| Algorithm | POD | $POD_n$ | AE | VE |
|---|---|---|---|---|
| ARPS SLW | 0.08 | 1.00 | 1.51 | 1.09 |
| NCAR/RAP | 0.44 | 0.97 | 0.67 | 0.46 |
| Stovepipe | 0.35 | 0.97 | 0.78 | 0.61 |
| AFGWC | 0.35 | 0.98 | 0.45 | 0.33 |
| Tremblay | 0.39 | 0.97 | 0.79 | 0.32 |
| LAPS | 0.09 | 1.00 | 1.43 | 1.08 |

**Table 4: Average performance statistics for forecasting any icing. AE and VE are in units of $10^{-6}$ $km^{-2}$ and $10^{-6}$ $km^{-3}$, respectively.**

| Algorithm | POD | $POD_n$ | AE | VE |
|---|---|---|---|---|
| ARPS SLW | 0.08 | 0.98 | 1.50 | 1.08 |
| NCAR/RAP | 0.58 | 0.88 | 0.88 | 0.61 |
| Stovepipe | 0.31 | 0.89 | 0.69 | 0.54 |
| AFGWC | 0.40 | 0.90 | 0.51 | 0.37 |
| Tremblay | 0.42 | 0.89 | 0.84 | 0.35 |
| LAPS | 0.08 | 0.98 | 1.27 | 0.96 |

**Table 5: Average performance statistics for forecasting light-to-moderate or greater icing. AE and VE are in units of $10^{-6}$ $km^{-2}$ and $10^{-6}$ $km^{-3}$, respectively.**

| Algorithm | POD | $POD_n$ | AE | VE |
|---|---|---|---|---|
| ARPS TKE | 0.61 | 0.67 | 0.66 | 0.60 |
| TI | 0.52 | 0.60 | 0.64 | 0.19 |

**Table 6: Average performance statistics for forecasting any turbulence. AE and VE are in units of $10^{-6}$ $km^{-2}$ and $10^{-6}$ $km^{-3}$, respectively. TKE statistics exclude 00-hr forecasts.**

| Algorithm | POD | $POD_n$ | AE | VE |
|---|---|---|---|---|
| ARPS TKE | 0.58 | 0.49 | 0.62 | 0.57 |
| TI | 0.58 | 0.55 | 0.71 | 0.21 |

**Table 7: Average performance statistics for forecasting light-to-moderate or greater turbulence. AE and VE are in units of $10^{-6}$ $km^{-2}$ and $10^{-6}$ $km^{-3}$, respectively. TKE statistics exclude 00-hr forecasts.**

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P5.3

# OBJECTIVE CLASSIFICATION OF AUSTRALIAN CLIMATES

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## 1. INTRODUCTION

Köppen's scheme to classify world climates was devised in 1918 by Dr Wladimir Köppen of the University of Graz in Austria (Köppen, 1931; Köppen and Geiger, 1928; Köppen and Geiger, 1930-39). The present paper presents a modification of Köppen's scheme.

## 2. BACKGROUND

### *2.1 Outline of the Köppen classification*

The Köppen classification is based on the concept that native vegetation is the best expression of climate, climate zone boundaries having been selected with vegetation limits in mind (Trewartha, 1943). The classification may be applied to present-day climatic conditions. Alternatively, it also may be used to develop a future climatology that is implied by the output of a numerical climate model (Löhmann *et al.*, 1993).

Köppen recognises five principal groups of world climates that are intended to correspond with five principal vegetation groups. These five climatic groups may be described as tropical rainy, dry, temperate rainy, cold snowy forest, and polar.

The dry climates are defined on the basis of there being an excess of evaporation over precipitation (this is determined from the mean annual temperature and the mean annual rainfall). The tropical rainy climates are other climates with a mean temperature of the coolest month of at least 18°C. The polar climates are other climates with a mean temperature of the warmest month of below 10°C. The cold snowy forest climates are other climates with a mean temperature of the coolest month of below -3°C. Remaining climates are defined as temperate rainy. Each of these climates is further divided into sub-divisions based upon differences in the seasonal distribution of temperature and precipitation. For example, Köppen climates with distinctly dry winters are defined as those temperate rainy climates and cold snowy forest with at least ten times as much rain in the wettest summer month as in the driest winter month. Trewartha (1943) presents a full description of all of the subdivisions.

