A NOTE ON THE CLASSIFICATION OF DRY CLIMATES IN THE KOPPEN SYSTEM

Clyde P. Patton
University of Oregon

Recently there appeared in *The Professional Geographer* an article describing a set of "dichotomous keys" to be used by students in classifying climatic stations according to the system of Wladimir Köppen.[1] And although the keys are presented in such awe-inspiring comprehensiveness as to require a supplementary "Abbreviated Key," the author was struck by the fact that the letter and spirit of the scheme of classification is still misunderstood on a number of points, despite attempts by some American geographers to clarify Köppen's procedure.[2]

One may well be accused of straining at a gnat by producing yet another paper that is no more than an interpretation of a classification system of sharply limited utility. Still, the system is taught in introductory and advanced classes and most American texts concerned with climatology describe it in some detail. It may be useful, therefore, to try to clear up what the author considers to be minor errors that have accompanied the transliteration of the system into English and into English units of measure. Furthermore, the written[3] and spoken words of the author's colleagues seem to reinforce his personal observation of the needless pain endured by students exposed to this simple system of classification. Much of the difficulty lies, it seems to me, with the overly-literal transposition from metric to English units of measure. These comments are largely addressed to this second point. Finally, the author would like to comment briefly on the inherent lack of logic in Köppen's formulation of the Dry-Humid boundary.

As a beginning, the type of error and the kinds of misunderstanding involved may be illustrated by a translation of the following passage from *Die Klimate der Erde:*

> The following can serve as the simplest approximate definition of the limits of Deserts and Steppes; if r be the yearly rainfall in centimeters, t the annual temperature in °C, then, where the annual variability of t or r is small, r can be taken to be equal to $t + 33$ at the outer boundary of Steppe climates (that is, at the limit of B). However, where their variability is considerable, there, if r falls predominantly in the warm season, the boundary must be put higher, on account of the high evaporation; if r falls mostly in the cold season, it must be taken at a lower value. Appropriate thresholds are found

[1] Peirce F. Lewis, "Dichotomous Keys to the Köppen System," *The Professional Geographer*, Vol. XIII (1961), pp. 25-31. For a very similar scheme, see: Alfred H. Meyer, "An American Adaptation of the Köppen Classification of Climates," *Papers of the Michigan Academy of Science, Arts and Letters,* Vol. XXIII (1937), pp. 361-366.

[2] John B. Leighly, "Graphic Studies in Climatology," *University of California Publications in Geography,* Vol. 2 (1922), pp. 55-71; R. J. Russell, "Dry Climates of the United States," *University of California Publications in Geography,* Vol. 5 (1931), pp. 1-41; C. O. Sauer and J. B. Leighly, *An Introduction to Geography,* 6th ed., (Ann Arbor, 1932), p. 53, ff; C. W. Thornthwaite, "The Quantitative Determination of Climate," *Geographical Review,* Vol. XXII (1932), pp. 323-325.

[3] Lewis, *op. cit.,* p. 25.

to be: $t + 22$ for marked winter rain, $t + 44$ for marked summer rain. The boundary between *BS* and *BW* is put where r decreases to one-half this amount.

As an example we take Yalta ($r = 48$, $t = 13$) and Simferopol ($r = 42$, $t = 20$) in Crimea, both with rain in all months, but mostly in the winter at the first station, and mostly in summer at the second, so that the constants of addition should be about 28 in the former case, 38 in the latter.[4]

In the margin of the world map, which appears as a fold-out in the same publication, the limiting value of r for Desert climates is listed as being $t + 16½$; the values for climates with marked summer or marked winter rains are implied, but not stated. Obviously $t + 16½$ is not equal to one-half of $t + 33$. Nevertheless, as Thornthwaite[5] and Kesseli[6] have pointed out, the erroneous transcription on the world map was used by several authors, not only in describing the system, but also in applying it to particular areas. All this is of academically historical interest only, but it points out the kind of mis-transcription that has plagued Köppen's classification because of editorial shortcomings in the original publications.[7]

More interesting is the apparent misreading of Köppen's intentions with regard to which of the three sets of limiting values are to be used under particular conditions of t and r. His statement that the median formula, $r = t + 33$, needs to be increased or decreased under certain conditions is clearly meant to apply only in those cases where there is considerable seasonal contrast in both rainfall *and* temperature. To be sure, it is the rainfall regime that is emphasized by Köppen, but both the phraseology and the logic of the situation indicate that, in places without summer-winter temperature contrasts, it is absurd to consider "winter" rains more effective than "summer" rains. And yet this proviso does not appear in the American literature the author has seen, even though Köppen repeats it in succeding publications.[8] In large part, the neglect is attributable to the fact that Köppen in later writings directs the reader to nomographs in which no reference is made to the use of the median formula (or corresponding nomograph) in cases of near isothermality (Köppen indicates an annual range of 10°C as a limiting value[9]).

