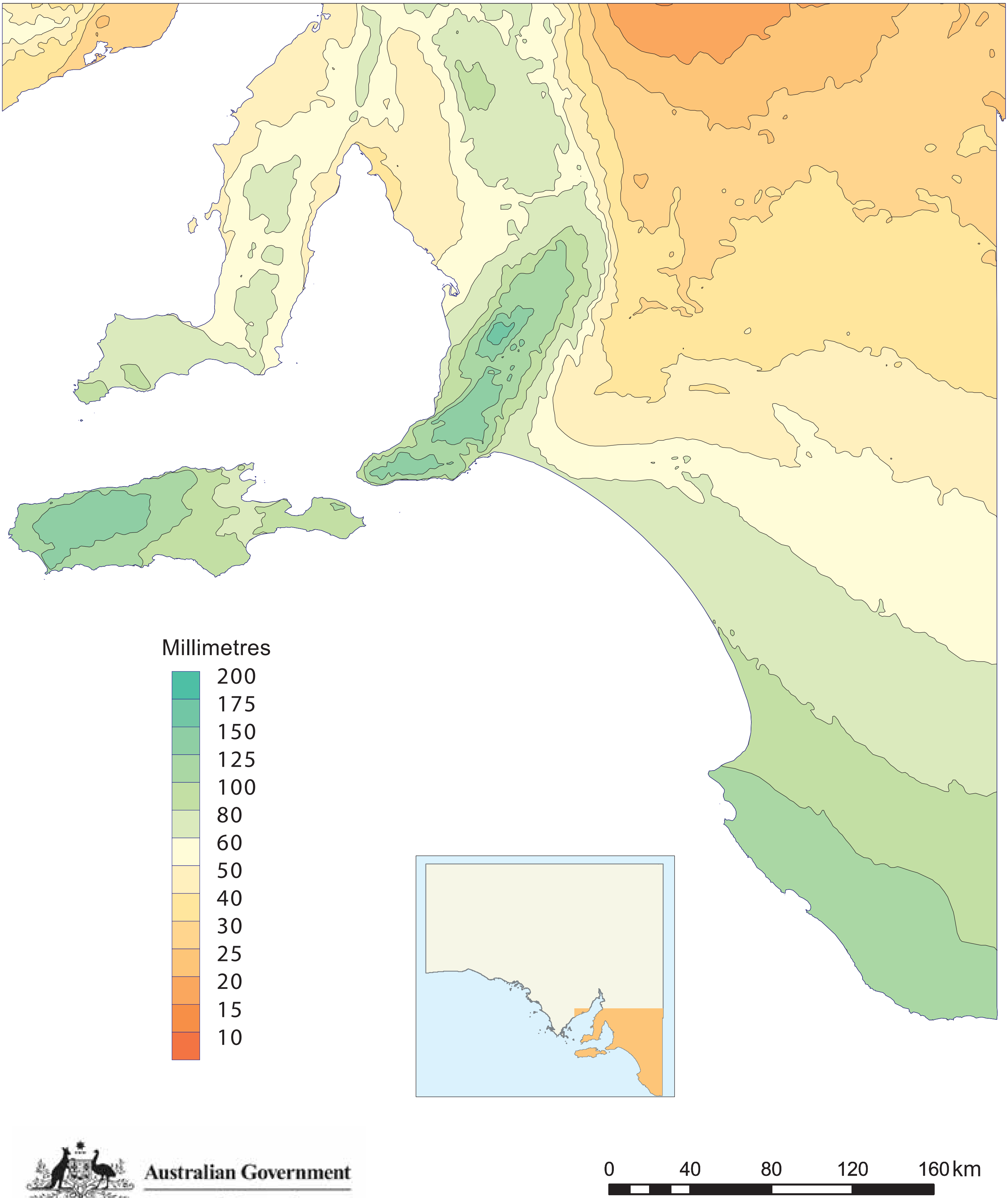
Projection: Lambert conformal with standard parallels 10°S, 40°S.
Based on a 30-year climatology (1971 - 2000).

Average rainfall - July



Scale 1 : 2,600,000

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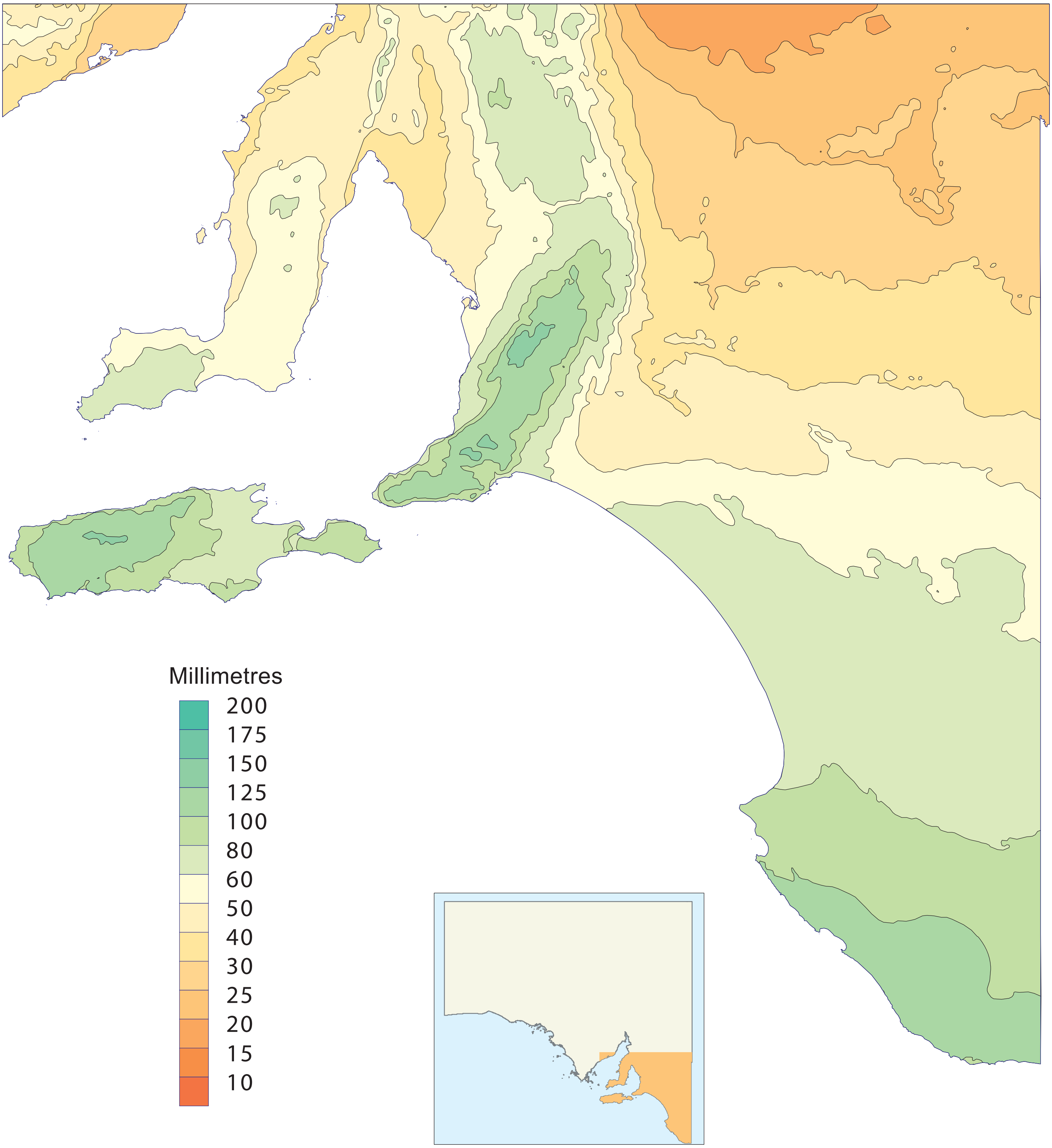
Projection: Lambert conformal with standard parallels 10°S, 40°S.
Based on a 30-year climatology (1971 - 2000).