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### *2.2 Purpose*

The purpose of this paper is two-fold. Firstly, a new modification of Köppen's classification of world climates is presented. Secondly, the modification is illustrated with its application to Australia.

## 3. DISCUSSION

### *3.1 Criticisms of the Köppen classification*

Trewartha (1943) notes that Köppen's classification has been criticised from "various points of view" (Thornthwaite, 1931; Jones, 1932; Ackerman, 1942). Rigid boundary criteria often lead to large discrepancies between climatic subdivisions and features of the natural landscape. Some boundaries have been chosen largely with natural landscape features in mind, whilst other boundaries have been chosen largely with human experience of climatic features in mind. Trewartha (1943) acknowledges the validity of these criticisms when he writes that "climatic boundaries, as seen on a map, even when precisely defined, are neither better nor worse than the human judgements that selected them, and the wisdom of those selections is always open to debate". He emphasises, however, that such boundaries are always subject to change "with revision of boundary conditions ... (and that) ... such revisions have been made by Köppen himself and by other climatologists as well".

Nevertheless, the telling evidence that the Köppen classification's merits outweigh its deficiencies lies in its wide acceptance. Trewartha (1943) observes that "its individual climatic formulas are almost a common language among climatologists and geographers throughout the world ... (and that) ... its basic principals have been ... widely copied (even) by those who have insisted upon making their own empirical classifications".

Trewartha's (1943) comments are as relevant today as they were half a century ago (see, for example, Müller (1982); Löhmann *et al.* (1993)).

### *3.2 Modifying the Köppen classification*

For the aforementioned reasons, in modifying the Köppen classification, the present authors have chosen to only depart slightly from the original. Nevertheless, the additional division of some of the Köppen climates and some recombining of other Köppen climates may better reflect human experience of significant features. In recognition of this, the following changes have been adopted by the present work:

(1) The former tropical group is now divided into two new groups, an equatorial group and a new tropical group. The equatorial group corresponds to the former tropical group's isothermal subdivision. The new tropical group corresponds to that remaining of the former tropical group. This is done to strongly distinguish between those climates with a significant annual temperature cycle from those climates without one. Under this definition some climates, distant from the equator, are classified as equatorial. This is considered acceptable on account of that characteristic being typical of climates close to the equator.

(2) The equatorial and tropical group monsoon subdivisions are re-named as rainforest (monsoonal) subdivisions. This is done because, in these subdivisions, the dry season is so short, and the total rainfall is so great, that the ground remains sufficiently wet throughout the year to support rainforest.

(3) The former dry group is now divided into two new groups, a desert group and a grassland group. The new groups correspond to the former subdivisions of the dry group with the same name. This is done because of the significant differences between desert and grassland climates.

(4) The new desert and grassland winter drought (summer drought) subdivisions now require the additional criterion that there is more than 30 mm in the wettest summer month (winter month) to be so classified. This is done because drought conditions may be said to prevail throughout the year in climates without at least a few relatively wet months.

(5) The former temperate group is divided into two new groups, a temperate group and a subtropical group. The new subtropical group corresponds to that part of the former temperate group with a mean annual temperature of at least 18°C. The new temperate group corresponds to that part of the former temperate group remaining. This is done because of the significant differences in the vegetation found in areas characterised by the two new groups, and in order that there is continuity in the boundary between the hot and warm desert and grassland climates where they adjoin rainy climates.

(6) For the temperate, subtropical, and cold-snowy-forest group, the distinctly dry winter subdivision requires the additional criterion of no more than 30 mm in the driest winter month to be so classified. This is done in order that there be consistency between the criteria for the distinctly dry winter and the distinctly dry summer subdivisions.

(7) Carved out of the temperate, subtropical, and cold snowy forest groups no distinctly dry season subdivision is the moderately dry winter subdivision. This new subdivision receives at least three times (but less than ten times) the rainfall in the driest winter month. This subdivision has been added in order that there be a match with that part of the distinctly dry summer subdivision that was not matched by the distinctly dry winter subdivision.

