A REVISED THORNTHWAITE-TYPE GLOBAL CLIMATE CLASSIFICATION

Johannes J. Feddema
Department of Geography
University of Kansas
Lawrence, Kansas 66045

Abstract: Although the Köppen climate classification is the most common climate classification in use today, the 1948 Thornthwaite classification is frequently cited as an improved climate classification system for its rational approach. However, the Thornthwaite classification is infrequently used because it tends to be too complex for use in everyday settings and world maps of the classification were never produced. This paper will present global maps of all four components of the 1948 Thornthwaite climate classification—a long-time wish of John "Russ" Mather, to whom this paper is dedicated. In addition, a revised Thornthwaite-type climate classification is presented with the intent of providing a more rational climate classification for everyday use in a classroom setting. This classification uses an amended version of the Thornthwaite moisture index, not only to delineate climatic moisture gradients but also to define a single seasonality index responsive to mean seasonal variation in both thermal and moisture conditions. Replacing the two cumbersome seasonality indicators in the original Thornthwaite classification with one variable greatly improves the utility of the classification. Results from this classification are compared to the Köppen and original Thornthwaite climate classification schemes. [Key words: climate classification, moisture index, W. Köppen, C. W. Thornthwaite, J. R. Mather.]

INTRODUCTION

In the last few decades, John "Russ" Mather frequently discussed the idea of producing a world map of the Thornthwaite climate classification. Thornthwaite (1948) only applied his final classification scheme to the United States, in part because he did not have access to sufficient climate data to do a global study. To remedy this problem, C. W. Thornthwaite Associates did much work to develop and improve water budget applications and to collect climatic data for the entire world (Field, 2005 [this issue]). However, those data have never been applied to the 1948 Thornthwaite classification on a global scale. Russ's wish was to publish the full classification; however, he was also aware that the full classification was too complex for everyday classroom use. Therefore, we also developed a modified, less complex classification scheme was also developed. Like Thornthwaite himself, the objective of this work is to present a more systematic approach to classifying global climates that is easy to interpret and can be easily conveyed to students in a classroom setting.

Although climate classification schemes have existed since the Ancient Greeks, modern climate classifications really began, and continue to this day, with the work of Wladimir Köppen (Köppen, 1900). The Köppen classification was a great achievement; first for identifying distinct climates, and second because it linked numerical climate statistics to vegetation distributions. The Köppen classification has been modified many times since its inception because of problems with the way

Physical Geography, 2005, **26**, 6, pp. 442–466.

its boundaries are defined and the way the classification determined climatic moistness. Thornthwaite (1943), in his first classification attempt, focused on an improved determination of the moisture factor. Using the concept of a moisture index, first developed by Karl Linsser (Thornthwaite, 1943), he developed a new classification structured around the moisture factor. In 1948, Thornthwaite developed a second classification based on improved water balance metrics (Thornthwaite, 1948). He also made the system more "rational" by using even class intervals. Carter and Mather (1966) provide excellent insight into these decisions and the relative merits of the two Thornthwaite classification methods.

Like Köppen's classification, Thornthwaite distinguished climates based on two primary factors—relating to moisture and heat—and two seasonality components as secondary factors. This paper will present a brief discussion of each component and present maps of Thornthwaite's global classification. In addition, it will present a new simplified Thornthwaite type climate classification that is intended for use in the classroom and as an aid to teaching the spatial variability of climates in a systematic way. The maps are all based on data from a half degree in latitude and longitude gridded monthly climatologies of precipitation and temperature (Legates and Willmott, 1990a, 1990b) and a water balance model developed by the author. The model assumes a 150 mm soil water-holding capacity and uses soil moisture retention curve G (Mather, 1978), which allows free loss of water until soil moisture reaches 70 percent of water-holding capacity and then decreases linearly until water-holding capacity reaches zero.

THE THORNTHWAITE CLIMATE CLASSIFICATION

The Moisture Factor

Thornthwaite realized that precipitation (P) alone is not a good indicator of moisture conditions in an environment. He considered this a significant drawback to most climate classification systems. Instead, he developed the concept of potential evapotranspiration (PE), derived from temperature and day length, to estimate the water need of plants in a given environment. Using PE in combination with P, he developed his water budget methodology to create a moisture index. Unlike other moisture indices, however, Thornthwaite derived his index from separately calculated humidity (I_h) and aridity (I_a) indices, based on moisture surplus and deficit calculations from the water budget

$$I_h = 100\ S/PE \text{ and}$$
$$I_a = 100\ D/PE \tag{1}$$

where S is the water surplus and D is the water deficit.

Thornthwaite suggested that perennial plants are sufficiently deeply rooted to be able to access surplus moisture that percolates below the soil layer, thus minimizing the effects of drought. For this reason, he decided that 6 inches (~15 cm) of water surplus was sufficient to offset 10 inches (~25 cm) of moisture deficit for deep-rooted vegetation and subsequently developed the following weighted moisture index:

Table 1. Thornthwaite Moisture Derived Climate Types

Climatic type	Moisture index
A Perhumid	100 and above
B_4 Humid	80 to 100
B_3 Humid	60 to 80
B_2 Humid	40 to 60
B_1 Humid	20 to 40
C_2 Humid	0 to 20
C_1 Humid	-20 to 0
D Semiarid	-40 to -20
E Arid	-60 to -40

$$I_m = I_h - 0.6I_a \tag{2}$$

Values for this index range from -60 to infinity and Thornthwaite used values from -60 to 100 in rational increments of 20 to classify climates into humidity classes, labeled in a similar fashion to the Köppen system with capital letters (Table 1). The Thornthwaite and Mather (1955) revision of the water budget methodology implied a modification of this index so that the weighting of deficit and surplus became the same. Removing the 0.6 weighting the moisture index was simplified to either

$$I_m = 100[(S - D)/PE] \text{ or}$$
$$I_m = 100(P/PE - 1) \tag{3}$$

With this formulation, the classification lost its rational increment of 20 since the three dry climate types were now bound by -33, -66, and -100 (Thornthwaite and Mather, 1955). Figure 1 presents a global map of the moisture factor classification using the original 1948 moisture index.

Following the 1955 revision, Mather spent considerable time focusing on two questions. First, he felt that the 1955 modification defeated the original concept of a "rational" classification (i.e., the use of even class intervals) and he frequently debated the validity of the modified scheme in this context. Second, while the moisture index has traditionally been applied on an annual time scale, he debated the validity of using the index on a sub-annual time scale, for example, on monthly or seasonal time scales. As will be shown, use of a sub-annual time scale allows the moisture index to be manipulated to provide significant additional information about a climate.