Produced by the Bureau of Meteorology, National Climate Centre.

Average rainfall - August



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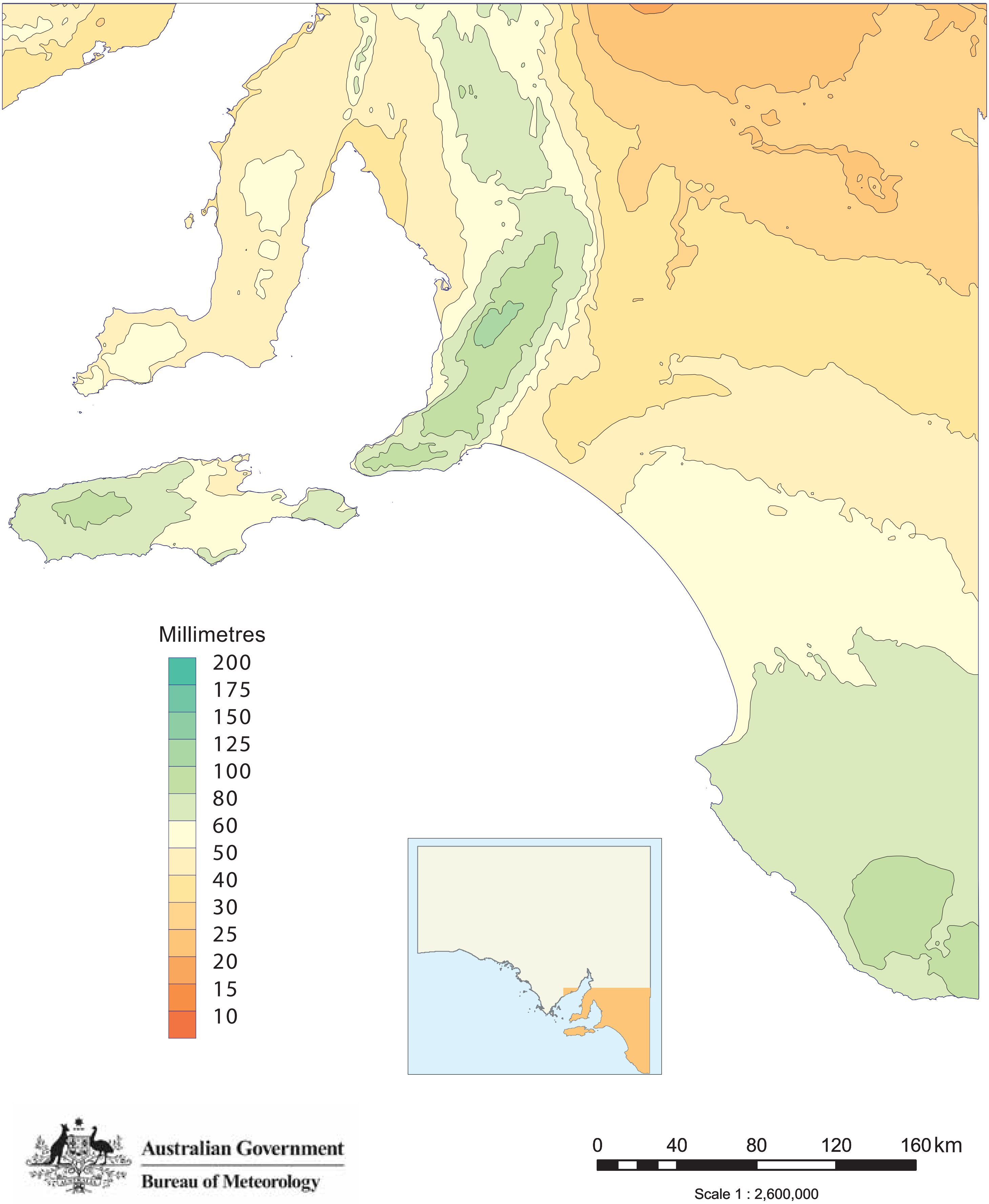
0 40 80 120 160 km

Scale 1 : 2,600,000

Projection: Lambert conformal with standard parallels 10^{o}S, 40^{o}S.
Based on a 30-year climatology (1971 - 2000).

Produced by the Bureau of Meteorology, National Climate Centre.

