A NEW METHOD FOR THE CLASSIFICATION OF THE CLIMATES OF THE ARID AND SEMI-ARID REGIONS*

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Abstract

After pointing out the limitations of the existing systems of climatic classification a new system based on the Effective Growth Index has been evolved. This system is applied to classify the arid and semi-arid regions of India and vicinity by using climatic normals, such as temperature and precipitation of sixty stations situated in and around the arid and semi-arid regions. The computed Effective Growth Indices were plotted on a map and through the study of vegetation, soil and landscape it was found that places having the Effective Growth Indices between 0 and 20 have arid climate while those with Effective Growth Indices between 20 and 40 belong to the semi-arid one.

The purpose of climatic classification is to characterise climatic regions in terms of those principal elements, such as temperature and precipitation, which are the most decisive in the formation of the vegetation and soil groups of the earth's surface. It attempts to develop the similarities which the climatic elements bear to each other and their relation to their principal causes, the effect of latitude, of atmospheric and oceanic circulation, in opposition to geographical accidents.

Climatic classifications owe their origin to phytogeographical descriptions though in recent years there has been some controversy in defining this subject and its relation to meteorology, geography and statistics. The physiognomic descriptions of plant associations are related to the first descriptive maps of the distribution of temperature and rainfall, and in this connection we should cite valuable contribution of de Candolle (1875), Grisebach (1875), and Schimper (1903), that include the analysis of the diverse plant types of the world in relation to the principal climatic elements which determine them.

Köppen, a St. Petersberg-trained biologist, and a contemporary of the phytogeographers mentioned above, was the first to attempt a rational classification of the major climatic groups, taking as a basis the phyto-geographical manifestations which they determined and adopting a terminology and symbolism similar to those used by de Candolle. His first classification appeared in 1900 and it has been repeatedly changed both by himself and others. It finally appeared in the Handbuch der Klimatologie published by him in 1936.

Köppen's system was widely accepted by several authors but each one of them admitted its obvious defects. Köppen, in his work, had recognised the importance of evaporation to distinguish between humid and dry climates but being unable to measure it, he developed as his indices relations between precipitation and temperature weighing both in such a manner that the resulting indices would correspond to the boundaries between the actual vegetation types. Since then, many authors have directed their attention to solve this problem, with an

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idea to improve upon the primary concept laid down by Köppen. Notable among such formulae being Mayer's (1926) "Total Precipitation to mean Saturation Deficit", Vazquez's (1933) "Phyto-climatic Index", Rosenkranz's (1936) "Index of Oceanicity" and Davidson's (1934) "Precipitation-Evaporation ratio".

The "Precipitation-Evaporation ratio" though very attractive to use, could not be computed for all regions due to lack of necessary data and hence demanded some alternative, and the formulae put forward usually took into account precipitation and temperature or these in some of their functional forms. Among such fomulae mention may be made of Lang's (1915) P/T, Albert's (1928) "Reduced Rain Factor," de Martonne's "Index of Aridity".

Thornthwaite (1931), in his first attempt, rejected both Köppen's and de Martonne's classifications and offered a new one obtained by summing the individual month's "Temperature Efficiency" and "Precipitation Effectiveness". This "Precipitation Effectiveness" is a function of rainfall and temperature evolved to fit the loss of water from open pans run by U.S. Weather Bureau at 21 stations in the western part of the country and is applicable to only those figures, as has been proved by Bharucha and Shanbhag (1957). His formula when solved for evaporation shows that the evaporation varies directly as the approximate temperature and has a small inverse dependence on precipitation. This relation is true to some extent (if we do not reach the limiting condition) where unlimited supply of water is available for evaporation, but in case of soil surfaces in nature it would be contrary to our experience to say that the evaporation increases as the amount of water in the soil decreases.

There are many expressions with the aid of which evaporation from open water surfaces can be predicted though all of them are to some extent empirical, but they make at least some attempt at physical realities. One such formula is by Rowher (1931) which has been thoroughly tested both in the laboratory and outside, the second is by Thornthwaite himself derived in collaboration with Holzman (1942) and the third is by Penman (1948). Evaporation data obtained from any one of these formulae can be used in conjunction with precipitation to classify the climates instead of using the expression as laid down by Thornthwaite which gives results quite contrary to our experience.

It may, however, be doubted whether evaporation from pans or large bodies of water, is in any way representative of the evaporation from soils covered with vegetation. In nature there are two processes viz., (i) the evaporation from the soil and (2) the transpiration from the plants which are active in transporting the precipitated water back into the atmosphere. These processes are governed mainly by the sun and the sky radiation, the atmosphere immediately above the ground in which actual vapour pressure is less than the saturation vapour pressure, the wind movements which remove the excess of water in the air above the evaporating surface and thus prevent the saturation point being reached, and finally the temperature of the air. The last, viz., the air temperature plays an important rôle in at least two ways :—(i) it controls the temperature of the water through thermal convection and thus acts as a source or sink for heat energy depending upon whether the air is warmer or colder than water ; and (ii) since it controls the temperature of water it partially determines the vapour pressure deficit.

