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Objective classification of Australian climates

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Köppen's scheme to classify world climates was devised in 1918 by Dr Wladimir Köppen of the University of Graz in Austria. Over the decades it has achieved wide acceptance amongst climatologists. However, the scheme has also had its share of critics, who have challenged the scheme's validity on a number of grounds. For example, Köppen's rigid boundary criteria often lead to large discrepancies between climatic subdivisions and features of the natural landscape. Furthermore, whilst some of his boundaries have been chosen largely with natural landscape features in mind, other boundaries have been chosen largely with human experience of climatic features in mind. The present paper presents a modification of Köppen's classification that addresses some of the concerns and illustrates this modification with its application to Australia.

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, 1930-39). This paper presents a modification of Köppen's scheme.

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) – although the reliability of such a future climatology would be dependent upon the reliability of the numerical climate model output.

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 (which is determined from the mean annual temperature and the mean annual rainfall). The tropical rainy

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climates are climates, as yet unclassified, with a mean temperature of the coolest month of at least 18°C. The polar climates are climates, as yet unclassified, with a mean temperature of the warmest month of below 10°C. The cold snowy forest climates are climates, as yet unclassified, 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 subdivisions 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 climates 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 and provides a detailed map depicting the distribution around the globe of the original Köppen climates.

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.

Discussion

Trewartha (1943) notes that Köppen's classification has been criticised from 'various points of view' (Thornthwaite 1931; Jones 1932; Ackerman 1941). 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 (for example, 'rainforest'), whilst other boundaries have been chosen largely with human experience of climatic features in mind (for example, 'monsoon'). 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 principles 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)).

For the above reasons, in modifying the Köppen classification (Figs 1 and 2), the authors have chosen to depart only 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, which are also summarised in Table 1, have been adopted in this 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 distinguish strongly between those cli-

Table 1. A summary of key differences between Köppen's original scheme and the new scheme.

Köppen's original scheme	*New scheme*
Tropical group	Divided into equatorial & tropical groups
Monsoon subdivision	Becomes rainforest (monsoonal) subdivision
Dry group	Divided into desert & grassland groups
Summer/winter drought subdivisions	Now requires 30+mm in wettest month
Temperate group	Divided into subtropical & temperate groups
Cold-snowy-forest group	Cold group
Dry summer/winter subdivisions	Moderately dry winter subdivision added
Polar group	Maritime subdivision added
Frequent fog subdivision	Applies now only to the desert group
Frequent fog subdivision	Becomes high humidity subdivision
High-sun dry season subdivision	Absorbed into other subdivisions
Autumn rainfall max subdivision	Absorbed into other subdivisions
Other minor subdivisions	Absorbed into other subdivisions

mates with a significant annual temperature cycle from those climates without one (although this feature is not as marked in the Australian context, as elsewhere in the world). Under this definition some climates, distant from the equator, are classified as equatorial. This is considered acceptable as that characteristic is typical of climates close to the equator. Figure 1 shows that, in Australia, equatorial climates are confined to Queensland's Cape York Peninsula and the far north of the Northern Territory.

(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. Figure 2 shows that, in Australia, rainforest subdivisions are found along sections of the northern part of Queensland's east coast.

(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 desert and steppe subdivisions of the dry group. This is believed necessary because of the significant differences between the types of vegetation found in deserts and grasslands. That there is a part of central Australia covered by the grassland group of climates (Fig. 1) is a consequence of the higher rainfall due to the ranges in that region.

(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 change is carried out because drought conditions may be said to prevail throughout the year in climates without at least a few relatively wet months. It should be noted that the original set of Köppen climates employed the phrases ‘winter drought’ and ‘summer drought’ to respectively describe climates that are seasonally dry. Figure 2 shows that the summer drought subdivisions are found in the southern half of the country, whilst the winter drought subdivisions are found in the northern half of the country.

(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. Figure 1 shows that a large region, covering much of southeast Queensland and some elevated areas further north, is now characterised as subtropical.