Average rainfall - September



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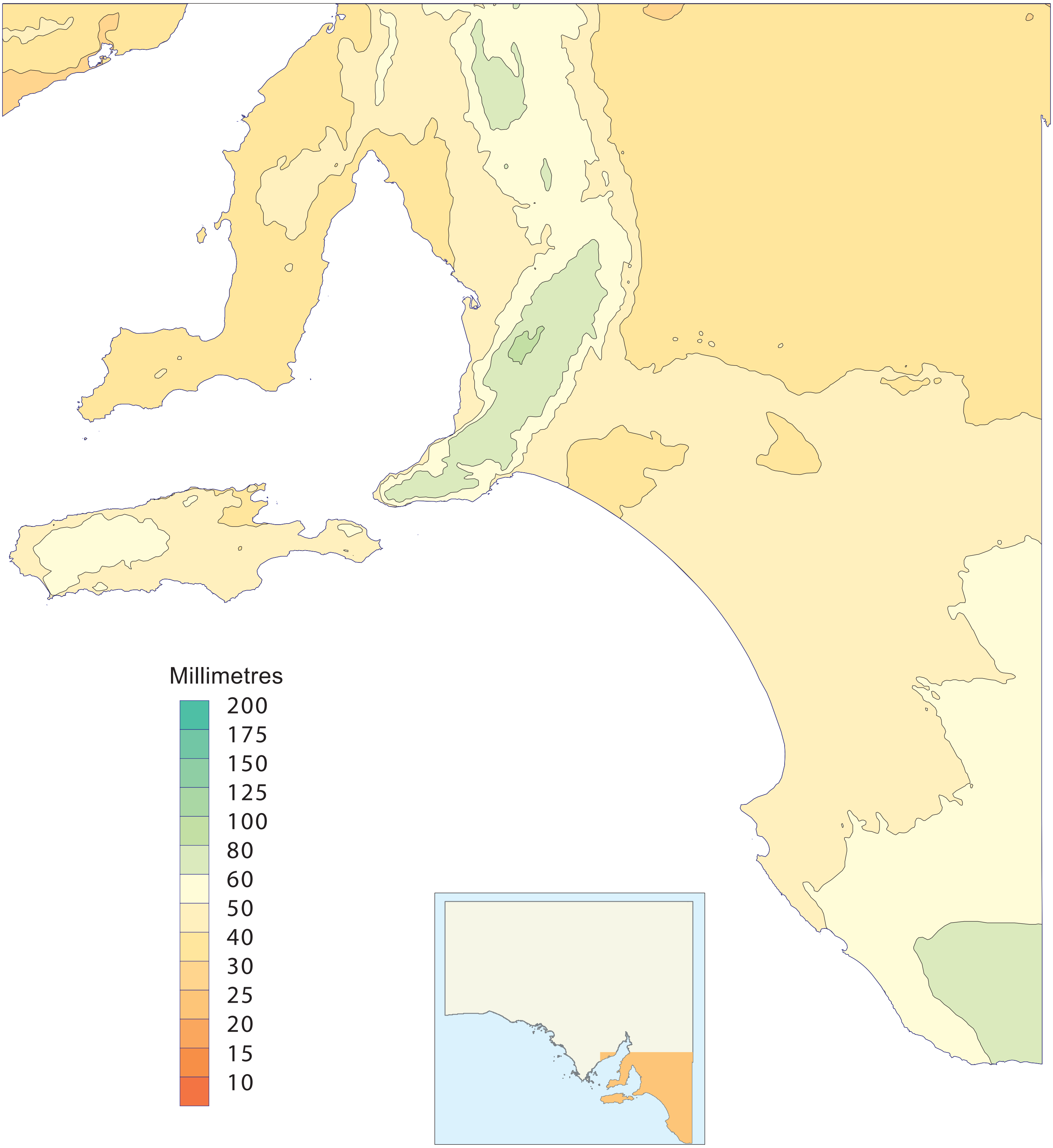
Projection: Lambert conformal with standard parallels 10°S, 40°S.
Based on a 30-year climatology (1971 - 2000).

Produced by the Bureau of Meteorology, National Climate Centre.

Average rainfall - October



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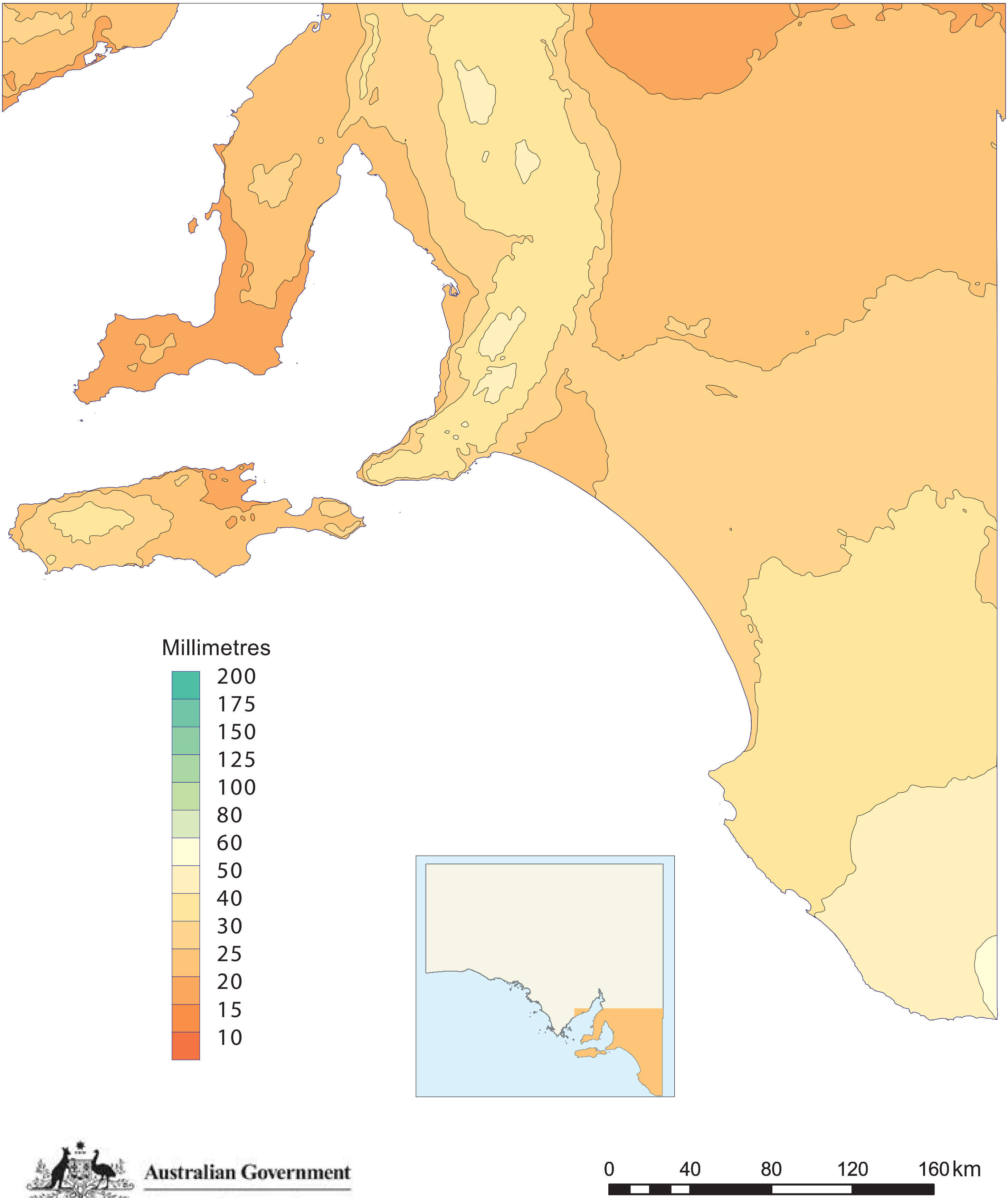
0 40 80 120 160 km