The Thermal Factor

Thornthwaite based his thermal factor, called the Index of Thermal Efficiency, on PE. Most climate classifications use temperature as an indicator of thermal efficiency. However, Thornthwaite recognized that temperature alone was not necessarily an adequate indicator of the productivity of an environment, especially for

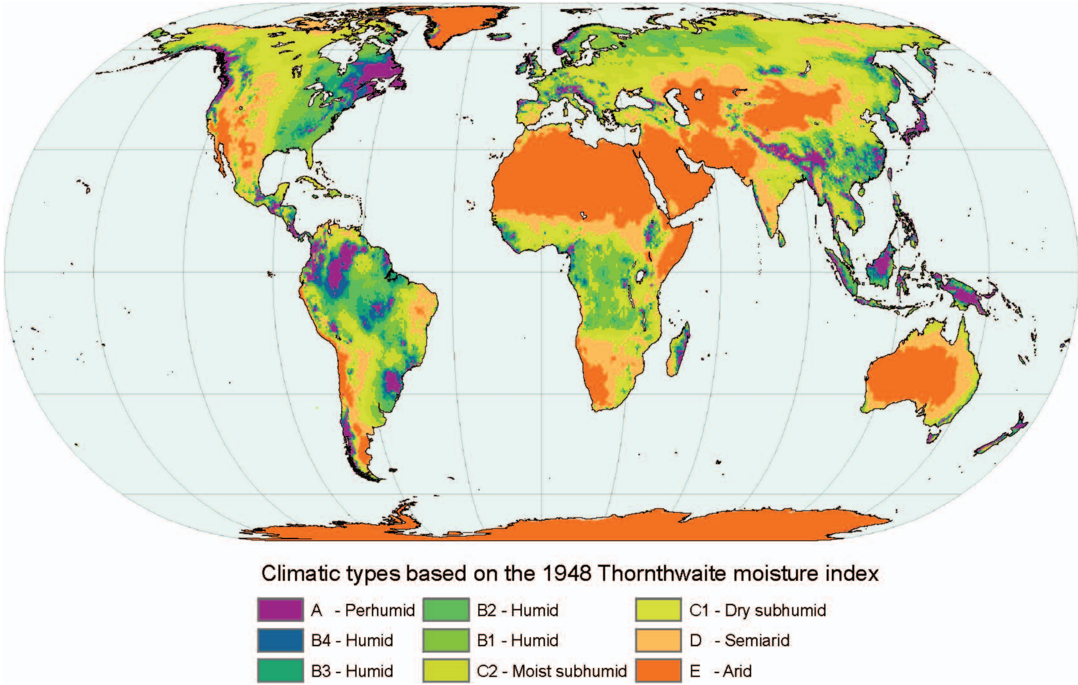

Fig. 1. The global Thornthwaite moisture regions.

Table 2. Thornthwaite Thermal Climate Types

Climatic type	TE index (PE; cm)
A′ Megathermal	114 and above
B'_4 Mesothermal	99.7 to 114
B'_3 Mesothermal	60 to 80
B'_2 Mesothermal	40 to 60
B'_1 Mesothermal	57 to 71.2
C'_2 Microthermal	0 to 20
C'_1 Microthermal	-20 to 0
D′ Tundra	-40 to -20
E′ Frost	-60 to -40

climate-dependent ecological processes. PE represents the potential water use by an ecosystem, and, as such, is a measure of potential plant productivity. In a sense, it is similar to the growing degree-day concept and both measures have a baseline condition below which there is deemed to be insufficient energy to do useful work toward plant productivity and other ecological processes. For PE, this value is zero (associated with sub-freezing temperatures) and therefore annually integrated PE values are a useful measure of the total biological energy demand of a particular location.

As with the Moisture Index, Thornthwaite wanted to use a rational scale to delineate his thermal climate classes. Starting with the assumption that, at its lower climatic limit, an evergreen tropical climate would have an annual PE of 114 cm (equivalent to a 22°C monthly averaged temperature), he created his five major thermal classes by progressively halving this value (Table 2; Fig. 2). Like the moisture index, he subdivided the middle classes into equal intervals to further differentiate mid-latitude climates—an operation that seems to contradict the "rational" methodology he so strongly espoused.

Seasonal Variation of Effective Moisture

Like Köppen before him, Thornthwaite needed to incorporate seasonality in his classification scheme. However, as any student of either scheme can attest, classifying seasonality in a simple index is very difficult, especially since seasonality can be caused by either moisture or thermal variations. Thornthwaite's solution to this problem was to create two seasonality indices, one for each climate factor.

Thornthwaite devised separate moisture seasonality classes for wet and dry climates, based on whether climates had moisture index values above or below 0. For moist climatic types—those that received more annual precipitation than annual PE—he used the aridity index to identify the intensity of drought conditions and to further distinguish between winter and summer deficiencies. For dry climatic types, he used the humidity index to identify the intensity of wet conditions, again distinguishing between winter and summer surplus moisture conditions (Table 3; Fig. 3). However, this classification is very cumbersome to use and the large number of

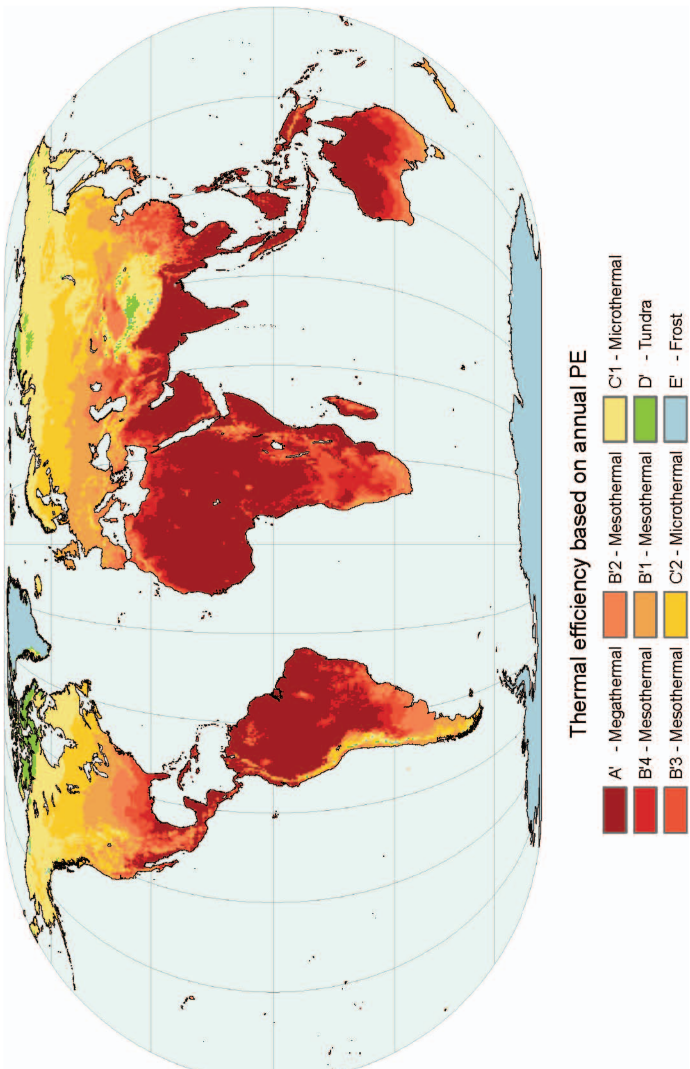

Fig. 2. The global Thornthwaite average annual thermal efficiency.