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[4] W. Köppen, *Die Klimate der Erde,* (Berlin, 1923), p. 121. In this translation the author has changed Köppen's nomenclature slightly so as to maintain uniformity throughout this article. The symbol t has been used to represent the mean annual temperature in °C, and r for the mean annual rainfall in cm. The letters T and R represent the identical quantities, but expressed in °F and inches, respectively.

[5] Thornthwaite, *op, cit.*, p. 324.

[6] John E. Kesseli, "The Climates of California According to the Köppen Classification," *Geographical Review,* Vol. XXXII (1942), p. 476.

[7] Another example of the confusion engendered by inconsistency in the original publication is the rendition of the boundary between s and f climates. In his *Grundriss der Klimakunde,* 2d ed., (Berlin, 1931), p. 129, Köppen sets this boundary where (among other things) the driest month receives 3 cm. of precipitation. In the *Handbuch der Klimatologie,* Band I, Teil C, (Berlin, 1936), edited by Köppen and R. Geiger, he repeats the same value on page C22 (as 30 mm.); but in the summary on page C43, he lists the criterion as 40 mm. As this is the only place the author has found the value of 40 mm. used by Köppen, it is assumed to be a misprint. A number of American authors use 3 cm. (or, rather, 1.2 inches) for the delimitation of these climatic types; others use 40 mm., 1.57 inches, or 1.6 inches.

[8] Köppen, *Grundriss der Klimakunde,* p. 128; Köppen, *Handbuch der Klimatologie,* p. C21.

[9] *Loc. cit.*

Another curious misinterpretation is also partly attributable to the prominent position of the nomographs as an aid in classification. In the second paragraph of the translated section, Köppen uses several examples to illustrate his method. It is clear from these examples that he does not restrict himself to the values 22, 33, and 44 as constants of addition in the formulae. In the case of Yalta, which has, in his words, rain in all months but mostly in winter, he uses neither 22 nor 33, but rather the intermediate value 28; for Simferopol with its slight summer maximum, he uses a value of 38, intermediate between 33 and 44. It seems obvious that he intends the formulae $r = t + 22$ and $r = \frac{1}{2}(t + 22)$ to apply only to cases with quite pronounced winter concentration of precipitation, and analogously with the other pairs of formulae. Places with intermediate seasonal distribution of precipitation are to be judged on the basis of formulae having intermediate values for the addition constants. The logical necessity for such interpolation is clearly pointed out by Van Royen[10] and by Russell[11] whose ideas are used by Kendall.[12] However, Russell's analysis is not carried to its logical conclusion. To be sure he points out that if one shifts from a value such as $r = t + 44$, as the boundary line between Humid and Steppe climates, to a value of $r = t + 33$, for the same boundary line, there will be a discontinuity (an "offset" in Russell's words) along the isoline that is used to demarcate those places with predominantly summer rains from those with an even rainfall regime; but Russell solves this problem by substituting nine formulae for Köppen's three, instead of developing a single continuously applicable formula. Such a simple formula, in which one of the variables is a parameter of the seasonal distribution of precipitation, is presented later. Before proceeding further, however, it is necessary to outline briefly the historical development of the formulae used by Köppen to delimit Dry climates.

The following table indicates the amounts of precipitation that Köppen considered to mark the outer edge of the Steppe climates, at various stages in the development of the classification. The Steppe-Desert boundary was set, in all cases, at one-half the values for the Steppe-Humid boundary, so it is omitted.

Date of Publication	Boundary between Steppe and Humid Climates			
	Even rainfall regimes		Winter rain	Summer rain
1918[13]	$r = 2t + 20$, or	Text, p. 197	None formulated	
	$r = 4/3\ (t + 20)$			
	$r = 5/4\ t + 30$	Map, p. 240		
1919[14]	$r = 5/4\ t + 30$		None formulated	
1923[4]	$r = t + 33$		$r = t + 22$	$r = t + 44$
	For BS—BW boundary:			
	$r = \frac{1}{2}\ (t + 33)$	Text, p. 121		
	$r = t + 16\frac{1}{2}$	Map, frontispiece		
1928[15]	$r = 2t + 14$		$r = 2t$	$r = 2t + 28$
1931[8]	same as 1928		same as 1928	same as 1928
1936[8]	same as 1928		same as 1928	same as 1928
1953[16]	same as 1928		same as 1928	same as 1928