(6) For simplicity, the former Köppen cold snowy forest group of climates is re-named as the cold group. Figure 1 shows that this climate is not found on the Australian mainland or in Tasmania.

(7) For the temperate, subtropical, and the cold groups, the distinctly dry winter subdivision requires the additional criterion of no more than 30 mm in the driest winter month to be so classified. In order that there be consistency between the criteria for the distinctly dry winter and the distinctly dry summer subdivisions, this is thought to be a worthwhile change. Figure 2 shows that, whereas that part of Western Australia characterised as subtropical has a distinctly dry summer, much of subtropical southeast Queensland has no distinctly dry season.

(8) Carved out of the temperate, subtropical, and the cold groups with 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. Figure 2 shows that parts of subtropical southeast Queensland have a moderately dry winter.

(9) 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’). Figure 1 shows that this climate is not found on the Australian mainland or in Tasmania.

(10) 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 cli-

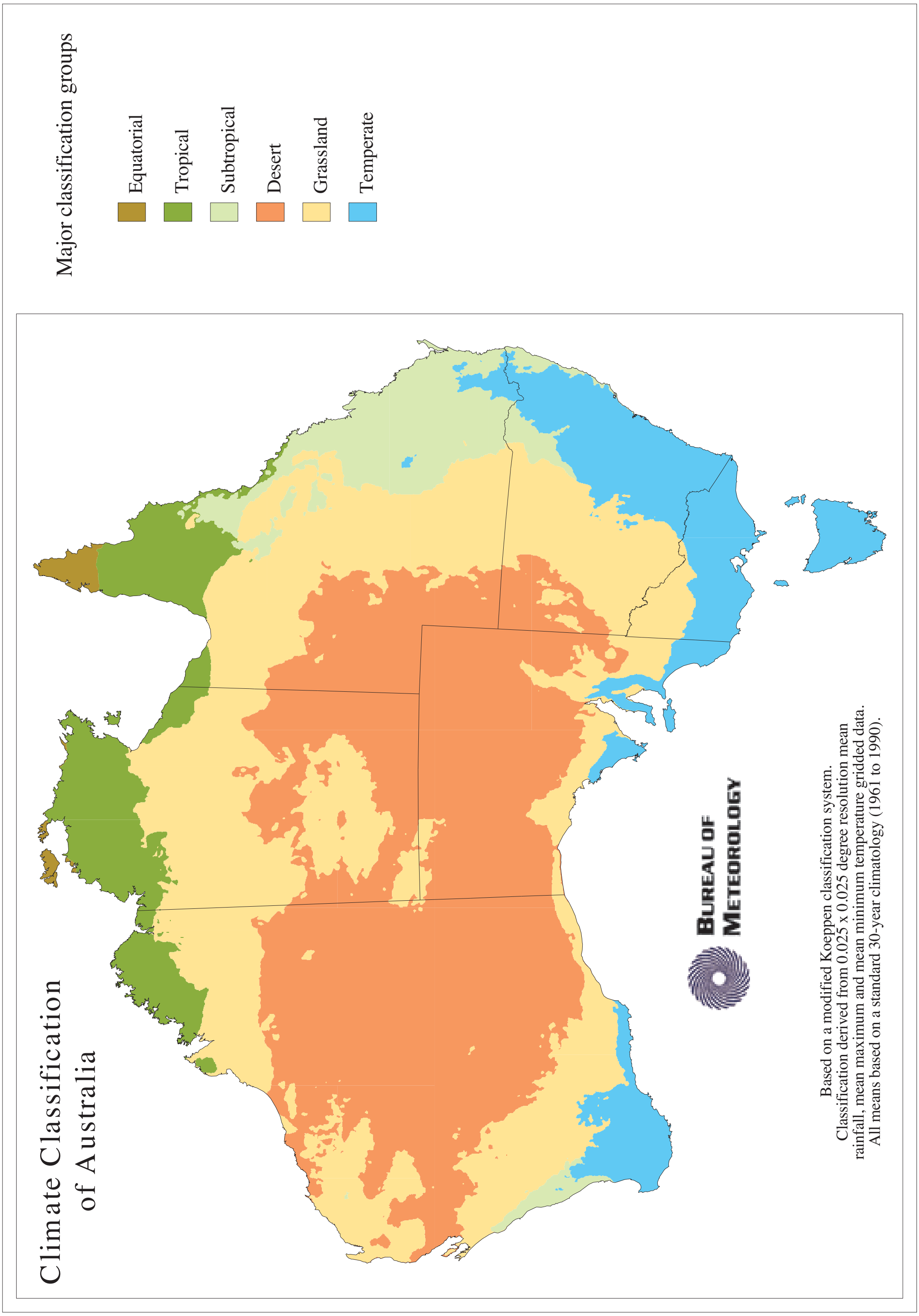

Fig. 1 The key climate groups.