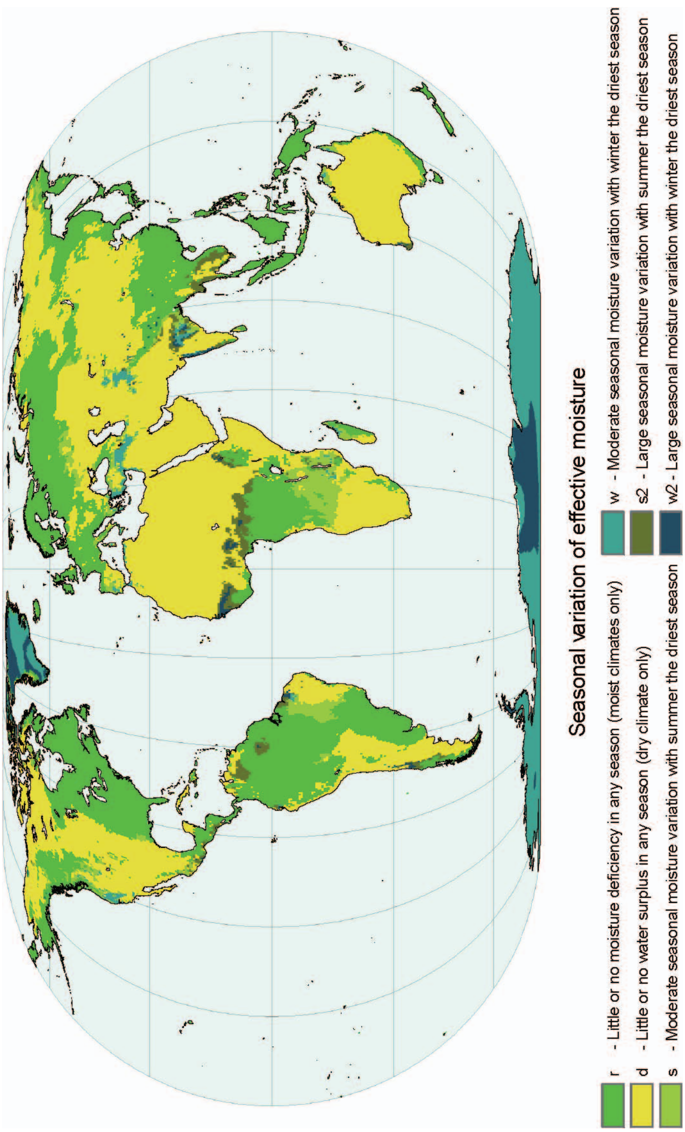

Fig. 3. The global Thornthwaite seasonal variation of effective moisture.

Table 3. Thornthwaite Seasonal Variation of Effective Moisture Types

Seasonality type	Index
Moist climates (A, B, C)	Aridity
r little or no water deficiency	0 to 16.7
s moderate summer water deficiency	16.7 to 33.3
w moderate winter water deficiency	16.7 to 33.3
s_2 large summer water deficiency	33.3+
w_2 large winter water deficiency	33.3+
Dry climates (A, B, C)	Humidity
d little or no water surplus	0 to 10
s moderate summer water surplus	10 to 20
w moderate winter water surplus	10 to 20
s_2 large summer water surplus	20+
w_2 large winter water surplus	20+

Table 4. Thornthwaite Summer Concentration of Thermal Efficiency

Seasonality type	Summer PE concentration (%)
a′	<48.0
b'_4	48.0 to 51.9
b'_3	51.9 to 51.9
b'_2	56.3 to 51.9
b'_1	61.6 to 51.9
c'_2	76.3 to 68.0
c'_1	88.0 to 76.3
d′	>88.0

classes makes it very difficult to implement the full Thornthwaite climate classification on a global scale. In addition, the letter scheme he proposed is difficult follow.

Summer Concentration of Thermal Efficiency

Thornthwaite made a further seasonality distinction based on the seasonality in the distribution of PE. He began with the premise that in a tropical climate, with constant energy resources throughout the year, the three "summer" months would contribute 25% of the total annual PE. These locations represent a climate without thermal seasonality. For polar climates, however, the three summer months would contribute 100% of the annually integrated PE. Given that annual PE values vary systematically from the equator to the poles, he developed a logarithmic relationship between annual PE and the relative concentration or contribution of summer PE to that total. This created a relationship between the total PE or Thermal Efficiency Type and its expected summer concentration of PE. If, for a given location, the summer concentration was within the expected range for its particular Thermal Efficiency Type, the location was classified as a normal seasonality, designated by a small letter in the classification scheme (Table 4; Fig. 4). If the seasonality were lower/higher than expected for a location, the summer concentration type would show a letter associated with a higher/lower Thermal Efficiency and vice versa.

Thornthwaite's 1948 climate classification was a significant improvement on the Köppen classification in a number of ways. First, the new moisture index made possible the clear distinction between moist and dry climates. Second, the Thermal Efficiency index is more closely tied to the plant and energy usage of the environment as compared to temperature-based criteria used by Köppen. Third, because it is more systematic or rational in its definition of the intervals used, these two variables are much more straightforward to use and fit better with a systematic view of climate variation. Finally, the classification was not so closely tied to vegetation boundaries. It recognized that the variables mapped are continuous in space and therefore the emphasis was not on the exact placement of boundaries but on identifying core climate regions using continuously varying fields. For reference the Köppen classification is presented using the same temperature and precipitation dataset (Legates and Willmott, 1990a, 1990b; Matsuura and Willmott, 2004) used throughout this paper (Fig. 5).

A REVISED THORNTHWAITE TYPE CLASSIFICATION

While the Thornthwaite classification was immediately recognized as a conceptual improvement over the Köppen classification, it never gained much acceptance for several reasons. First, the full classification system was just too complex to be used, resulting in well over 800 climate types at the global scale. In fact, neither Thornthwaite nor any subsequent champions of the method ever produced a global version of the system because of its complexity. Second, calculation of PE for the classification also was a hindrance to acceptance of the system, especially before the advent of computing resources. Simply put, the Köppen system succeeded in large part because of precedence and because it was presented as a world map. By providing a map instead of a methodology, the system alleviated the need for calculations. Certainly, most users have little knowledge of how the boundaries are derived or the computational complexities associated with those criteria. The inability of the Thornthwaite system to provide a similar map-based system made it unsuitable for classroom application.

Therefore, an improved Thornthwaite classification must consider two factors. First, it must be simpler than the original. Second, it must be presented so that it is intuitive to novice users, even without knowledge of how the criteria are calculated.

Reducing the complexity of the classification can be accomplished in three ways. First, the need to use all four factors that comprise the original classification can be reduced. Two seasonality factors are too cumbersome and they should to be simplified or collapsed into a single seasonality factor. Second, the number of classes must be reduced. In particular, the subclasses that comprise the mid-latitude climates are a problem, as they do not follow the rational doubling rule of the initial classification. Third, the naming conventions and letter symbols should be simplified to be

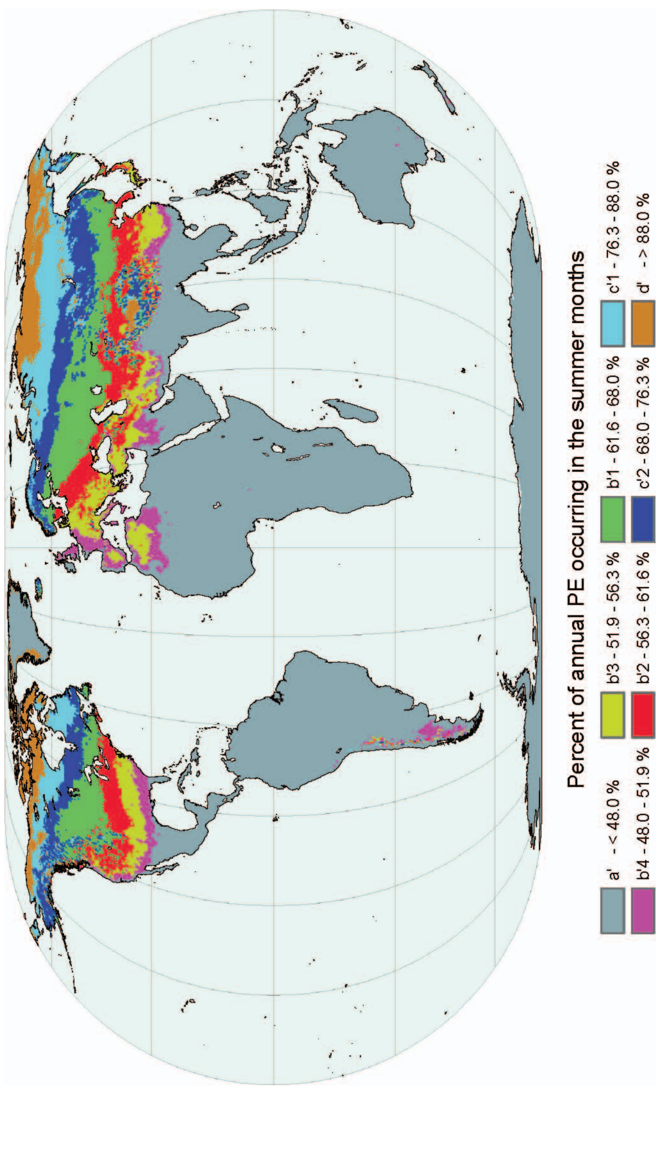

Fig. 4. The global Thornthwaite summer concentration of thermal efficiency.