The table points out three things: first, the discrepancies in the 1918 and 1923 publications between criteria indicated in the text and those shown in the map legends; second, the similarity in form of all these formulae, the only difference between them lying in the value of the approximate emperical constants, and third, the rather cavalier treatment of the empirical constants. For instance, in the 1918 article, Köppen states that "within the limits of accuracy one can also say: . . . . . $r = 2t + 20$ [instead of $r = 4/3(t + 20)$], and the limits on the map would not be changed thereby."[17] The point to be made is that Köppen thought of these formulae as convenient approximations, no more, else he would never have equated $2t + 20$ with $4/3(t + 20)$.

The presently-used formula should, I think, be thought of in the same way. Its transliteration from $r = 2t + 14$ (for evenly distributed rainfall) into English units as $R = .44T - 8.5$ gives a rather false impression of the degree of accuracy inherent in the original, an impression never intended by Köppen. A formula with simple constants, such as $R = \frac{1}{2}T - 12$, much better represents the spirit of the system, and approximates its metric counterpart closely enough when T lies between 30 and 80 (it gives values within 5% of $R = .44T - 8.5$ for $48 < T > 81$; and within 10% for $42 < T < 166$). This simplification does not, however, solve the problem of replacing three separate formulae for three different rainfall regimes with one continuously applicable formula.

As many authors have pointed out,[18] Köppen is never entirely clear as to what he means by a climate with predominantly summer rain, or winter rain, or an even rainfall regime. But in the *Handbuch der Klimatologie* he is reasonably specific, at least about summer rain climates. The formula $r = 2t + 28$ is to be used only when "the fraction $\frac{r}{t + 7}$ is greater in the warm season than in the cold."[19] In this instance, r and t refer to rainfall and average temperature for the respective six-month seasons, and not to yearly values, of course.

If we take Köppen's formulation, using the subscripts s and w to indicate precipitation and temperature in the summer and winter half-years, respectively, we get, for summer rain climates, $\frac{r_s}{t_s + 7} > \frac{r_w}{t_w + 7}$. This can be written in the form, $\frac{r_s}{r_s + r_w} > \frac{t_s + 7}{t_s + t_w + 14}$; which yields values for

[10] W. Van Royen, "The Climatic Regions of North America," *Monthly Weather Review,* Vol. 55 (1927), p. 319.

[11] Russell, *op. cit.*, p. 15, ff.

[12] Henry M. Kendall, "Notes on Climatic Boundaries in the Eastern United States," *Geographical Review,* Vol. XXV (1935), p. 120.

[13] W. Köppen, "Klassifikation der Klimate nach Temperatur, Niederschlag und Jahreslauf," *Petermanns Mitteilungen,* Vol. 64 (1918), pp. 197 and 240.

[14] W. Köppen, "Klimaformel und reduzierte Regenmenge," *Meteorologische Zeitschrift,* Vol. 36 (1919), p. 6.

[15] W. Köppen and R. Geiger, *Köppen-Geiger Klimakarte der Erde,* 1:20,000-000, (Gotha, 1928).

[16] Köppen-Geiger, *Klima der Erde,* 1:16,000,000, Darmstadt, (1953).

[17] Köppen, "Klassification der Klimate," p. 197.

[18] P. E. James, *A Geography of Man,* 2d ed., (Boston, 1959), p. 537, for example.

[19] Köppen, *Handbuch der Klimatologie,* p. C21.

$\frac{r_s}{r_s + r_w}$ (the percentage of the precipitation that falls in the six months of summer) that range from $>50\%$, where $t_s = t_w$ (any excess of summer rainfall over winter is considered enough to class the climate as having summer rains, if there is no seasonality of temperature), to $> 100\%$, where $t_w = -7$. These two extremes are rather absurd, but for $t_s = 25$ and $t_w = 5$ (i.e., t is about 15 and the annual range is 20°C) the required percentage of summer rainfall becomes about 73%. This gives a rough idea of what Köppen meant by summer rain climates, in terms of the proportion of the annual precipitation that falls in the summer. Köppen says nothing about the delimitation of winter rain climates. He may have meant the two sets of criteria to be symmetrical. James and others[20] have used 70% and 30% summer concentration of precipitation as marking off summer rain, even, and winter rain regimes. These values fit fairly well with the results obtained from Köppen's statement and calculated for something like average conditions of temperature.