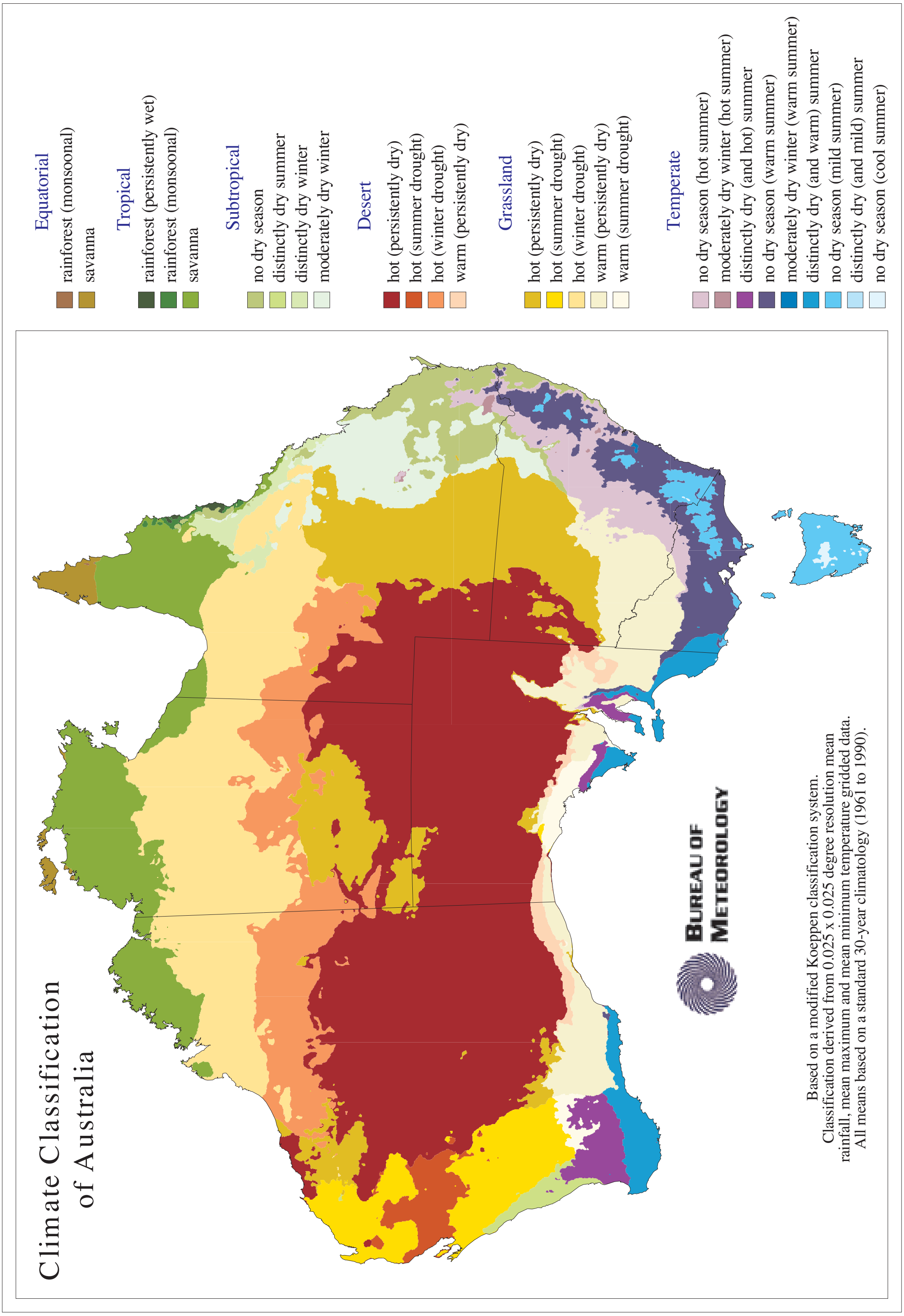

Fig. 2 Subdivisions within the key climate groups.

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 arises 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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Finally we thank the two *Australian Meteorological Magazine* reviewers (Terry Skinner and an unknown reviewer), and Associate Editor Neil Plummer, for their helpful suggestions.

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Appendix

Defining the climate groups and subdivisions.

The source data upon which the classification is based

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↓

Where → 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+ … +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)

ra= (rn1+rn2+ … +rn12)
rw= max(rn1,rn2,..rn12) rd= min(rn1,rn2,..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 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)

↓
↓(defining the **Humidity** element)

h= (rh1+ rh2+ … + rh12)/12

↓
↓(defining the **Humidity** criterion)

h1= (h)gt70

↓
↓

Defining the climate classes

↓

↓(generating the **Desert** climates)

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

↓

↓(generating the **Grassland** climates)

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

↓

↓(generating the **Equatorial** climates)

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

↓

↓(generating the **Tropical** climates)

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

↓

↓(generating the **Subtropical** climates)

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