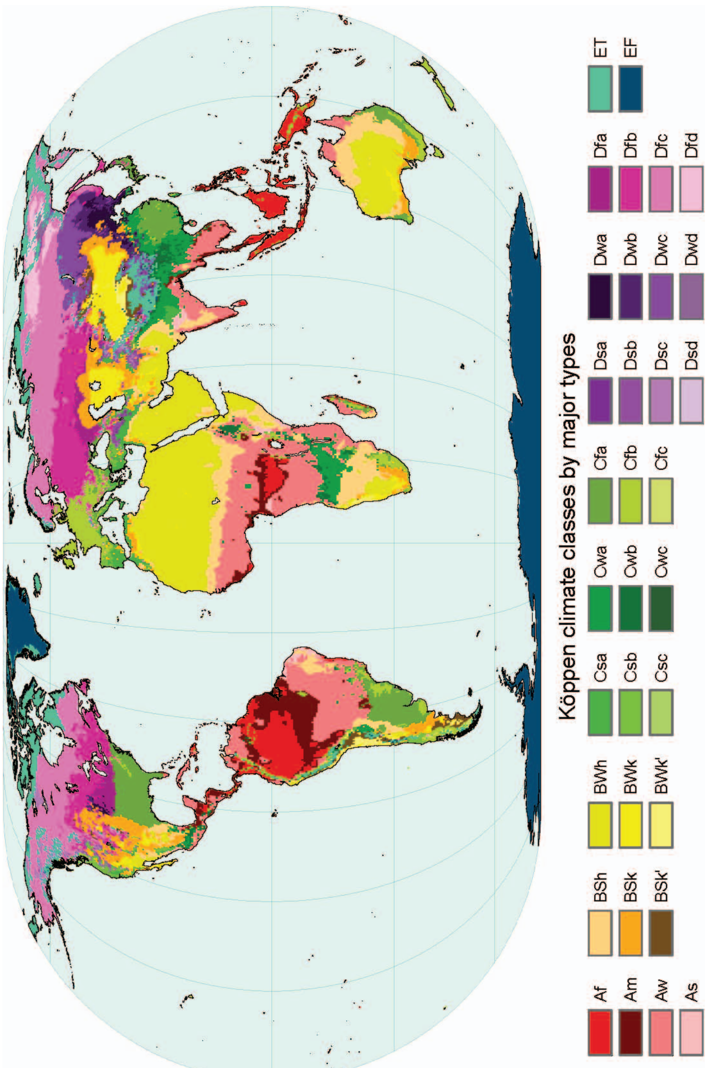

Fig. 5. The Köppen climate classification scheme.

more intuitive. These symbols do not add significantly to the classification and are just an extra step to interpreting the climate of a location. Classes that describe the climate attributes through a simple meaningful terminology should replace these symbols.

For today's classroom environment, the classification must also be systematic and couple with a systems approach of climate analysis. Therefore, a map of world climates must be tied to a simple legend that explains the main characteristics of a climate at a given location. When identifying a climate on the legend, a user should be able to follow clearly defined scales to see where it fits within the range of moisture and thermal regimes present on the Earth. In fact, whether presenting the classification in a text or as a wall map, the individual factors of the classification should be presented separately to encourage understanding of the concept presented (e.g., moisture, thermal efficiency, seasonality). These maps can also be used to demonstrate how continuous variables are collapsed into finite classes, by representation of variables on a continuum overlain by contours to represent the class intervals of the classification. After each individual factor is presented, it should be merged with the other factors to demonstrate the final global classification.

The Moisture Factor

The modified classification will continue to use a moisture index to delineate climate on the basis of moisture availability. However, it uses an updated version of the moisture index to eliminate the unwieldy range of the original Thornthwaite formulation (Willmott and Feddema, 1992). The Willmott and Feddema moisture index (I_m) is

$$I_m = \begin{bmatrix} 1 - PE/P \\ 0 \\ P/PE - 1 \end{bmatrix} \text{ and}$$

$$I_m = \begin{bmatrix} P > PE \\ P = PE = 0 \\ P \leq PE \end{bmatrix} \quad (4)$$

This formulation results in moisture index values that range from -1 (when there is no precipitation) to +1 (when there is no PE). A value of 0 indicates that annual moisture supply (P) equals the annual moisture demand (PE). Because the dry and wet components of this index are symmetrical with respect to positive and negative values and because the index does not become unstable (i.e., reach values approaching infinity), this index lends itself to more straightforward interpretation, manipulation and categorization compared to other indices available.

Many previous climate classifications have gone to extreme lengths to identify meaningful climatic boundaries (e.g., the various versions of the Köppen classification). Usually these boundaries attempt to follow natural vegetation boundaries. However, two specific examples show the futility of attempting this on the basis of climate criteria alone. First, simulation of the prairie wedge in the northern Midwest

Table 5. Moisture Types for the New Classification

Moisture type	Moisture index (I_m)
Saturated	0.66 to 1.00
Wet	0.33 to 0.66
Moist	0.00 to 0.33
Dry	-0.33 to 0.00
Semiarid	-0.66 to -0.33
Arid	-1.00 to -0.66

region of the United States is nearly impossible on the basis of climate statistics alone, because it is thought to be an artifact of local fire regimes (Changnon et al., 2002). A second example is the Flint Hills regions of Kansas, where grasslands persist, even though from a water balance perspective the region could support arboreal vegetation, as is the case in surrounding areas. In this case, the main difference in vegetation is caused by soil properties. Soils of the Flint Hills are too shallow to store adequate water during frequent dry periods, while in the surrounding areas deeper soils support the less drought-adapted arboreal species.

If we recognize that climates continuously vary over space, the need for specific boundaries is not required. Indeed, climate variables could be presented or mapped as gradient maps; however, these can be difficult to interpret for a precise value. Therefore, climatic divisions in this new classification are based on a reasonable set of climate classes and relatively few boundaries are drawn at even (or rational) intervals along the range of values present in the indices used. The description of the climates between these boundaries can then be viewed as sample climates along a continuum.

For the new classification, the annual I_m values are divided into six different moisture regimes—three wet and three dry—symmetrically defined about zero (Table 5). The mapped distribution of the moisture index shows that the driest or arid class covers a much greater spatial extent compared to the wettest or saturated class (Fig. 6). The saturated areas are typically only found on the windward side of mountain ranges and in the polar regions. It would be easy to argue for more or irregular classes in this case. For example, the *World Desertification Atlas* (Middleton and Thomas, 1997) uses a moisture index value that translates to an I_m value of -0.95 to delineate the limits of vegetation and human use of an environment. While such limits may be very useful for specific applications, more than six classes would make the classification too complex when fully implemented.