(8) The polar group has added to it the subdivision polar maritime, this subdivision reflecting the climate of the sub-antarctic islands, which otherwise would have been classified (inappropriately) as polar tundra. Polar tundra would be an inappropriate description for climates where the average temperature of the coldest month is -3°C or above. This is because, with the temperature not well below freezing, it is difficult for the ground to become frozen (a characteristic of "polar tundra").

(9) The frequent fog desert and grassland climates are re-named as high-humidity climates. They are also defined in terms of mean annual relative humidity, rather than in terms of fog frequency. This is on account of the dew-fall that results from the high humidity being a significant contributor to plant moisture in regions with such climates. They are also restricted to desert climates. 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).

(10) 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.

(11) 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.

The above issues have been addressed in preparing the new climate classification, defined in Figure 1 and illustrated in Figure 2. The data, upon which the analysis in Figure 2 is based, are "smoothed" to a 25 km grid spacing using the Barnes analysis technique, as modified and described by Jones and Weymouth (1997). This analysis is further "smoothed" to eliminate regions with fewer than six adjacent grids of the same climate subdivision (unless this eliminates the only region with such a climate). It may be said that this smoothing is 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. Nevertheless, to show such fine detail on maps the scale of the Australian continent may diminish the map's primary aim, which is to provide a general picture of the distribution of climates.

## 4. CONCLUSION

### 4.1 Summary

A modification of the Köppen classification of world climates has been presented. The extension has been illustrated by its application to Australian climates. The classification does not identify 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".

### 4.2 Future Work

In the future, it is planned to prepare climate classification maps on a global scale, as well as on a regional-Australian scale, and to experiment with finer grids and analysis schemes that directly take altitude into account.

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**FIGURE 1** Defining the climate groups and subdivisions (continued over subsequent two pages).

```
Where → min1, max1, rn1; rh1, min2, max2, rn2; rh2... etc. represent the mean minimum temperature, maximum temperature, total rainfall and relative humidity of January, February, ... etc.
```

↓(defining the **Temperature** elements)

```
tm1= (min1+max1)/2  tm2= (min2+max2)/2 ... etc.
ta= (tm1+tm2+ ... +tm12)/12
tw= max(tm1,tm2, ... ,tm12)
tc= min(tm1,tm2, ... ,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)+ ... +((tm12)ge10))gt3)
t8= (tc)ge18  t9= (tc)ge-3  t10= (tc)ge -38
```

↓(defining the **Precipitation** elements)

```
rw= max(rn1,rn2,  rn12)   rd= min(rn1,rn2,  rn12)
rws= max(rn11,rn12,rn1)  rds= min(rn11,rn12,rn1)
```

**next column→**

```
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 and (rww)gt30 and (rww)ge(3*(rds)))
and not ((rws)ge(10*(rdw)))
p2= ((rdw)le30 and (rws)gt30 and
(rws)ge(10*(rdw))) 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= not (((p2) and (p5)) or ((p1) and (p3)) or ((p4)
and not ((p1) or (p2))) or ((p2) and (p8) and not
(p5)) or ((p1) and (p6) and not (p3)) or ((p7) and not
((p1) or (p2) or (p4)))
p12= ((rws)ge(3*(rdw))) and ((rdw)le30) and not
((rww)ge(3*(rds)))
p13= (rwau) gt max(rws, rww) and rwsp gt max(rws,
rww)
```

**next page→**

↓(defining the **Humidity** element)

h= (rh1+ rh2+ ... + rh12)/12

↓(defining the **Humidity** criterion)

h1= (h)gt70

↓(generating the **Desert** climates)

de1= p4 and t2 and not(p1 or p2 or h1) = hot (persistently dry)
de2= p1 and p3 and t2 and not(h1) = hot (summer drought)
de3= p2 and p5 and t2 and not(h1) = hot (winter drought)
de4= p4 and t3 and not(p1 or p2 or t2 or h1) = warm (persistently dry)
de5= p1 and p3 and t3 and not(t2 or h1) = warm (summer drought)
de6= p2 and p5 and t3 and not(t2 or h1) cont. → warm (winter drought)
de7 = p4 and t5 and not(p1 or p2 or t3 or h1) = cool (persistently dry)
de8 = p1 and p3 and t5 and not(t3 or h1) = cool (summer drought)
de9 = p2 and p5 and t5 and not(t3 or h1) = cool (winter drought)
de10 = ((p4 and not(p1 or p2)) or (p1 and p3) or (p2 and p5)) and h1 = humid