↓

↓(generating the **Temperate** climates)

te1= [t4 and t9 and not(t2)] and [not(p1 or p2 or p7 or p12)] = no dry season (hot summer)
te2= [t4 and t9 and not(t2)] and [p12 and not(p1 or p2 or p7)] = moderately dry winter (hot summer)
te3= [t4 and t9 and not(t2)] and [p2 and not(p8)] = distinctly dry winter (hot summer)
te4= [t4 and t9 and not(t2)] and [p1 and not(p6)] = distinctly dry (and hot) summer
te5= [t3 and t9 and not(t4)] and [not(p1 or p2 or p7 or p12)] = no dry season (warm summer)
te6= [t3 and t9 and not(t4)] and [p12 and not(p1 or p2 or p7)] = moderately dry winter (warm summer)
te7= [t3 and t9 and not(t4)] and [p2 and not(p8)] = distinctly dry winter (warm summer)
te8= [t3 and t9 and not(t4)] and [p1 and not(p6)] = distinctly dry (and warm) summer
te9= [t7 and t9 and not(t3)] and [not(p1 or p2 or p7 or p12)] = no dry season (mild summer)
te10= [t7 and t9 and not(t3)] and [p12 and not(p1 or p2 or p7)] = moderately dry winter (mild summer)
te11= [t7 and t9 and not(t3)] and [p2 and not(p8)] = distinctly dry winter (mild summer)
te12= [t7 and t9 and not(t3)] and [p1 and not(p6)] = distinctly dry (and mild) summer
te13= [t5 and t9 and not(t7)] and [not(p1 or p2 or p7 or p12)] = no dry season (cool summer)
te14= [t5 and t9 and not(t7)] and [p12 and not(p1 or p2 or p7)] = moderately dry winter (cool summer)
te15= [t5 and t9 and not(t7)] and [p2 and not(p8)] = distinctly dry winter (cool summer)
te16= [t5 and t9 and not(t7)] and [p1 and not(p6)] = 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(t7or 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