A More Rational Climatic Moisture Index*

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A climatic moisture index ($I_m$) used extensively by C. W. Thornthwaite and others is examined, and a modified version of the index is proposed. Arbitrary limits [$-100 \leq I_m \leq 100$ ($\infty - 1$)], combined with its dimensionless property, make the original index difficult to interpret. Our refined version also is dimensionless, but the limits have been recast so that $-1 \leq I_m \leq 1$. Wet climates have positive values of $I_m$ while dry climates are negative, and the index is symmetric about zero. The spatial distribution of our modified annual-average moisture index over the world's continents is mapped and described. Key Words: water balance, moisture index, global climate

Introduction

Climate is largely characterized by the heat and moisture states of the earth's surface and near surface (Willmott 1987) and, therefore, concern for their (the states') spatial and temporal variability has commanded the attention of climatologists for centuries. Moisture has received most of the attention, owing to its paramount role in biological processes (Carter and Mather 1966). Climatologists often have used simple indices to describe the moisture state of the earth's surface, and one such index—Thornthwaite's index—is the subject of this note.

Moisture indices typically are functions of the ratio of time-averaged precipitation to time-averaged moisture demand by the atmosphere. Their value lies in their ability to characterize the relative wetness or dryness of places based solely on climatic data (Mather 1974). Perhaps the moisture-index concept can be traced to Linsser (Thornthwaite 1943), although it was Thornthwaite who first replaced the early surrogates of moisture demand (pan evaporation and air temperature) with a climatologically meaningful moisture demand, termed potential evapotranspiration (Mather 1990). Thornthwaite and his colleagues' many hydroclimatological publications during the 1930s, 1940s, and 1950s served to disseminate widely their contributions, including the moisture index (Thornthwaite 1943, 1948; Thornthwaite and Mather 1955).

The evaluation and mapping of moisture indices continue to be educational. Delworth and Manabe (1988), for instance, use a moisture index to illustrate relationships that might occur between climate and moisture availability at the earth's surface. As Thornthwaite's moisture index is well known and typical, our purpose within this paper is to examine several of its properties and present a more rational, modified version of the index.

Thornthwaite's Moisture Index

Thornthwaite (1948) specified his moisture index as

$$I_m = 100 \left[ \frac{S - 0.6D}{E^*} \right]$$

(1)

where $I_m$ is the moisture index, $S$ is the moisture surplus, $D$ is the moisture deficit, and $E^*$ is the potential evapotranspiration; that is, the evapotranspiration that would occur if the vegetation experiences no water stress. His moisture deficit (D) is merely ($E^* - E$), where $E$ is the actual evapotranspiration rate. Thornthwaite and Mather (1955) later dropped the 0.6 scaling coefficient. Thornthwaite's surplus can be written

$$S = \begin{cases} r - [E+(w^*-w)], & r > [E+(w^*-w)] \\ 0, & r \leq [E+(w^*-w)] \end{cases}$$

* Thoughtful suggestions on a preliminary draft of this note were made by J. R. Mather, K. Klink, and S. M. Robeson, and we gratefully acknowledge their assistance. We also thank K. Matsura for his help in drafting the map. A portion of this paper is based on work supported by NASA under grant NAGW-1884.

Professional Geographer, 44(1) 1992, pages 84-87 © Copyright 1992 by Association of American Geographers
Initial submission, June 1991; revision submission, July 1991; final acceptance, August 1991
where \( r \) is the precipitation rate, \( w^* \) is the available water-holding capacity of the root zone, and \( w \) is the actual available soil moisture. Units associated with \( S \), \( D \), \( E^s \), \( E \) and \( r \) are typically mm/month or mm/year whereas \( w^* \) and \( w \) are depths. Computational means of obtaining \( E^s \), \( E \), and the other terms are discussed by Willmott et al. (1985) and, therefore, are not presented here.

When Thornthwaite and Mather's (1955) expression is integrated over the "average" year, \( S = \max[(r - E), 0] \) and \( I_m \) becomes

\[
I_m = 100 \left[ \frac{r}{E^s} - 1 \right] \quad (2)
\]

Equation (2), in other words, represents the Thornthwaite annual moisture index that is commonly used to characterize climates (e.g., Thornthwaite and Mather 1955) as well as other aspects of the environment such as vegetation (Mather and Yoshioka 1968).

A difficulty in applying and interpreting the annual moisture index, as it is represented by equations (1) and (2), is that it is dimensionless with arbitrary limits. It also is asymmetric about zero. Cursory examination of equation (2) indicates that \(-100 \leq I_m \leq 100 \) \((= -1)\) or, with the scaling deleted, \(-1 \leq I_m \leq (\infty - 1)\). Without the signpost of meaningful physical units, such a wide range precludes the clear-cut comparison of such values as \(-0.3, 14, \) or \(3.8 \times 10^5\). Relatively wet climates are the main problem inasmuch as there is no upper bound on the index.