↓(generating the **Grassland** climates)

gr1= p7 and t2 and not(p1 or p2 or p4) = hot (persistently dry)
gr2= p1 and p6 and t2 and not(p3) = hot (summer drought)
gr3= p2 and p8 and t2 and not(p5) = hot (winter drought)
gr4= p7 and t3 and not(p1 or p2 or p4 or t2) = warm (persistently dry)
gr5= p1 and p6 and t3 and not(p3 or t2) = warm (summer drought)
gr6= p2 and p8 and t3 and not(p5 or t2) = warm (winter drought)
gr7= p7 and t5 and not(p1 or p2 or p4 or t3) = cool (persistently dry)
gr8= p1 and p6 and t5 and not(p3 or t3) = cool (summer drought)
gr9= p2 and p8 and t5 and not(p5 or t3) = cool (winter drought)

↓(generating the **Equatorial** climates)

eq1= p11 and t1 and t8 and not(p9) = rainforest (persistently wet)
eq2= p9 and p11 and t1 and t8 and not(p10 or p13)= rainforest (monsoonal)
eq3= p9 and p11 and p13 and t1 and t8 and not(p10) = rainforest(double monsoonal)
eq4= p9 and p10 and p11 and t1 and t8 = savanna

↓(generating the **Tropical** climates)

tr1= p11 and t8 and not(p9 or t1) = rainforest (persistently wet)
tr2= p9 and p11 and t8 and not(p10 or t1) = rainforest (monsoonal)
tr3= p9 and p10 and p11 and t8 and not(t1) = savanna **next column→**

↓(generating the **Subtropical** climates)

st1= t2 and not(p1 or p2 or p7 or p12 or t8) no dry season
st2= p12 and t2 and not(p1 or p2 or p7 or t8) moderately dry winter
st3= p2 and t2 and not(p8 or t8) distinctly dry winter
st4= p1 and t2 and not(p6 or t8) distinctly dry summer

↓(generating the **Temperate** climates)

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

↓(generating the **Cold** climates)

co1= t4 and t10 and not(p1 or p2 or p7 or p12 or t2 or t9) = no dry season (hot summer)
co2= p12 and t4 and t10 and not(p1 or p2 or p7 or t2 or t9) = moderately dry winter (hot summer)
co3= t4 and t10 and not(p1 or p2 or p7 or p12 or t2 or t9) = distinctly dry winter (hot summer)
co4= p1 and t4 and t10 and not(p6 or t2 or t9) = distinctly dry (and hot) summer
co5= t3 and t10 and not(p1 or p2 or p7 or p12 or t4 or t9) = no dry season (warm summer)
co6= p12 and t3 and t10 and not(p1 or p2 or p7 or t4 or t9) = moderately dry winter (warm summer)
co7= t3 and t10 and not(p1 or p2 or p7 or p12 or t4 or t9) = distinctly dry winter (warm summer)
co8= p1 and t3 and t10 and not(p6 or t4 or t9) = distinctly dry (and warm) summer
co9= t7 and t10 and not(p1 or p2 or p7 or p12 or t3 or t9) = no dry season (mild summer) **next page→**



co10= p12 and t7 and t10 and not(p1 or p2 or p7 or t3 or t9) = moderately dry winter (mild summer)
co11= t7 and t10 and not(p1 or p2 or p7 or p12 or t3 or t9) = distinctly dry winter (mild summer)
co12= p1 and t7 and t10 and not(p6 or t3 or t9) = distinctly dry (and mild) summer
co13= t5 and t10 and not(p1 or p2 or p7 or p12 or t5 or t7 or t9) = no dry season (cool summer)
co14= p12 and t5 and t10 and not(p1 or p2 or p7 or t7 or t9) = moderately dry winter (cool summer) **next column→**

co15= t5 and t10 and not(p1 or p2 or p7 or p12 or t7 or t9) = distinctly dry winter (cool summer)
co16= p1 and t5 and t10 and not(p6 or t7 or t9) = distinctly dry (and cool) summer
co17= t5 and not (t10) = Cold: 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