If we now take the three Köppen formulae of 1928, or, rather, their nearly exact equivalents in English units of measure, $R = .44T - 14$ (for winter rain climates), $R = .44T - 8.5$ (for climates with even rainfall), $R = .44T - 3$ (for summer rain climates), and assume that the winter rain formula is meant to apply to places having X% of their rain in winter, the even distribution formula to places having 50% of their rain in winter, and the summer rain formula to places with $(100 - X)$% of their rain in winter, we can transform the three discontinuous equations into a single one, of the form $R' = .44T - a(P_w + b)$, where P_w is the observed winter percentage of rain at a particular place. The constants a and b can be computed so as to make R' equal to $.44T - 14$ when some appropriate value of X is substituted for P_w, R' becomes equal to $.44T - 8.5$ when 50% is substituted for P_w, and R' becomes equal to $.44T - 3$ when $(100 - X)$ is substituted. The following transformations result when various values of X are used (X being the winter rain concentration that is considered typical for winter rain climates):

For X = 100%	$R' = .44T - .11P_w - 3.00$
For X = 90%	$R' = .44T - .14P_w - 1.63$
For X = 80%	$R' = .44T - .18P_w + 0.67$
For X = 70%	$R' = .44T - .28P_w + 5.25$

These are rather more elaborate looking formulae than are wanted. Fortunately, when $X = 82.5\%$, R' is approximately equal to $.44T - \frac{1}{6}P_w$. The percentage, 82.5, seems to be a reasonable value for X; it implies that the typical concentration of rainfall in winter for winter rain climates is roughly half-way between the two limits, 70% and 100%. Furthermore it yields a formula for R' of only two terms, $.44T$ and $-\frac{1}{6}P_w$, both easily learned. A further simplification can be achieved by substituting the slightly grosser approximation $R'' = \frac{1}{2}T - \frac{1}{4}P$ for the nearly exact formula $R' = .44T - \frac{1}{6}P_w$.

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[20] James, *op. cit.*, p. 537; Henry M. Kendall *et al.*, *Introduction to Geography*, (New York, 1951), p. 668.

From a pedagogical view, a lot can be said in favor of the formulation of R″. The coefficients are as simple as could be wished for; the formula gives precisely the right impression of the kind of exactness that is meant to be implied—the very simple nature of the coefficients indicates that the formula is meant to be a useful approximation, no more; there is only one formula to remember in place of three; there is no longer any problem of which of three formulae to use, and the classification by means of the simple formula yields results not very different from those obtained by the more cumbersome and less logical scheme of three different formulae (or nomographs).

The major objection that can be raised against the attempt at simplification, aside from considering Köppen's formulations to be definitive and exact boundary values rather than convenient approximations, is that it makes for a lack of correspondence between the criteria used for classifying a station and the criteria used to construct the several world maps of the Köppen system currently in use. The simplest counter to this objection is some familiarity with the lines drawn on such world maps. On the 1953 Köppen-Geiger wall map,[21] for example, there are some minor discrepancies between the limits of Desert and Steppe as drawn and those which might be drawn by applying the standard Köppen formulae to published climatic data.[22] These differences are, in fact, slight enough to make them completely unimportant when considering the pattern of climatic regions on a world scale. The author has only drawn the Steppe and Desert boundaries as determined by the simple approximation, $R'' = \frac{1}{2}T - \frac{1}{4}P_w$, in Eastern Oregon and on the margins of the Sahara, west of Long. 10° E. In those places, the lines drawn according to the new formula accord better, in many cases, with those shown on the wall map, than the lines computed according to the conventional formulae! In any case, the differences are so slight (except possibly for the Steppe margin in Oregon) as not to be worth troubling about. This is not to say that the formula presented here gives a nearly exact boundary for Desert and Steppe climates. The only claim is that it is as good as the conventional ones, much simpler to use and learn, and can be used in conjunction with existing maps. After all, Köppen used essentially the same map to illustrate his system in his publications of 1918, 1923, and 1928,[23] even though he changed the formulation of the Dry-Humid boundaries in 1923 and in 1928. In fact, if we are to believe the legend of the 1918 map, the criteria used to delimit the Dry climates on that map and, therefore, on the maps of 1923 and 1928 as well (since they appear to have boundaries identical to those of the 1918 map), are different from *any* of the changing criteria indicated in the text of his articles![24]

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21 Köppen-Geiger, *Klima der Erde,* 1:16,000,000, (Darmstadt, 1953).