Scale 1 : 2,600,000

Projection: Lambert conformal with standard parallels 10°S, 40°S.
Based on a 30-year climatology (1971 - 2000).

Average rainfall - November



Scale 1 : 2,600,000

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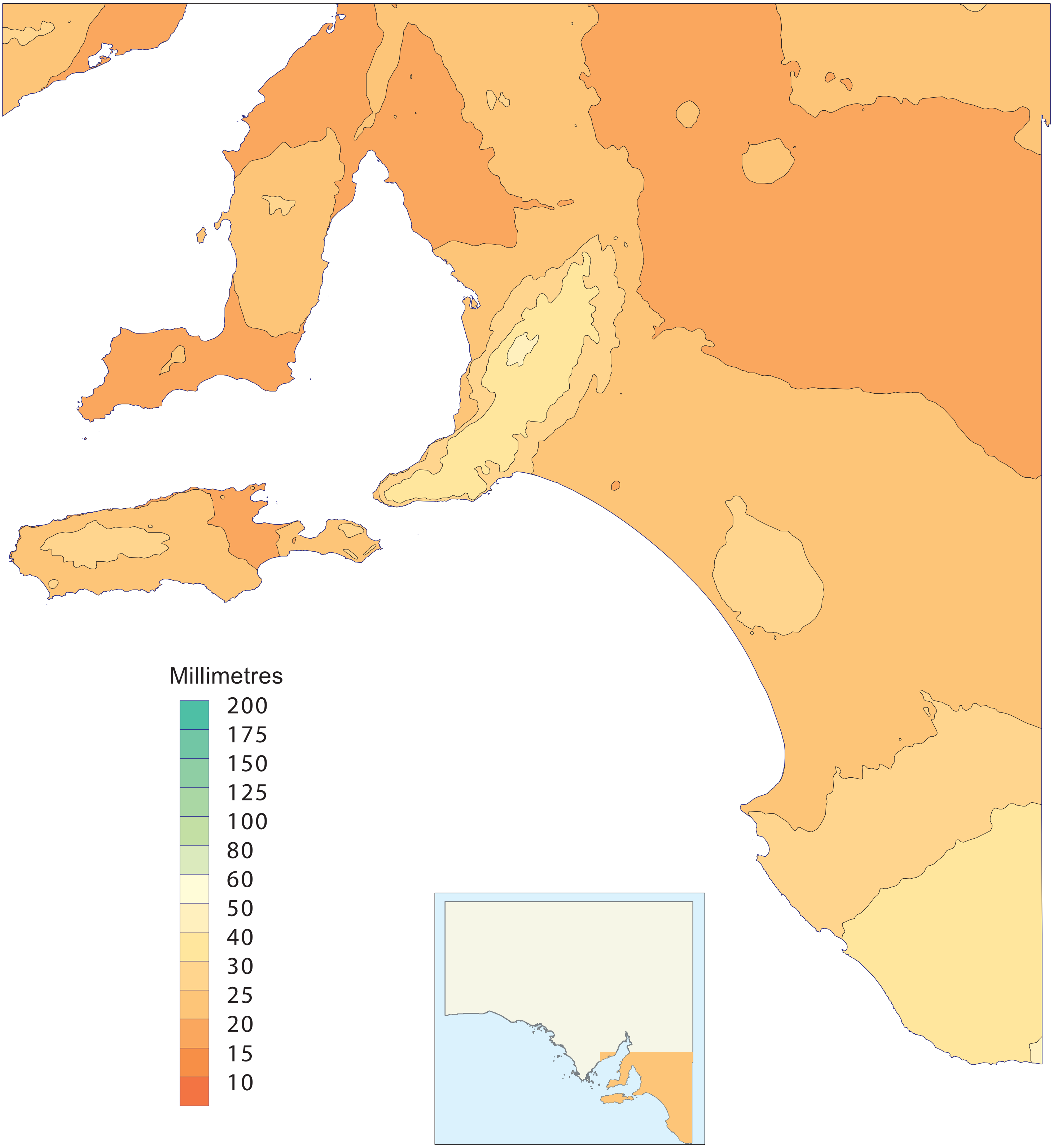
Department of Water, Land and Biodiversity Conservation

Projection: Lambert conformal with standard parallels $10^{o}S$, $40^{o}S$.
Based on a 30-year climatology (1971 - 2000).

Produced by the Bureau of Meteorology, National Climate Centre.