The Thermal Factor

Like the 1948 Thornthwaite climate classification, the new index also uses PE as a surrogate for thermal efficiency or energy input to the environment. This is done for the same reasons given by Thornthwaite—mainly that the integrated PE values more closely represent biologically effective energy availability. The new classification deviates from Thornthwaite's original classes by using six equal interval classes

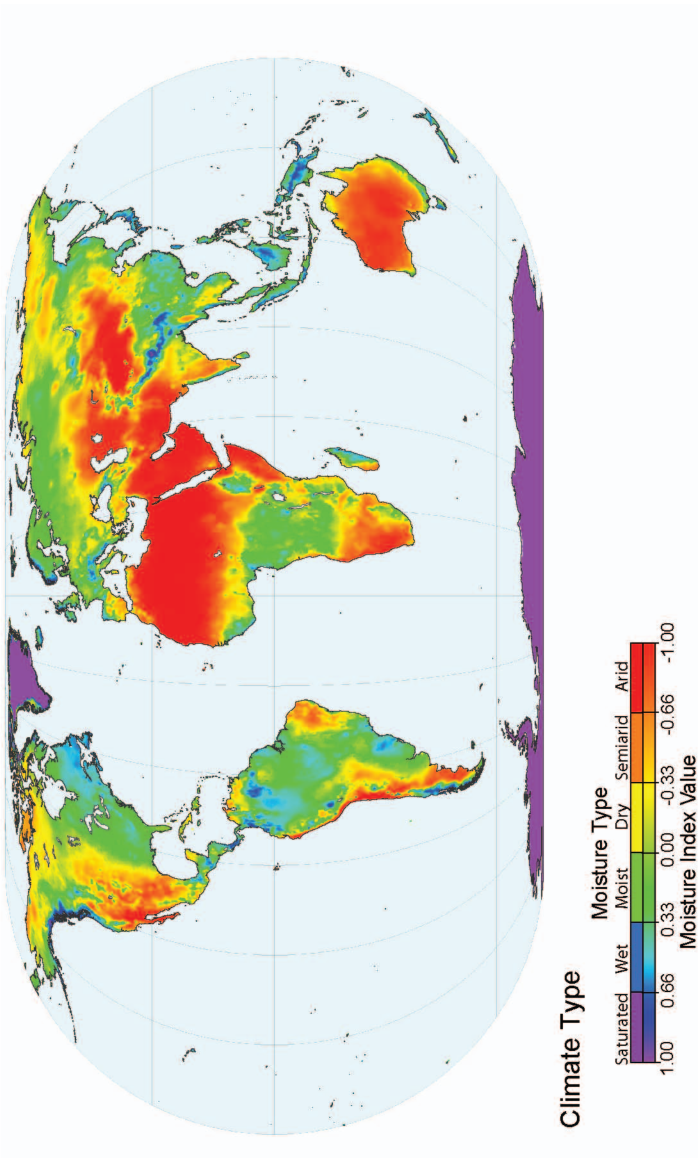

Fig. 6. Global distribution of moisture variation for the new classification.

Table 6. Thermal Types for the New Classification

Thermal type	Annual PE (mm)
Torrid	>1500
Hot	1200 to 1500
Warm	900 to 1200
Cool	600 to 900
Cold	300 to 600
Frost	0 to 300

of 300 mm instead of doubling the scale between classes, and then inserting the mid-latitude sub-classes (Table 6).

The mapped thermal index follows the expected equator to polar/mountain top gradients (Fig. 7). However, there is an interesting difference from temperature-based schemes. In this case, the highest gradients are found in the subtropical to tropical regions of the Earth, while temperature-based schemes tend to have higher gradients in the polar areas. This is a reflection of the nonlinear relationship between temperature and PE and reflects the long dormant seasons at high latitudes that do not contribute to annual PE totals. While there are strong temperature gradients in these areas, those gradients occur over temperature ranges below the freezing point; generally, these extreme temperatures do not significantly alter the productivity of life forms in the locations. The PE index ignores these cold temperature conditions and only indicates the usable energy to a location. This formulation captures the vast expanse of the boreal forest or taiga very well.

The Seasonality Factor

Determination of the seasonality of climate is treated differently from previous classifications. As stated previously, the Thornthwaite methods are cumbersome and difficult to interpret. Another problem with Thornthwaite's and many other seasonality definitions is the concept of a "summer" or "winter" month—what are summer and winter in an equatorial location? Similarly, how do we determine a summer wet or dry climate in a place like East Africa where there are two distinct rainy seasons, neither of which fall in winter or summer? Other schemes have been proposed to identify seasonality, including many that attempt to assess the duration of a dry or wet period. But, as is pointed out by Carter and Mather (1966), the intensity of the dry or wet period is perhaps a better measure of seasonality. In this new classification, seasonality will be determined by measuring the range or variation in a climate over the period of a year.

Because the Willmott and Feddema (1992) formulation of the moisture index is symmetric about zero, and numbers on either side of the scale are equivalent in terms of dryness or wetness of a climate, it is possible to mathematically manipulate the index in a meaningful way. The other benefit of using the I_m to measure seasonality is that it varies with respect to both thermal (PE) and moisture (P) variability. By using I_m, we can therefore collapse the two seasonality indices used by Thornthwaite

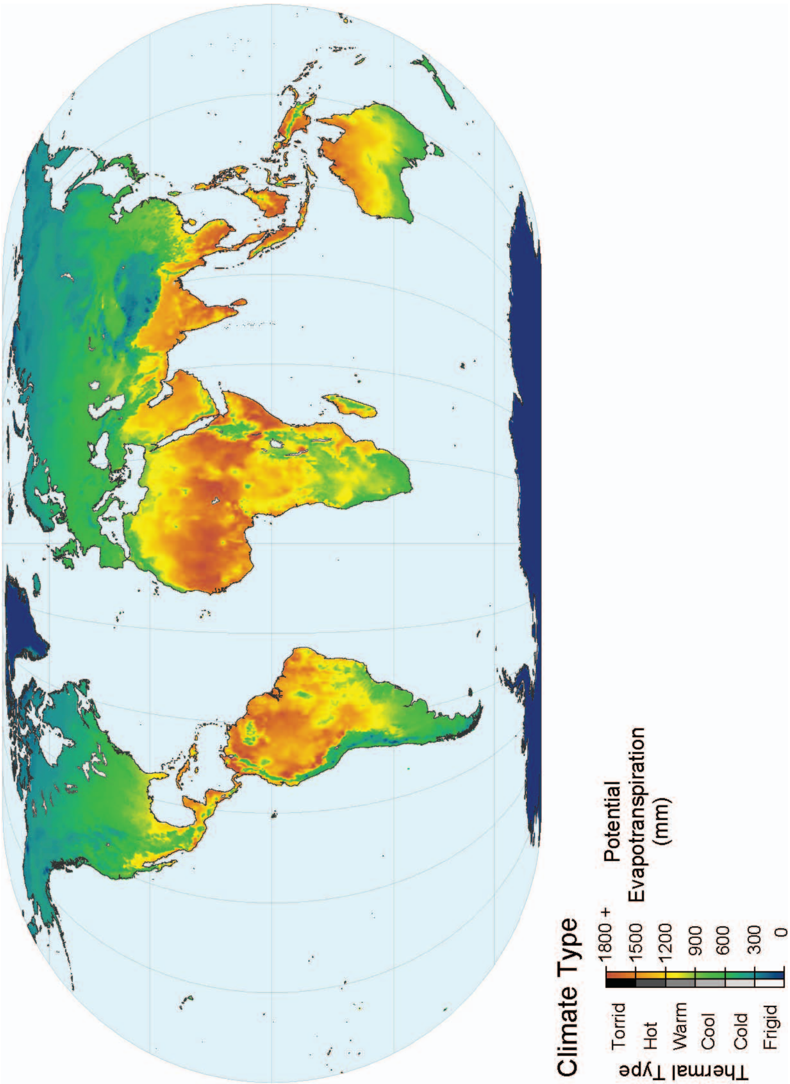

Fig. 7. Global distribution of thermal variation for the new classification.

