

mates. This is on account of the dew-fall in grassland climates not being a significant moisture contributor (in comparison with the total rain that falls in grassland climates). Whereas this climate subdivision is found in the desert regions on the west coasts of the other two southern hemisphere continents, the relative humidity in the west coast desert region of Australia is far too low for the climate to be characterised as high humidity.

- (11) Some equatorial and tropical subdivisions (those equatorial and tropical climates with an autumn rainfall maximum, those with a high-sun dry season, and those with a hottest month prior to the summer solstice) are considered to be minor and have therefore been absorbed into the other equatorial and tropical subdivisions.
- (12) Some subtropical and temperate subdivisions (those subtropical and temperate climates that are isothermal, those that have a hottest month prior to the summer solstice, and those with a late-spring/early-summer rainfall maximum) are also considered to be minor and have therefore been absorbed into other subtropical and temperate subdivisions.

Method of analysis

The above issues have been addressed in preparing the new climate classification. The new climate classification is defined in the Appendix. It is illustrated over Australia in Fig. 1, which presents the key climate groups, and Fig. 2, which presents the subdivisions within those groups. Figures 1 and 2 may be contrasted with the presentation of Köppen's original scheme, as depicted by Trewartha (1943). Although many features are depicted in a similar manner in both the old and new schemes, the detail is greatly enhanced in the new scheme.

A previous paper by the present authors (Stern et al. 1999) depicted an analysis of climate groups and subdivisions over Australia. That analysis, also as defined in the Appendix, is based on a 'smoothed' 25 km grid spacing. That paper employed the Barnes analysis technique, as modified and described by Jones and Weymouth (1997). However, the disadvantages of that approach were that the smoothing was too great to allow depiction of some of the very fine detail, and that the Barnes approach does not adequately reflect the impact of altitude in sparse data and mountainous areas.

The present paper's analyses are generated using Hutchinson's interpolation method of thin plate smoothing splines (Hutchinson 1995). The analysis

and interpolation are done in three dimensions, incorporating elevation as well as latitude and longitude, at a resolution of 0.025 degrees. The interpolated (gridded) data are then smoothed using a one-pass 13x13 binomial smoother.

The gridded data are based on the Australian Bureau of Meteorology's (BoM) mean monthly rainfall, mean annual rainfall, mean maximum temperature, and mean minimum temperature gridded datasets (39 gridded datasets in total), the datasets forming part of an updated Australian rainfall and temperature climatology. Humidity data were not available in gridded form but, because no Australian desert station's humidity data came close to satisfying the 'humid' criterion, it was assumed that no Australian desert climate should be classified as 'humid'. Station data used to generate the gridded datasets were extracted from the BoM's national climate database, ADAM (Australian Data Archive for Meteorology). The data extracted from ADAM, approximately 6000 sites with rainfall data and approximately 600 sites with temperature data, conformed to the WMO (World Meteorological Organization) guidelines for the quality and continuity of data used in climatological analyses (WMO 1989). Also, in keeping with the WMO guidelines, the 30-year period 1961–1990 was used as the standard averaging period. The 39 smoothed rainfall and temperature grids are then objectively combined (on a gridcell by gridcell basis) according to the rules for classification.

One possible deficiency of the approach may arise if an inappropriate grid length is used. For example, if the grid length is too large, important detail may be lost; by contrast, if the grid length is too small, unimportant detail may clutter the maps.

A second possible deficiency is that in some parts of Australia, notably central Australia, observation sites are well scattered, although the statistical technique used largely overcomes the impact of this deficiency by taking into account the influence of topographical features of the landscape.