Average rainfall - December



Millimetres

200
175
150
125
100
80
60
50
40
30
25
20
15
10

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0 40 80 120 160 km

Scale 1 : 2,600,000

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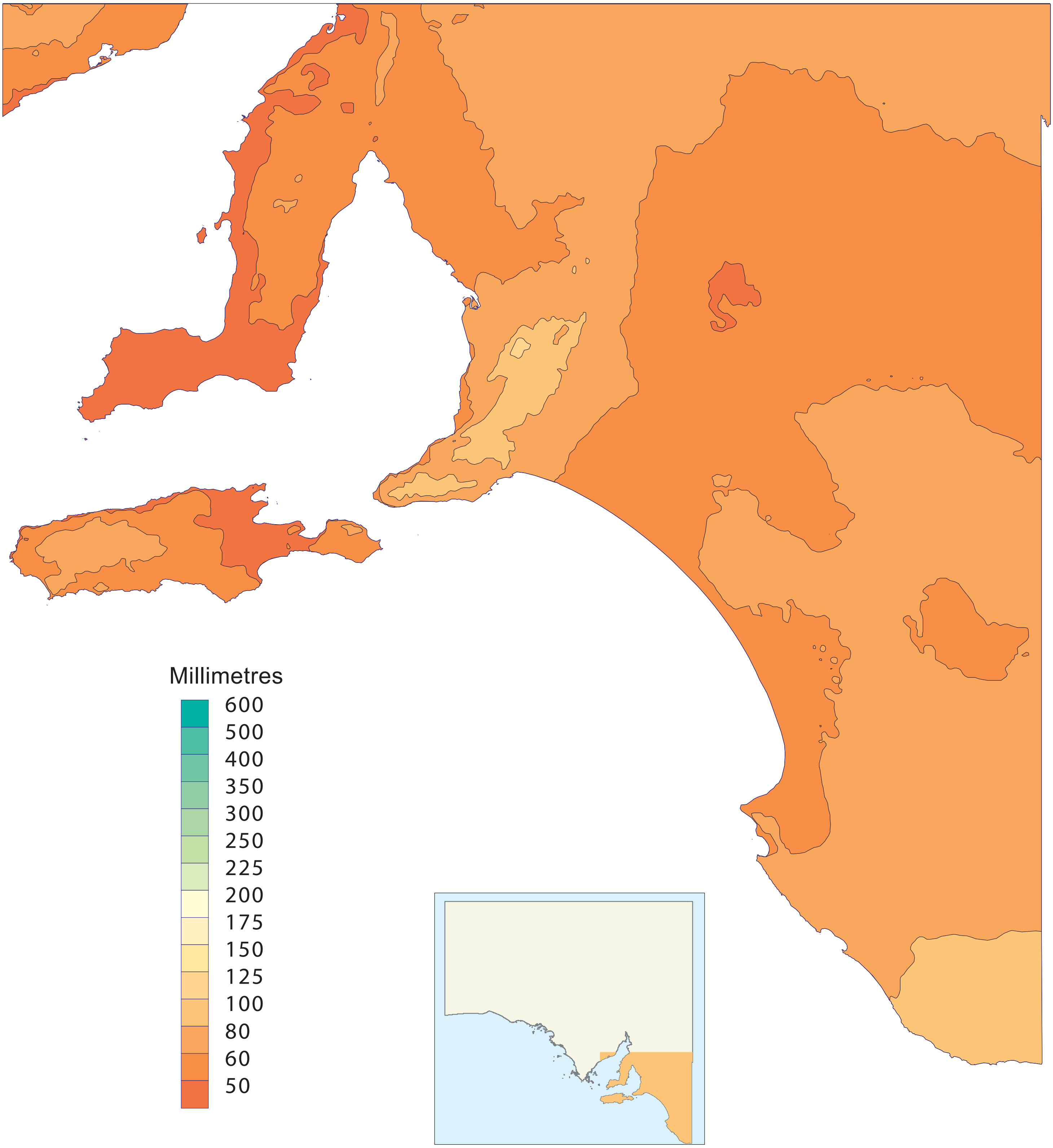
Based on a 30-year climatology (1971 - 2000).

Average rainfall - Summer



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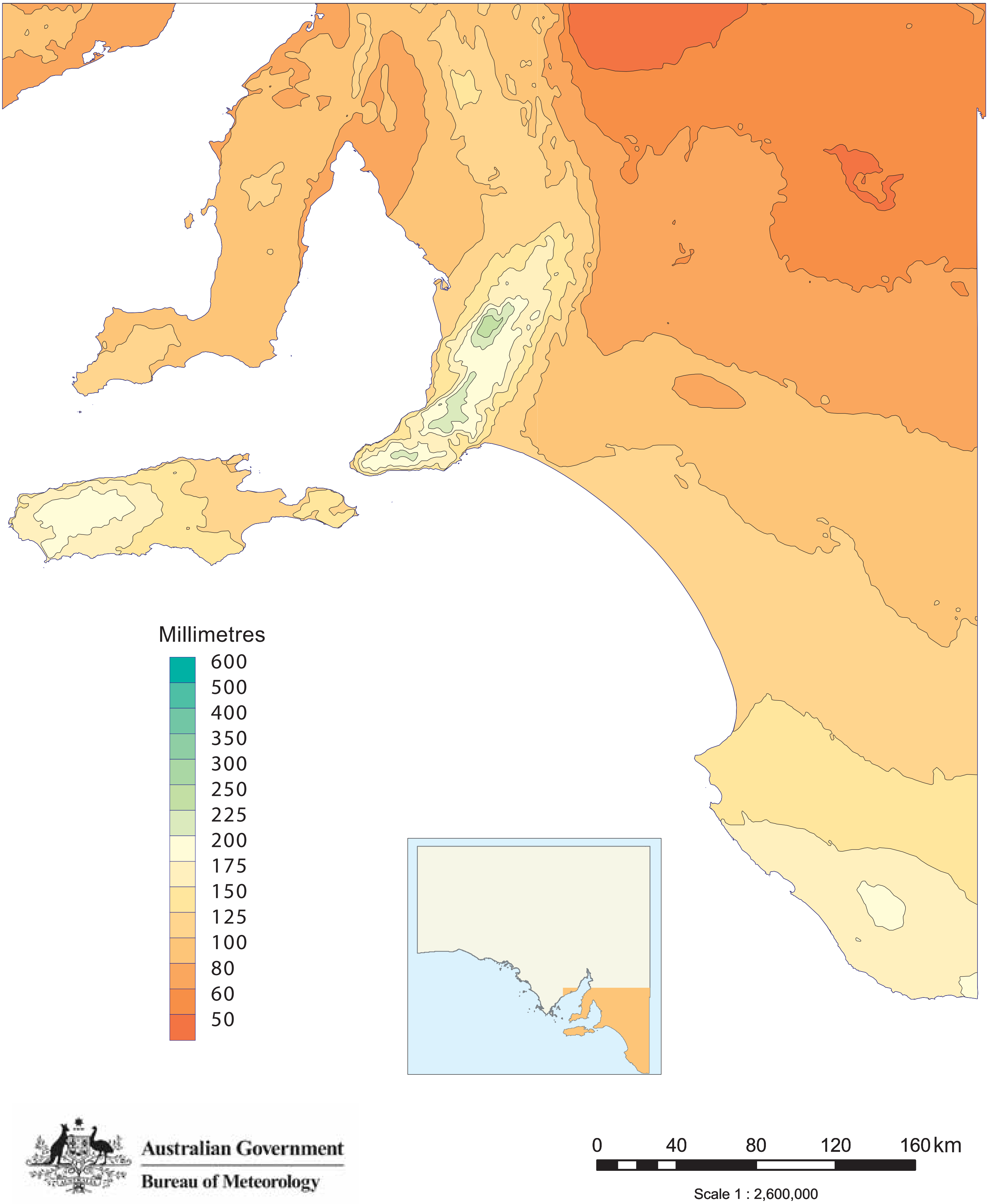
0 40 80 120 160 km