Table 7. Seasonality Types for the New Classification

Seasonality type	Annual I_m range (mm)
Low	0.0 to 0.5
Medium	0.5 to 1.0
High	1.0 to 1.5
Extreme	1.5 to 2.0

into one index. The seasonality index is based on the annual range of monthly I_m values. The maximum possible range for any given location is a value of 2.0; meaning there is one month that receives no rainfall on average (I_m = -1.0) and another where PE is zero on average (I_m = 1.0). We define four seasonality classes, from low to extreme (Table 7). The geographic distribution of this variable shows some interesting climatic features (Fig. 8). In the tropics, there are a few true rainforest locations with little variation in climate. Generally poleward of these locations, there is a rapid transition to high/extreme variability in the tropical wet and dry climates before transitioning back to low variability in the deserts. The variability in these regions is typically tied to variations in annual precipitation. Poleward of the sub-tropical deserts, variability typically increases again because of variations in PE or thermal regimes. Exceptions include coastal climates.

Initially, the classification was to end at this step. However, because of the systematic explanation of seasonality, a secondary causal factor was added to the seasonality index, creating a fourth criterion in the classification. As a modifier of the seasonality index, however, it does not carry the same weight as the other components of the classification.

The Seasonality Cause Modifier

To distinguish whether seasonality is caused by the thermal or moisture factor, the following rule was developed. Since both PE and P are measured in the same units, they can be directly compared. If a climate is highly seasonal because of variability in precipitation, we can expect a large range between the months of maximum and minimum precipitation. Similarly, a large range in PE can be expected where temperature is the leading cause of seasonality. Using the ratio between the range of monthly P and the range of monthly PE, we defined three causes of seasonality. If the ratio is less than 0.5, then P is nearly constant over the year while PE varies at least twice as much as P. Similarly, if the ratio exceeds a value of 2.0, then P varies by more than twice the amount of PE. In between these extremes, a combination of both (or neither) variables are responsible for the seasonal variation (Table 8). Thus, reasons for the change in seasonality over space can be mapped (Fig. 9).

MAPPING THE CLASSIFICATION

As stated previously, one important consideration in presenting a new climatic classification is the need to make it an intuitive and useful tool for interpreting

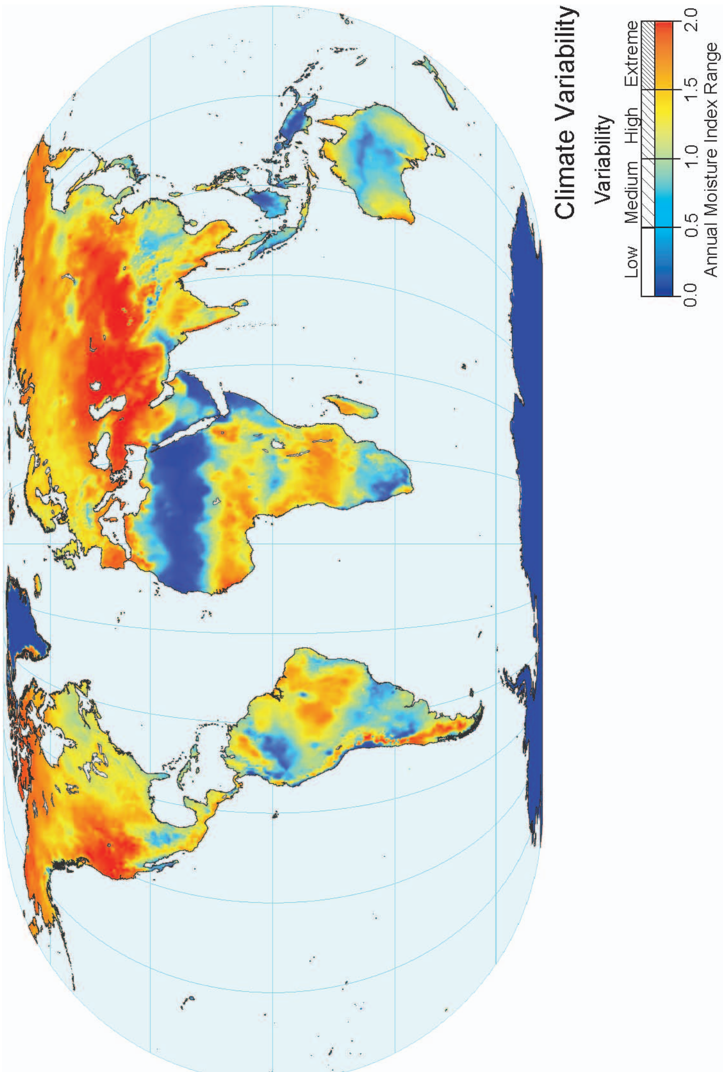

Fig. 8. Global distribution of seasonality for the new classification.

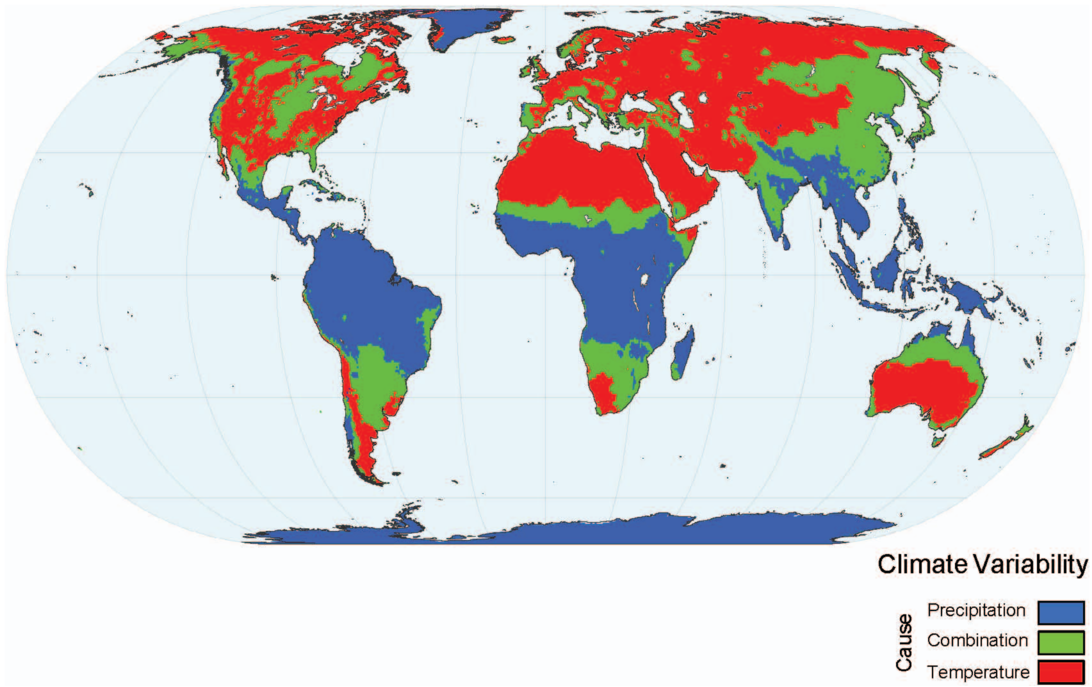

Fig. 9. Global distribution of the cause of seasonal variation for the new classification.