Summary and conclusion

A modification of the Köppen classification of world climates has been presented. The extension has been illustrated by its application to Australian climates. Even with the additional complexity, the final classification contains some surprising homogeneity. For example, there is a common classification between the coastal areas of both southern Victoria and southern New South Wales. There is also the identical classification of western and eastern Tasmania. This aris-

es due to the classification not identifying every climate variation because a compromise has to be reached between sacrificing either detail or simplicity. For example, regions with only a slight annual cycle in rainfall distribution do not have that variation so specified in the classification. Similarly, regions with only slightly different mean annual temperatures are sometimes classified as being of the same climate.

The classification descriptions need to be concise, for ease of reference. As a result, the descriptions are not always complete. For example, the word 'hot' is used in reference to those deserts with the highest annual average temperatures, even though winter nights, even in hot desert climates, can't realistically be described as 'hot'.

In conclusion, the authors see the classification assisting in the selection of new station networks. There is also the potential for undertaking subsequent studies that examine climate change in the terms of shifts in climate classification boundaries by using data from different historical periods, and by using different characteristics to define climate type such as 'inter-annual variability of precipitation'. In the future, it is planned to prepare climate classification maps on a global scale, as well as on a regional Australian scale.

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Appendix

Defining the climate groups and subdivisions.

The source data upon which the classification is based

Where \rightarrow min1, max1, rn1, rh1; min2, max2, rn2, rh2; etc., represent the mean minimum temperature, maximum temperature, total rainfall and relative humidity of Jan., Feb., etc.

Defining the derived data and classification criteria

↓(defining the **Temperature** elements)

$tm1 = (\min1 + \max1) / 2$ $tm2 = (\min2 + \max2) / 2$ etc.
 $ta = (tm1 + tm2 + \dots + tm12) / 12$ $tw = \max(tm1, tm2, \dots, tm12)$ $tc = \min(tm1, tm2, \dots, tm12)$

↓(defining the **Temperature** criteria)

$t1 = (tw - tc)lt5$ $t2 = (ta)ge18$ $t3 = (tw)ge18$ $t4 = (tw)ge22$ $t5 = (tw)ge10$ $t6 = (tw)ge0$
 $t7 = (((tm1)ge10) + \dots + ((tm12)ge10))gt3$ $t8 = (tc)ge18$ $t9 = (tc)ge-3$ $t10 = (tc)ge-38$

↓(defining the **Precipitation** elements)

$ra = (rn1 + rn2 + \dots + rn12)$ $rd = \min(rn1, rn2, \dots, rn12)$ $rws = \max(rn12, rn1, rn2)$ $rds = \min(rn12, rn1, rn2)$
 $rww = \max(rn6, rn7, rn8)$ $rdw = \min(rn6, rn7, rn8)$
 $rwau = \max(rn3, rn4, rn5)$ $rwsp = \max(rn9, rn10, rn11)$

↓(defining the **Precipitation** criteria)

$p1 = ((rds)le30 \text{ and } (rww)gt30 \text{ and } (rww)ge(3*(rds))) \text{ and not } ((rws)ge(10*(rdw)))$
 $p2 = ((rdw)le30 \text{ and } (rws)gt30 \text{ and } (rws)ge(10*(rdw))) \text{ and not } ((rww)ge(3*(rds)))$
 $p3 = (ra)lt(10*(ta))$ $p4 = (ra)lt(10*((ta)+7))$ $p5 = (ra)lt(10*((ta)+14))$ $p6 = (ra)lt(20*(ta))$
 $p7 = (ra)lt(20*((ta)+7))$ $p8 = (ra)lt(20*((ta)+14))$ $p9 = (rd)lt60$ $p10 = (rd)lt(100-(ra/25))$
 $p11 = \text{not } (((p2) \text{ and } (p5)) \text{ or } ((p1) \text{ and } (p3)) \text{ or } ((p4) \text{ and not } ((p1) \text{ or } (p2))) \text{ or } ((p2) \text{ and } (p8) \text{ and not } (p5)) \text{ or } ((p1) \text{ and } (p6) \text{ and not } (p3)) \text{ or } ((p7) \text{ and not } ((p1) \text{ or } (p2) \text{ or } (p4))))$
 $p12 = ((rws)ge(3*(rdw))) \text{ and } ((rdw)le30) \text{ and not } ((rww)ge(3*(rds)))$
 $p13 = (rwau) \text{ gt } \max(rws, rww) \text{ and } (rwsp) \text{ gt } \max(rws, rww)$