Scale 1 : 2,600,000

Projection: Lambert conformal with standard parallels 10°S, 40°S.
Based on a 30-year climatology (1971 - 2000).

Average rainfall - Autumn



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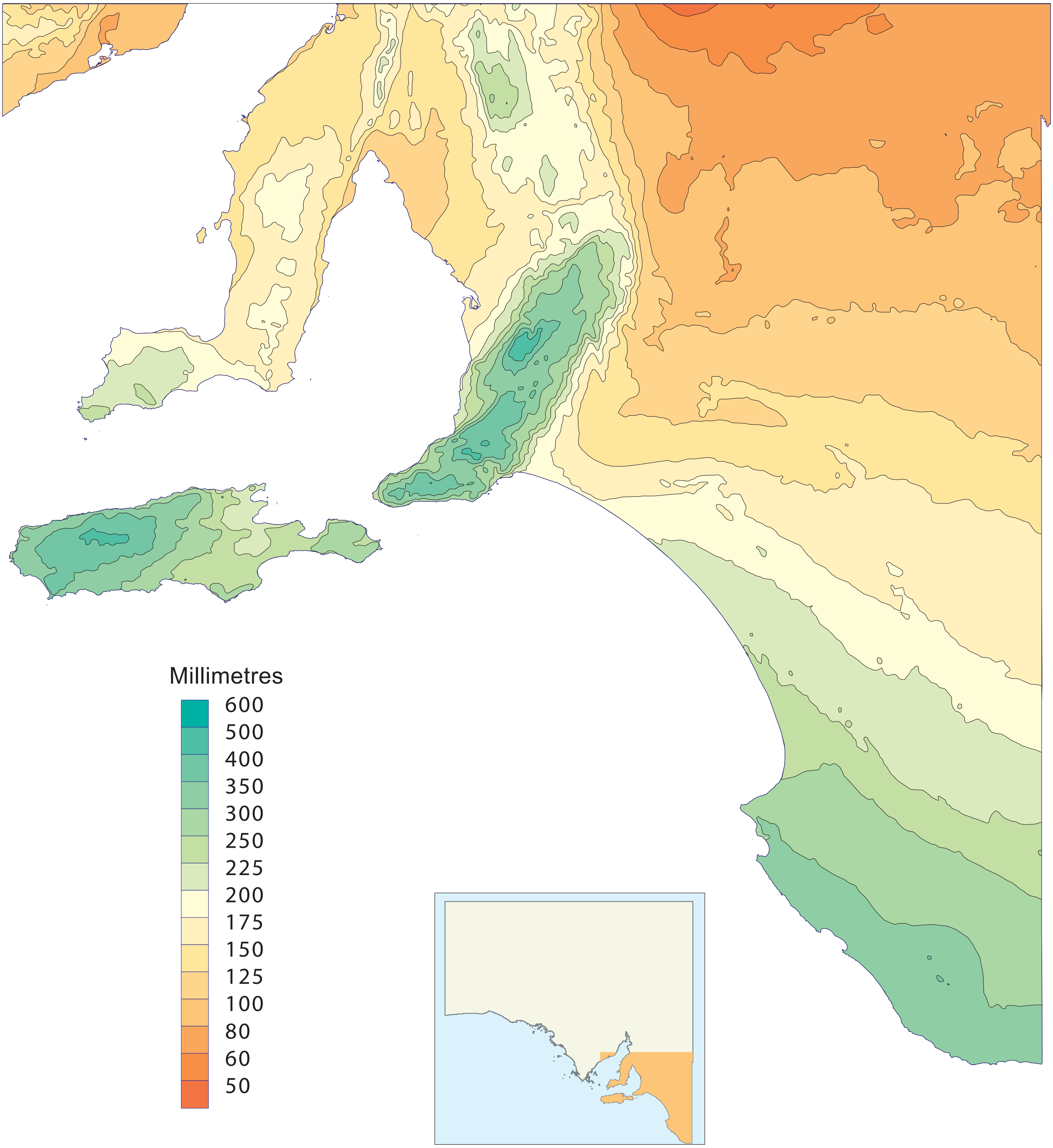
Projection: Lambert conformal with standard parallels 10°S, 40°S.
Based on a 30-year climatology (1971 - 2000).

Produced by the Bureau of Meteorology, National Climate Centre.