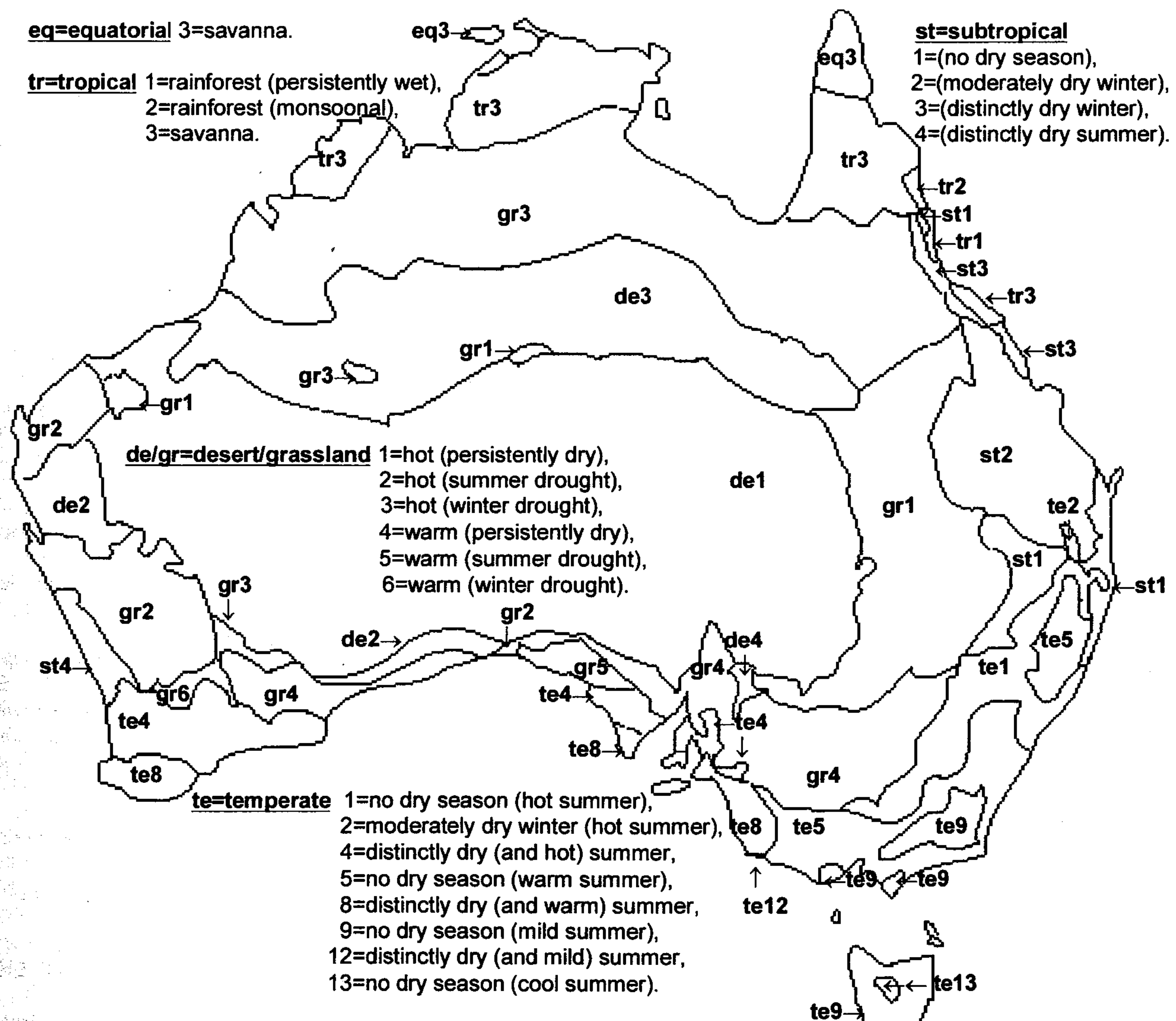


FIGURE 2 Classification of Australian Climates