↓(defining the **Humidity** element)

$h = (rh1 + rh2 + \dots + rh12) / 12$

↓(defining the **Humidity** criterion)

$h1 = (h)gt70$

Defining the climate classes

↓(generating the **Desert** climates)

$de1 = [p4 \text{ and not}(p1 \text{ or } p2 \text{ or } h1)] \text{ and } t2 = \text{hot (persistently dry)}$
 $de2 = [p1 \text{ and } p3 \text{ and not}(h1)] \text{ and } t2 = \text{hot (summer drought)}$
 $de3 = [p2 \text{ and } p5 \text{ and not}(h1)] \text{ and } t2 = \text{hot (winter drought)}$
 $de4 = [p4 \text{ and not}(p1 \text{ or } p2 \text{ or } h1)] \text{ and } [t3 \text{ and not}(t2)] = \text{warm (persistently dry)}$
 $de5 = [p1 \text{ and } p3 \text{ and not}(h1)] \text{ and } [t3 \text{ and not}(t2)] = \text{warm (summer drought)}$
 $de6 = [p2 \text{ and } p5 \text{ and not}(h1)] \text{ and } [t3 \text{ and not}(t2)] = \text{warm (winter drought)}$
 $de7 = [p4 \text{ and not}(p1 \text{ or } p2 \text{ or } h1)] \text{ and } [t5 \text{ and not}(t3)] = \text{cool (persistently dry)}$
 $de8 = [p1 \text{ and } p3 \text{ and not}(h1)] \text{ and } [t5 \text{ and not}(t3)] = \text{cool (summer drought)}$
 $de9 = [p2 \text{ and } p5 \text{ and not}(h1)] \text{ and } [t5 \text{ and not}(t3)] = \text{cool (winter drought)}$
 $de10 = [h1] \text{ and } \{[p4 \text{ and not}(p1 \text{ or } p2)] \text{ or } \{p1 \text{ and } p3\} \text{ or } \{p2 \text{ and } p5\}\} = \text{humid}$

↓(generating the **Grassland** climates)

$gr1 = [p7 \text{ and not}(p1 \text{ or } p2 \text{ or } h1)] \text{ and } t2 = \text{hot (persistently dry)}$
 $gr2 = [p1 \text{ and } p6 \text{ and not}(h1)] \text{ and } t2 = \text{hot (summer drought)}$
 $gr3 = [p2 \text{ and } p8 \text{ and not}(h1)] \text{ and } t2 = \text{hot (winter drought)}$
 $gr4 = [p7 \text{ and not}(p1 \text{ or } p2 \text{ or } h1)] \text{ and } [t3 \text{ and not}(t2)] = \text{warm (persistently dry)}$
 $gr5 = [p1 \text{ and } p6 \text{ and not}(h1)] \text{ and } [t3 \text{ and not}(t2)] = \text{warm (summer drought)}$
 $gr6 = [p2 \text{ and } p8 \text{ and not}(h1)] \text{ and } [t3 \text{ and not}(t2)] = \text{warm (winter drought)}$
 $gr7 = [p7 \text{ and not}(p1 \text{ or } p2 \text{ or } h1)] \text{ and } [t5 \text{ and not}(t3)] = \text{cool (persistently dry)}$
 $gr8 = [p1 \text{ and } p6 \text{ and not}(h1)] \text{ and } [t5 \text{ and not}(t3)] = \text{cool (summer drought)}$
 $gr9 = [p2 \text{ and } p8 \text{ and not}(h1)] \text{ and } [t5 \text{ and not}(t3)] = \text{cool (winter drought)}$