Table 8. Seasonality causes for the new classification

Seasonality cause	Annual P range/annual PE range
Precipitation	<0.5
Combination	0.5 to 2.0
Temperature	>2.0

climate variability over the surface of the Earth. It also must fit in with a systems approach to climate education. The variables used inherently follow from a systematic treatment of climate variations over space. But in presenting the data, it is important that a student be able to understand the underlying systematic variations of the variables through space. When presenting this climate classification it is important that: (1) each variable be presented independently and as continuous-variable maps at the outset; (2) students should be able to see the reduction of these variables into fewer classes as they will be represented on a final map of the classification; and (3) students can easily evaluate the climate of a location by following an intuitive legend that easily allows them to extract the individual variables from a map location.

The final map projection used in this paper was carefully selected. On a global scale, it is important to use an equal area projection, and it should optimize readability and maximize the area used on a typical page. The Eckert IV projection was selected, it was specifically designed to present climate data in an equal area projection (Snyder, 1987).

Color schemes and a continuous color gradient from violet to red to indicate six basic moisture factor classes (Fig. 6) were also purposely selected. To show the thermal factor, color of each Moisture class was modified, creating six color groups. This was done by modifying the intensity of the moisture factor color. To illustrate this concept, the initial thermal classes are shown in color, but with a grayscale of 6 classes to indicate intensity shown on the scale bar (Fig. 7). Combining these two variables into one map then results in a map with six groups of moisture classes, each with six color intensities that modify the basic moisture color field (Fig. 10). By presenting this as a grid of colors, it is easy to identify the moisture type by looking across the color scale (left to right), and the thermal class can be identified by the color intensity (up and down the color scales). Note that this orientation of scale bars is also implied in Figures 6 and 7.

To add seasonality to the classification, one option is to further alter the color schemes of the map, but this is not really possible because colors would become indistinguishable. Instead, an overlay map was created that uses different hatching intensities to identify seasonality types (Fig. 11); the underlying colors in this intermediate step are removed in the final overlay. The hatching direction is then modified to indicate the seasonality cause associated with the seasonality index—right-leaning diagonal lines for precipitation, horizontal for the combination case, and left-leaning diagonal lines for temperature. A separate gridded legend is used to track seasonality from left to right and the cause of the seasonality is indicated by the angle of the hatching from top to bottom.

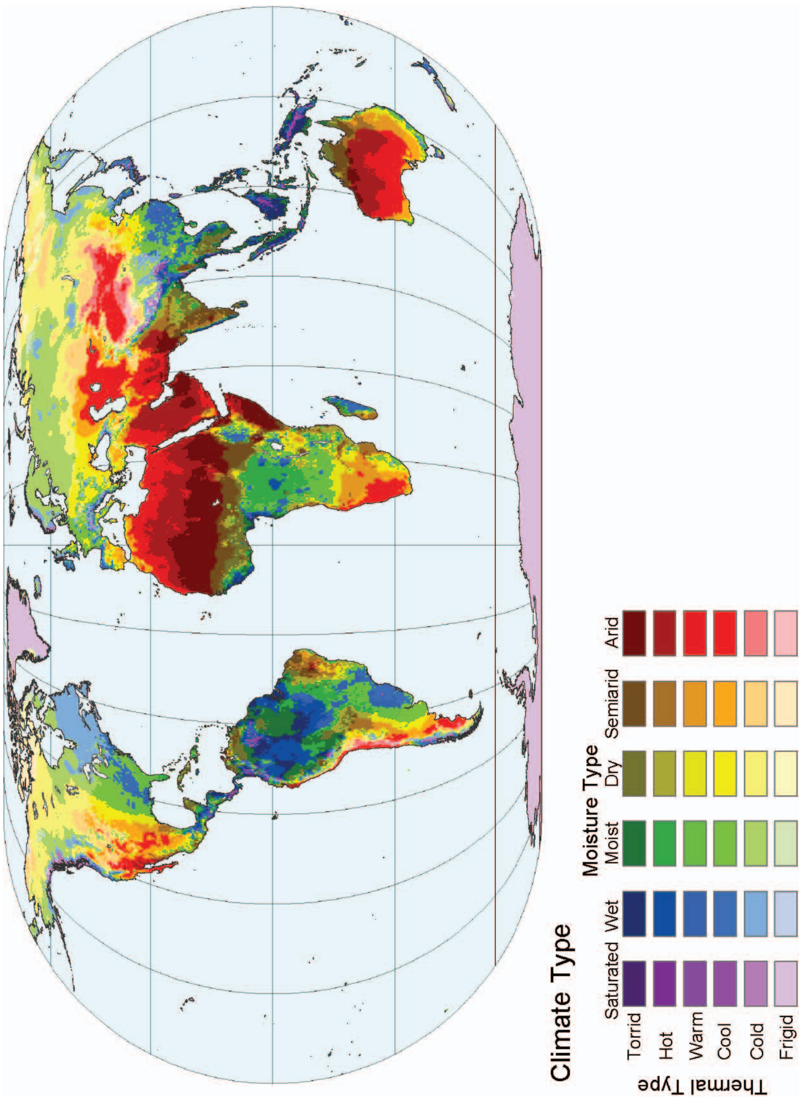

Fig. 10. Global climate types based on moisture and thermal factors.

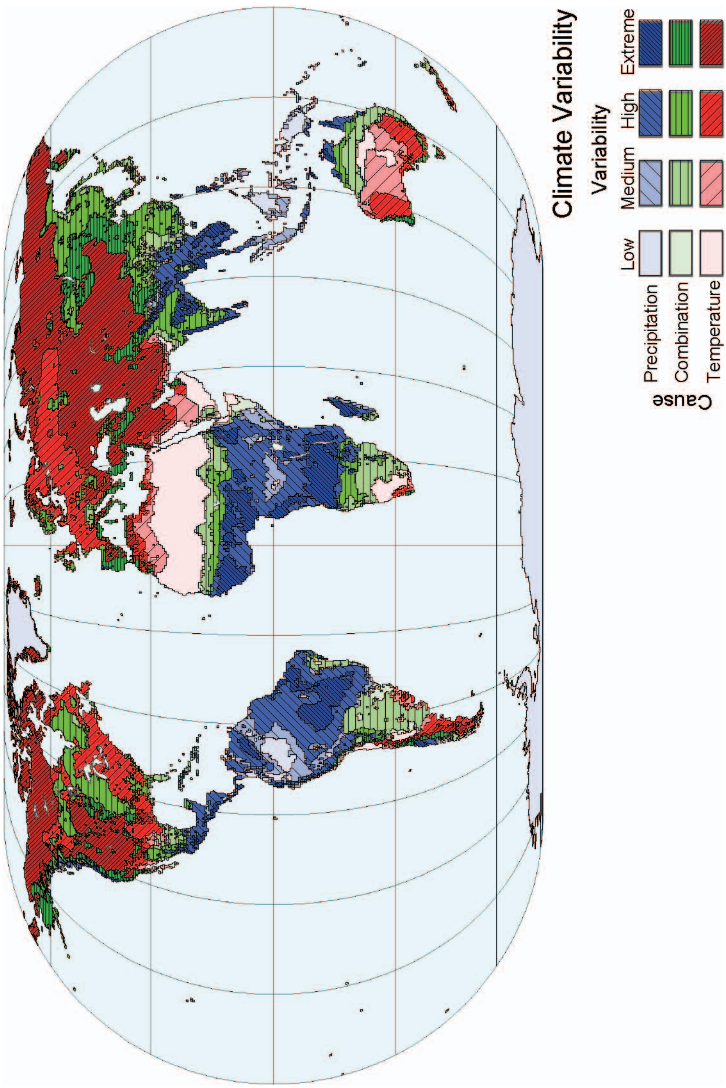

Fig. 11. Global variation of seasonality classified by cause.