Average rainfall - Winter



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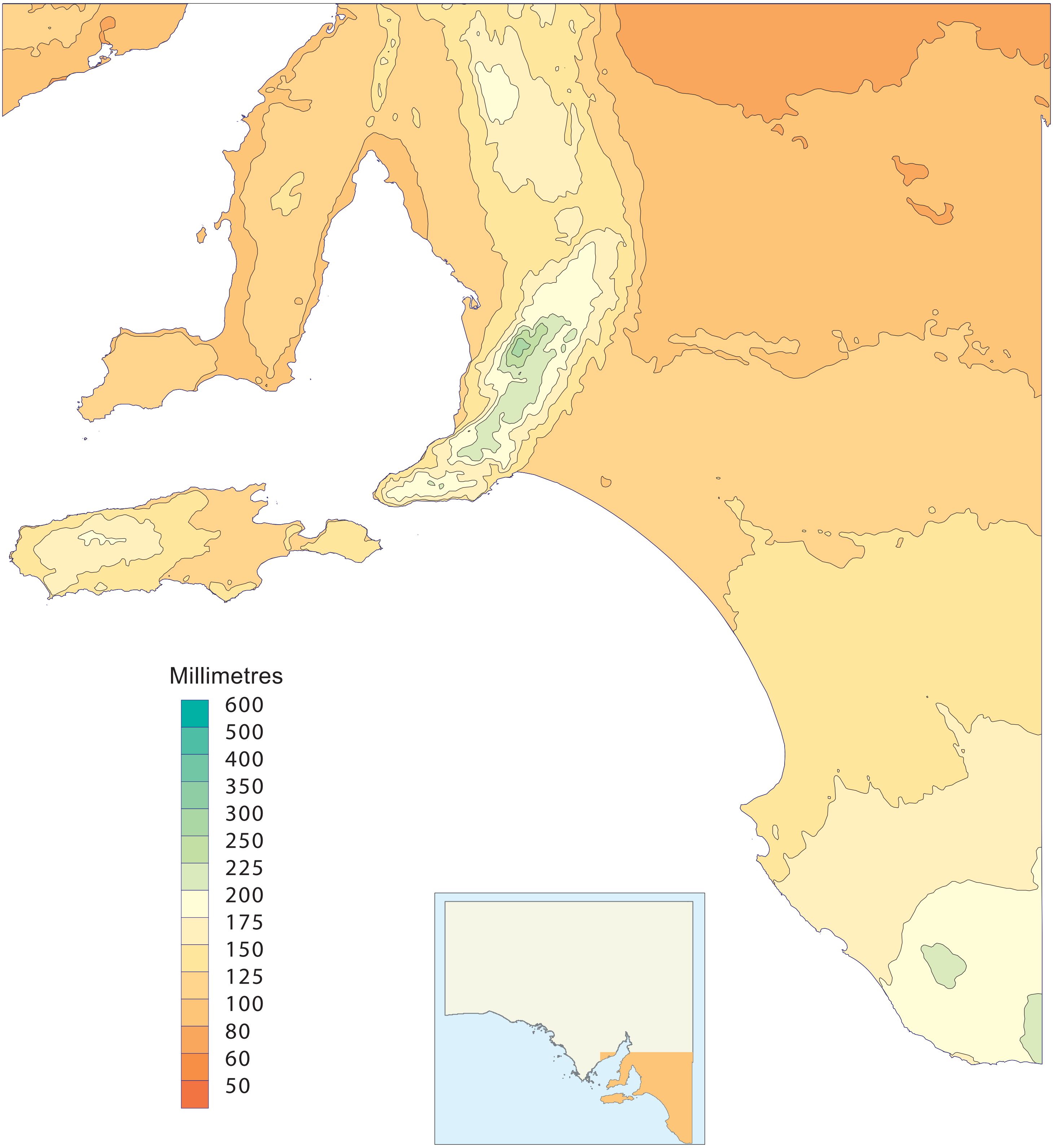
0 40 80 120 160 km

Scale 1 : 2,600,000

Projection: Lambert conformal with standard parallels 10°S, 40°S.
Based on a 30-year climatology (1971 - 2000).

Produced by the Bureau of Meteorology, National Climate Centre.

Average rainfall - Spring



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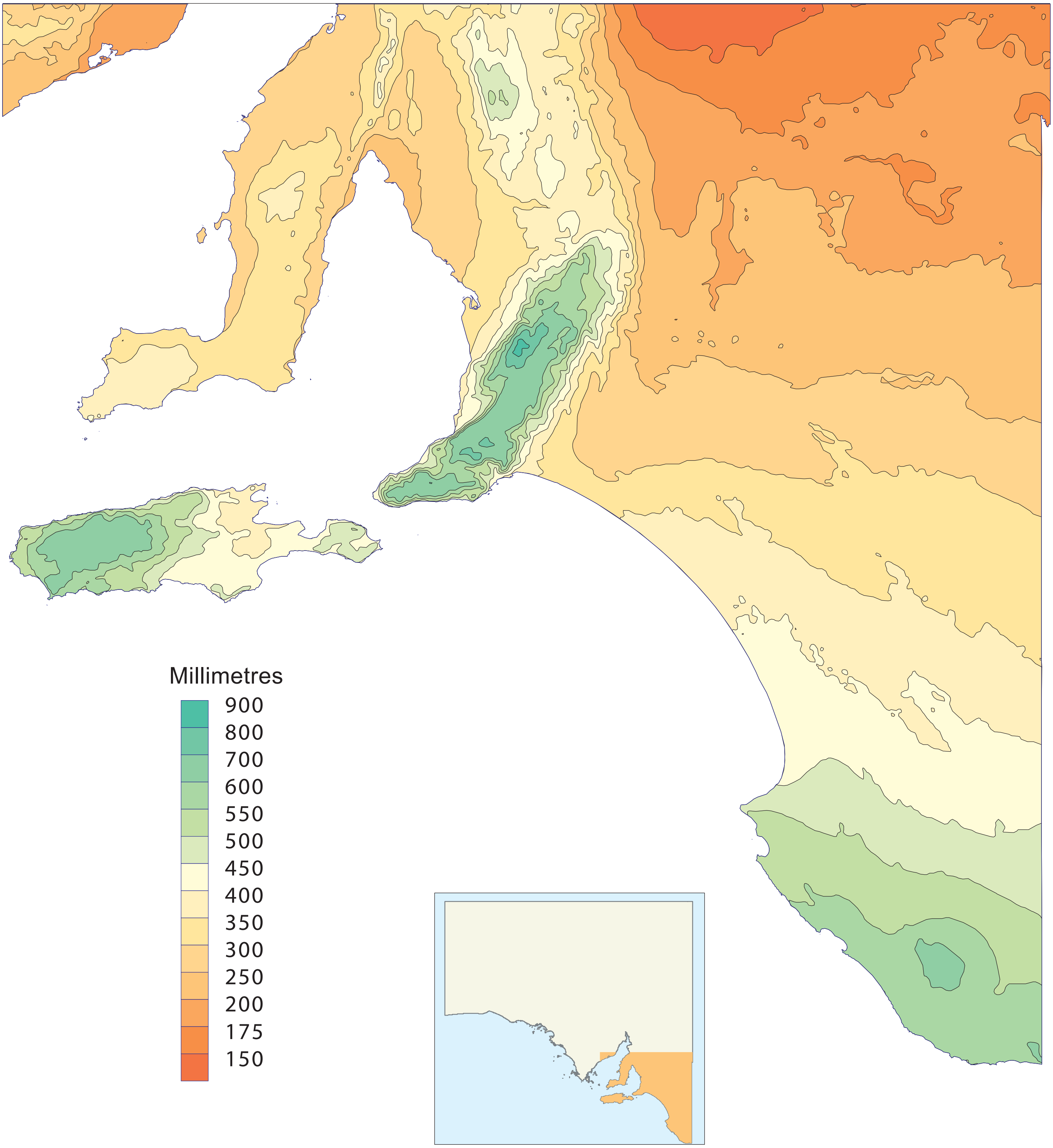
0 40 80 120 160 km