22 Frederick L. Wernstedt, *World Climatic Data: Africa,* (State College, Pennsylvania).

23 Köppen, "Klassifikation der Klimate," p. 240; Köppen, *Die Klimate der Erde,* foldout; Köppen, *Klimakarte der Erde.* See also, Köppen, *Grundriss der Klimakunde,* fold-out.

24 The criteria listed in the margin of the map accompanying his "Klassifikation der Klimate" can be equated with the formula: $r = 5/4\ t + 30$. This formula is not mentioned in the text of any subsequent publication, except in "Klimaformel." Yet the 1918 map seems to be the prototype for all later ones, except that of 1953.

When all this is said and done, we find that we have simplified the expression delimiting Dry from Humid climates, and have eliminated the possibility of offsets on a map. We have also taken care of a good number of the absurdities that are illustrated by the following hypothetical, but perfectly reasonable, pair of stations:

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temp. (°F)	Both Stations:	45	48	53	59	67	72	75	72	67	61	53	48	60
Precip. (in.)	Station A:	2.0	1.6	1.3	1.0	0.7	0.2	0.0	0.4	1.0	1.3	1.8	1.9	13.2
	Station B:	2.1	1.7	1.4	1.2	1.1	1.1	1.2	1.2	1.2	1.4	1.9	2.0	17.5

The two stations have identical annual marches of temperature but slightly different precipitation regimes. Station A receives 9.9 inches (or 75% of its total precipitation) in the winter six months. Station B receives 10.5 inches (or 60% of its total) in winter. Stations with more than 70% of their rainfall in winter are to be classified as having winter rain climates for purposes of defining the Humid-Arid boundary.[25] Hence we apply the criterion $R = .44T - 14$ to station A, and $R = .44T - 8.5$ to station B. The value of the first criterion is 12.4; and station A is therefore classified as *Csa*. The value of the second criterion is 17.9; and station B is classified as *BS*. We have managed to classify, as Dry, a station that receives in every month more rain than a station which we consider to be Humid!

For a similar situation that is not hypothetical, consider the climatic data for Carson City, Nevada, and Antelope, Oregon. Carson City receives 8.3 inches of precipitation in winter, or 78.5% of its annual total of 10.6 inches. Antelope receives only 0.4 inches less in winter than does Carson City, but this is only 63.5% of its annual total, which is 12.5 inches. Hence Carson City is classified as *Csb*, whereas Antelope despite higher precipitation and slightly lower temperature is called *BS*.

The formula here suggested avoids the great majority of such absurdities, though it is possible to imagine extreme cases in which even a continuously applicable formula fails to discriminate properly between stations. The reader may readily verify this by inventing examples in which one station is classified as Dry, whereas another, with the same temperatures and lower rainfall throughout the year, is classified as Humid.[26]

The problem lies not only in the fact that there are three formulae, discontinuously applicable, but also in the very nature of the formulae. Köppen's language and the interpretation of the American writers on this subject all give the impression that what counts in determining the effectiveness of a particular amount of precipitation is the proportion that falls

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[25] James, *loc. cit.*; Kendall, *Introduction to Geography, loc. cit.* Trewartha, in *An Introduction to Climate*, 3rd ed., (New York, 1954), p. 382, uses a 3:1 ratio between the rainfall of the extreme months to mark off winter rain climates, and a 10:1 ratio for summer rain climates. The hypothetical stations of the example fall into the same categories whether James' or Trewartha's criteria are used.

[26] To satisfy the conditions stated, the following inequalities (among others) must be satisfied: $R' < \frac{P'_w}{4K} < 25$; and $2R'(K + 1) < T < P'_w \left[\frac{1 + K}{2K}\right]$ where $K = \frac{R''}{R'}$, and the supercripts ′ and ″ identify the climatic values for the drier station that is classified as Humid, and the wetter station that is classified as Dry, respectively.

in a given six-month season. But, as the examples above are meant to demonstrate, it is quite possible for a high percentage of a relatively low annual total, at one place, to fall in one six-month season and yet be less than a lower percentage of a relatively higher annual total at another place. What is important is not the percentage of rain that falls in a given season, but rather the amount that falls under given conditions of potential evapotranspiration (for which temperature is implicitly used as a parameter in the Köppen formulations). The problem of improving Köppen's formulation while retaining the simple and easily-computed character of his delimiting criteria needs to be considered further. For the moment the author can only call attention to the logical absurdity inherent in the formulation as it stands.