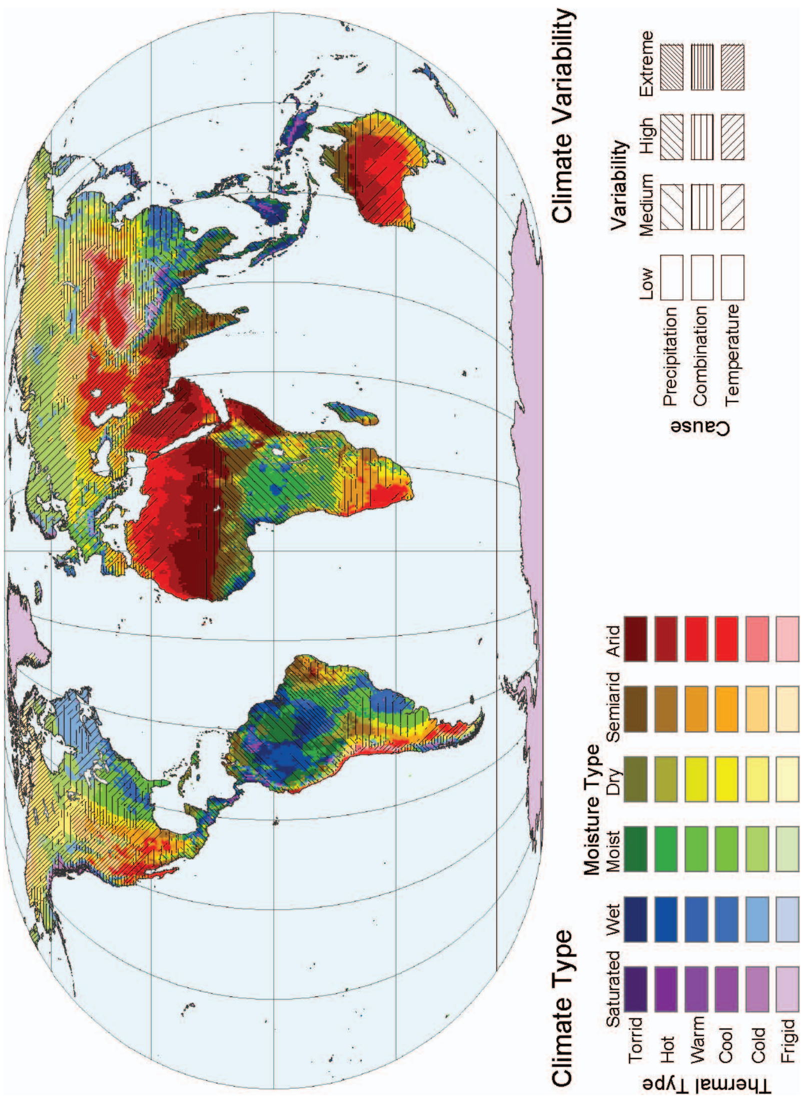

Fig. 12. The revised Thorthwaite-type climate classification.

The final map (Fig. 12) overlays the colored moisture and thermal climate types map (Fig. 10) with the hatched seasonality (Fig. 11). Two separate legends are used for each component. On the scale of the map presented here, it is difficult to identify exact locations and symbols. However, on the scale of wall or projected maps, the hatching is less dense and colors are more easily identified for better interpretation. A copy of the wall map can be obtained by contacting the author. The poster shows the progression of maps from the individual components to the final map.

INTERPRETATION OF THE NEW THORNTHWAITE CLIMATE CLASSIFICATION

The advantage of this new Thornthwaite climate classification is that the student inherently can place the climate type in the context of the gradients indicated in the legends. By examining the full range of moisture, thermal, and seasonality classes, and placing a particular climate along that range, a student can identify the relative position or intensity of that climate with respect to each of the factors. Furthermore, the names of each class have been selected to create the idea of a continuum along each variable, as was urged by Thornthwaite. By removing the intermediate step of using a letter code, interpretation is also more direct.

This new climatic classification has two big improvements over the ubiquitous Köppen classification. First, there is no need to memorize the letter codes of climate, and the systematic gradients make interpretation of how climate changes over space much more intuitive. But more importantly, an intuitive link now exists between climate types. In South America, for example, the dry climates are west of the Andes Mountains in the tropical regions while they are to the east in the southern part of the continent. Unlike the Köppen classification, where these regions do not appear to have any visual similarities, there is a direct visual clue that shows the similarity of the regions with respect to moisture resources (red color code). From a systems point of view, this can be easily related to the rain shadow effect as a consequence of the location of the Andes and climatological wind direction. Similarly, the tropical climates of Africa and South America are easily linked to the characteristics of the Inter-Tropical Convergence Zone by analysis of the moisture and climate variability trends in these regions. We hope that this classification scheme will make it easier to relate the moisture, thermal, and variability types to actual dynamic features and the causes of different climates over the terrestrial surface.

Acknowledgments: This paper is dedicated to the memory of John "Russ" Mather, a great mentor and friend. I would also like to thank Peter Gogol for his research on the map projection and for his suggestions on the methodology, John Bauer for his assistance in various aspects of the project, and David R. Legates, who participated in discussions on this topic and for assisting with the manuscript.

REFERENCES

Carter, D. B. and Mather, J. R. (1966) Climatic classification for environmental biology. *Puhlications in Climatology*, Vol. 19, No. 1, 305–395.

Changnon, S. A., Kunkel, K. E., Winstanley, D. (2002) Climate factors that caused the unique tall grass prairie in the central United States. *Physical Geography*, Vol. 23, 259–280.

Field, R. T. (2005) John Russell (Russ) Mather at the Laboratory of Climatology. *Physical Geography*, Vol. 26, 434–441. [This issue]

Köppen, W. (1900) Versuch einer Klassifikation der Klimate, Vorzugsweise nach ihren Beziehungen zur Pflanzenwelt [Attempted climate classification in relation to plant distributions]. *Geographische Zeitschrift*, Vol. 6, 593–611, 657–679.

Legates, D. R. and Willmott, C. J. (1990a) Mean seasonal and spatial variability in gauge-corrected, global precipitation. *International Journal of Climatology*, Vol. 10, 111–127.

Legates, D. R. and Willmott, C. J. (1990b) Mean seasonal and spatial variability in global surface air temperature. *Theoretical and Applied Climatology*, Vol. 41, 11–21.

Mather, J. R. (1978) *The Climatic Water Budget in Environmental Analysis*. Lexington, MA: Lexington Books.

Middleton, N. J. and Thomas, D. S. G. (1997) *World Atlas of Desertification* (Second edition). Geneva, Switzerland: United Nations Environment Programme.

Snyder, J. P. (1987) *Map Projections—A Working Manual*. Washington, DC: U. S. Government Printing Office, 253–258, *U.S. Geological Survey Professional Paper 1395*.

Thornthwaite, C. W. (1943) Problems in the classification of climates. *Geographical Review*, Vol. 33, No. 2, 233–255.

Thornthwaite, C. W. (1948) An approach toward a rational classification of climate. *Geographical Review*, Vol. 38, No. 1, 55–94.

Thornthwaite, C. W. and Mather, J. R. (1955) The water balance. *Publications in Climatology*, Vol. 8, 1–104.

Willmott, C. J. and Feddema, J. J. (1992) A more rational climatic moisture index. *The Professional Geographer*, Vol. 44, No. 1, 84–88.

Willmott, C. J. and Matsuura, K. (2004) *Global Climate Resource Page*. Retrieved August 2004 from http://climate.geog.udel.edu/~climate