Scale 1 : 2,600,000

Projection: Lambert conformal with standard parallels 10°S, 40°S.
Based on a 30-year climatology (1971 - 2000).

Produced by the Bureau of Meteorology, National Climate Centre.

Average rainfall - Wet



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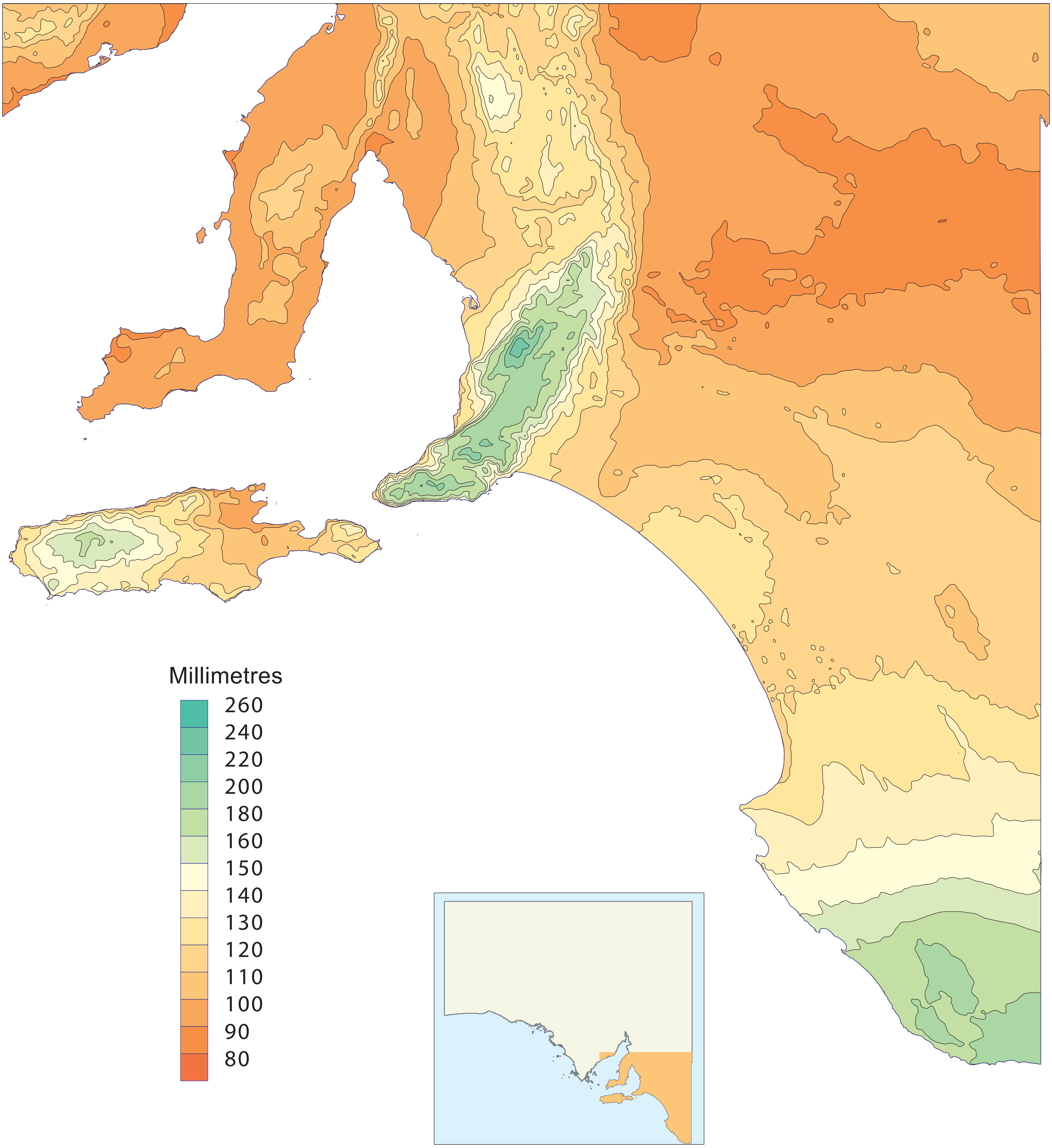
0 40 80 120 160 km

Scale 1 : 2,600,000

Projection: Lambert conformal with standard parallels 10°S, 40°S.
Based on a 30-year climatology (1971 - 2000).

Produced by the Bureau of Meteorology, National Climate Centre.

Average rainfall - Dry



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Department of Water, Land and Biodiversity Conservation

0 40 80 120 160 km

Scale 1 : 2,600,000

Projection: Lambert conformal with standard parallels 10°S, 40°S.
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