↓(generating the **Equatorial** climates)

$eq1 = [t1 \text{ and } t8] \text{ and } [p11 \text{ and not}(p9)] = \text{rainforest (persistently wet)}$
 $eq2 = [t1 \text{ and } t8] \text{ and } [p9 \text{ and } p11 \text{ and not}(p10 \text{ or } p13)] = \text{rainforest (monsoonal)}$
 $eq3 = [t1 \text{ and } t8] \text{ and } [p9 \text{ and } p11 \text{ and } p13 \text{ and not}(p10)] = \text{rainforest(double monsoonal)}$
 $eq4 = [t1 \text{ and } t8] \text{ and } [p9 \text{ and } p10 \text{ and } p11] = \text{savanna}$

↓(generating the **Tropical** climates)

$tr1 = [t8 \text{ and not}(t1)] \text{ and } [p11 \text{ and not}(p9)] = \text{rainforest (persistently wet)}$
 $tr2 = [t8 \text{ and not}(t1)] \text{ and } [p9 \text{ and } p11 \text{ and not}(p10)] = \text{rainforest (monsoonal)}$
 $tr3 = [t8 \text{ and not}(t1)] \text{ and } [p9 \text{ and } p10 \text{ and } p11] = \text{savanna}$

↓(generating the **Subtropical** climates)

$st1 = [t2 \text{ and not}(t8)] \text{ and } [not(p1 \text{ or } p2 \text{ or } p7 \text{ or } p12)] = \text{no dry season}$
 $st2 = [t2 \text{ and not}(t8)] \text{ and } [p12 \text{ and not}(p1 \text{ or } p2 \text{ or } p7)] = \text{moderately dry winter}$
 $st3 = [t2 \text{ and not}(t8)] \text{ and } [p2 \text{ and not}(p8)] = \text{distinctly dry winter}$
 $st4 = [t2 \text{ and not}(t8)] \text{ and } [p1 \text{ and not}(p6)] = \text{distinctly dry summer}$

↓(generating the **Temperate** climates)

$te1 = [t4 \text{ and } t9 \text{ and not}(t2)] \text{ and } [not(p1 \text{ or } p2 \text{ or } p7 \text{ or } p12)] = \text{no dry season (hot summer)}$
 $te2 = [t4 \text{ and } t9 \text{ and not}(t2)] \text{ and } [p12 \text{ and not}(p1 \text{ or } p2 \text{ or } p7)] = \text{moderately dry winter (hot summer)}$
 $te3 = [t4 \text{ and } t9 \text{ and not}(t2)] \text{ and } [p2 \text{ and not}(p8)] = \text{distinctly dry winter (hot summer)}$
 $te4 = [t4 \text{ and } t9 \text{ and not}(t2)] \text{ and } [p1 \text{ and not}(p6)] = \text{distinctly dry (and hot) summer}$
 $te5 = [t3 \text{ and } t9 \text{ and not}(t4)] \text{ and } [not(p1 \text{ or } p2 \text{ or } p7 \text{ or } p12)] = \text{no dry season (warm summer)}$
 $te6 = [t3 \text{ and } t9 \text{ and not}(t4)] \text{ and } [p12 \text{ and not}(p1 \text{ or } p2 \text{ or } p7)] = \text{moderately dry winter (warm summer)}$
 $te7 = [t3 \text{ and } t9 \text{ and not}(t4)] \text{ and } [p2 \text{ and not}(p8)] = \text{distinctly dry winter (warm summer)}$
 $te8 = [t3 \text{ and } t9 \text{ and not}(t4)] \text{ and } [p1 \text{ and not}(p6)] = \text{distinctly dry (and warm) summer}$
 $te9 = [t7 \text{ and } t9 \text{ and not}(t3)] \text{ and } [not(p1 \text{ or } p2 \text{ or } p7 \text{ or } p12)] = \text{no dry season (mild summer)}$
 $te10 = [t7 \text{ and } t9 \text{ and not}(t3)] \text{ and } [p12 \text{ and not}(p1 \text{ or } p2 \text{ or } p7)] = \text{moderately dry winter (mild summer)}$
 $te11 = [t7 \text{ and } t9 \text{ and not}(t3)] \text{ and } [p2 \text{ and not}(p8)] = \text{distinctly dry winter (mild summer)}$
 $te12 = [t7 \text{ and } t9 \text{ and not}(t3)] \text{ and } [p1 \text{ and not}(p6)] = \text{distinctly dry (and mild) summer}$
 $te13 = [t5 \text{ and } t9 \text{ and not}(t7)] \text{ and } [not(p1 \text{ or } p2 \text{ or } p7 \text{ or } p12)] = \text{no dry season (cool summer)}$
 $te14 = [t5 \text{ and } t9 \text{ and not}(t7)] \text{ and } [p12 \text{ and not}(p1 \text{ or } p2 \text{ or } p7)] = \text{moderately dry winter (cool summer)}$
 $te15 = [t5 \text{ and } t9 \text{ and not}(t7)] \text{ and } [p2 \text{ and not}(p8)] = \text{distinctly dry winter (cool summer)}$
 $te16 = [t5 \text{ and } t9 \text{ and not}(t7)] \text{ and } [p1 \text{ and not}(p6)] = \text{distinctly dry (and cool) summer}$