### A Modified Moisture Index

A dimensionless moisture index is indeed useful; however, it should be bounded meaningfully so that relative wetness or dryness can be ascertained easily. It additionally ought to be symmetric about zero so that \(-0.9, \) for instance, indicates that moisture supply is equivalent to one tenth the atmospheric demand while \(+0.9\) means that the supply exceeds demand by a factor of 10. In order to incorporate these desirable properties, our modified annual index takes the form

\[
I_m = \begin{cases} 
(r/E^s) - 1, & r < E^s \\
1 - (E^s/r), & r \geq E^s.
\end{cases} \quad (3a)
\]

In the rare case that \( r = E^s = 0 \), we suggest that \( I_m \) be set to zero. While \( I_m \) is usually evaluated on an annual basis, evaluation in seasonally snow-covered environs on subannual time scales requires \( r \) to be replaced by \((r_t + M)\) where \( r_t \) is liquid precipitation and \( M \) is snowmelt (Willmott et al. 1985).

It should be noted that the demand component of \( I_m (E^s) \) may be evaluated in several ways in addition to Thornthwaite's method. Jensen et al. (1990) and Rosenberg et al. (1983) discuss several means of evaluation. When estimates of net radiation are available, they too may be used to obtain estimates of \( I_m \). The calculation is

\[
I_m = \begin{cases} 
[(rL/Q) - 1, & rL < Q \\
1 - (Q/[rL]), & rL \geq Q
\end{cases} \quad (3b)
\]

where \( L \) is the latent heat of vaporization and \( Q \) is the time integral of the positive occurrences of net radiation. Thornthwaite and his colleagues were among the first climatologists to establish the strong connection between \( Q \) and \( E^s \) (Mather 1974; 1990).

Under a variety of conditions, estimates of \( E^s \) or \( Q \) can be biased representations of atmospheric moisture demand and, therefore, \( I_m \) should be cautiously interpreted. Biases may occur, for example, when equation (3) is evaluated on short time scales (subannual) or the area of interest is subject to nontrivial heat or moisture advection. Other biases in \( E^s \) may arise when it is estimated from an incompletely specified, empirical function of weather-station observations (Jensen et al. 1990; Willmott 1984). It also should be mentioned that rainfall measurements of \( r \) are underestimates, and this bias can be significant in seasonally snow-covered or windy regions (Legates and Willmott 1990a).

### An Illustration

The ability of our revised annual-average index (equation 3a) to characterize the relative wetness or dryness of climates is illustrated on a terrestrial map of \( I_m \) (Fig. 1). In this example, annual \( E^s \) was obtained according to Thornthwaite (Wilm et al. 1944), using air-temperature
Figure 1: Moisture regions of the terrestrial world as depicted by the modified Thornthwaite moisture index (Im). Values of the new index appear under the gray scale and, for comparative purposes, corresponding values of the original index (scaling by 100 deleted) appear atop the gray scale. The isoline interval is 0.25 with four levels of constant gray-scale shading from $-1.00$ to $-0.50$, $-0.50$ to $0.00$, $0.00$ to $0.50$, and $0.50$ to $1.00$. Our index was evaluated at a $0.5^\circ$ of latitude by $0.5^\circ$ of longitude resolution using the monthly average precipitation and temperature data sets described by Legates and Willmott (1990a, 1990b) and the climatic water-balance procedure discussed by Willmott et al. (1985).
data compiled by Legates and Willmott (1990b), while annual \( r \) was taken from the rainfall-corrected precipitation data set of Legates and Willmott (1990a). Soil available water-holding capacity (\( w^* \)) is held constant at 150 mm. Moist climates are represented by positive values of \( I_m \), while dry climates are negative. Supply (\( r \)) exceeds demand (\( E^* \)) over much of the tropics, in eastern North America, throughout much of Europe, in Southeast Asia, and in several other regions. Demand exceeds supply over the world's great deserts as well as in adjacent semi-arid zones.

While these results are expected, the new index is superior in that it varies only between \(-1.0\) and \(+1.0\), and it is symmetric about zero. This allows for a more rational (linear) progression of isolines for the wet climates, relative to the original index (Fig. 1). It also makes possible the use of a single, constant contour interval for both wet and dry climates. This, in turn, facilitates cross-comparisons among places. Within much of the forested area of western and central Brazil (\( I_m = 0.5 \)), for instance, only about half the rainfall can be evaporated back into the atmosphere whereas, in the relatively dry Caatinga region of eastern Brazil (\( I_m = -0.5 \)), only about half the atmospheric moisture demand can be met by the supply (Fig. 1). It should be noted that our 0.25 isoline interval was selected solely to describe the spatial variability of \( I_m \). Our isolines, therefore, do not represent boundaries associated with newly defined climatic types.

**Summary**

A modified version of Thornthwaite's annual moisture index has been presented. Our version of the index is symmetric about zero and bounded by \(-1.0\) and \(1.0\); as a result, it removes some of the difficulties associated with the original index (e.g., its asymmetric limits and variable contour intervals). The theoretical advantages of the new index have been discussed and the practical advantages illustrated by mapping the index for the terrestrial world. It is hoped that our refinement will be of use to those interested in describing and mapping the relative wetness and dryness of climates.

**Literature Cited**


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