↓(generating the **Cold** climates)

co1= [t4 and t10 and not(t2 or t9)] and [not(p1 or p2 or p7 or p12)] = no dry season
 (hot summer)
 co2= [t4 and t10 and not(t2 or t9)] and [p12 and not(p1 or p2 or p7)] = moderately dry winter (hot summer)
 co3= [t4 and t10 and not(t2 or t9)] and [p2 and not(p8)] = distinctly dry winter (hot summer)
 co4= [t4 and t10 and not(t2 or t9)] and [p1 and not(p6)] = distinctly dry (and hot) summer
 co5= [t3 and t10 and not(t4 or t9)] and [not(p1 or p2 or p7 or p12)] = no dry season
 (warm summer)
 co6= [t3 and t10 and not(t4 or t9)] and [p12 and not(p1 or p2 or p7)] = moderately dry winter (warm summer)
 co7= [t3 and t10 and not(t4 or t9)] and [p2 and not(p8)] = distinctly dry winter (warm summer)
 co8= [t3 and t10 and not(t4 or t9)] and [p1 and not(p6)] = distinctly dry (and warm) summer
 co9= [t7 and t10 and not(t3 or t9)] and [not(p1 or p2 or p7 or p12)] = no dry season
 (mild summer)
 co10= [t7 and t10 and not(t3 or t9)] and [p12 and not(p1 or p2 or p7)] = moderately dry winter (mild summer)
 co11= [t7 and t10 and not(t3 or t9)] and [p2 and not(p8)] = distinctly dry winter (mild summer)
 co12= [t7 and t10 and not(t3 or t9)] and [p1 and not(p6)] = distinctly dry (and mild) summer
 co13= [t5 and t10 and not(t7 or t9)] and [not(p1 or p2 or p7 or p12)] = no dry season
 (cool summer)
 co14= [t5 and t10 and not(t7 or t9)] and [p12 and not(p1 or p2 or p7)] = moderately dry winter (cool summer)
 co15= [t5 and t10 and not(t7 or t9)] and [p2 and not(p8)] = distinctly dry winter (cool summer)
 co16= [t5 and t10 and not(t7 or t9)] and [p1 and not(p6)] = distinctly dry (and cool) summer
 co17= t5 and not (t10) = very severe winter

↓(generating the **Polar** climates)

po1= t6 and t9 and not(t5) = maritime
 po2= t6 and not(t5 or t9) = tundra
 po3= not(t6) = perpetual frost