Evaporation is also controlled by the nature of the container through its response or relation to the meteorological factors mentioned above. Thus, for example, the sun and the sky radiation falling on the soil is retained in a thin layer near the surface since soil is opaque to light and thus will cause a large rise in the soil surface temperature as opposed to that of water which is translucent to light. Hence evaporation from saturated soil will be greater than that from a large mass of water under similar meteorological conditions. This is true for a wet soil surface, but as soon as the surface becomes dry other factors come into operation. At this stage evaporation does not take place from the interface of soil and air, but a few millimeters below. Hence the water molecules have to diffuse through the dry soil which acts as a "potential barrier" before being caught and blown away by the prevailing wind. This potential barrier which increases the path of molecular diffusion, reduces the rate of evaporation. Secondly, heat conduction from the surface into the deeper layer of the soil becomes smaller as the pores are filled with air whose thermal conductivity is smaller than that of water.

Transpiration which is more powerful than evaporation in reducing the available water is also governed by the same meteorological factors which bring about evaporation. Besides these it depends upon the physical and biological factors of the soil and plant respectively. The meteorological factors which bring about transpiration are considerably altered by the location, colour and orientation of trees and their leaves. The shaded leaves will transpire less than the unshaded ones because of the difference in the available sun and sky radiation. It is an established fact that the wind increases with height in the layers nearest the ground with the result that transpiration from short grasses will be less than that from isolated trees, other things being equal. The colour of the leaves which decides the albedo will in turn govern the rate of transpiration. Orientation of the leaves with respect to the incident beam of light determines the amount of absorbed energy and this in its turn fixes the rate of transpiration. There are numerous other examples to show that the rate of transpiration will be affected by the modification of the meteorological factors through the transpiring agent, the plant. The physical and biological factors which control the rate and amount of transpiration are too complicated to be mentioned here, but for a detailed account reference may be made to the present author's work (1957).

A short description of the processes of evaporation and transpiration given above makes it clear that both these phenomena depend upon several agents and they cannot be equal or in any way comparable to the water loss from the evaporating pans or atmometers. Furthermore, in the case of the evaporating pans or atmometers the substance to be evaporated, viz., water, is unlimited and the rate of evaporation is solely governed by the evaporating agents as modified by the nature of the container. In nature, however, such condition of unlimited supply of water occurs only during the wet season and even during this season the supply of water depends upon the intensity and distribution of the storm as well as on the soil, vegetation and landscape. The evaporation off an open water surface is sometimes regarded as being a measure of the evaporating power ; even if this proposition is accepted, it can however be regarded as sound only for unit area of an infinite water surface. The evaporation from small pans is affected by the turbulence set up across the rims of the pans. Under such condition it is rather difficult to tell as to what is being measured by these pans. For these reasons the results or relations derived from such studies cannot be used to define the aridity or humidity of a place. Realising that his precipitation-evaporation ratio and the temperature efficiency indices can give little hint of the complexity of soil moisture relationship and that they cannot be regarded as adequate measure of precipitation efficiency, Thornthwaite (1948) proposed his second classification based on the humidity and aridity indices which is the difference between the precipitation and the "consumptive use". The term "consumptive use" which was in vogue in irrigation practices was introduced into climatology by Thornthwaite, changing its name into what is called "potential evapotranspiration". It is defined as the amount of water which would be lost from a surface completely covered with vegetation and supplied with ample water. This quantity, according to Thornthwaite but not in the opinion of Blanny (1953) who introduced the term "consumptive use", depends only on the amount of solar energy received by the surface and the resulting temperature rather than on the kind of plant. This hypothesis is quite contrary to the findings of Henrici (1946) and Blanney and Criddle (1945).

Thornthwaite's concept of P–E which may be useful in irrigation practices, becomes highly hypothetical for the classification of climates since the required condition of land completely covered with vegetation and supplied with adequate water throughout the year occurs only in a limited part of the world. Secondly, the empirical relation between evaporation and temperature obtained by him is based on the data of water requirements of crops at 12 irrigated areas in U.S.A. in latitudes ranging from 29°N to 43°N and is subjected to the same criticism as was directed to his first. Thirdly, though he says that the P–E depends only on the amount of solar energy, his formula for obtaining the monthly or daily P–E is based on a correlation with the mean monthly temperature ; but the mean monthly temperature is in itself not a measure of the available energy for evaporation and transpiration. Any formula which is based on temperature and empirically corrected for latitudes gives erroneous values of P–E if the temperature of a locality is largely influenced by high altitude, presence of warm and cold ocean currents and advective air. His formula, as it stands, gives high values of P–E during the winter months than what could be explained on the energy consideration. Besides these there are other shortcomings in his system of classification. They are :—(a) that the water which could be held in the soil and is made available to the plant is 4 inches for all soils ; (b) that the energy needed to withdraw this amount of water is the same at all moisture contents till the wilting point is reached ; (c) that amount of water which is available for run-off is 50 per cent of the water surplus for all landscape and soils : which are not at all acceptable.

In nature transpiration and not evaporation from the soil, which stops as soon as an insulating dry cap is formed on its surface, is more powerful in removing water in unit time by acting simultaneously on the whole depth of the soil column occupied by the root zone and also removes more water in the long run since it reaches to a greater depth than what evaporation can do. Hence evaporation in nature which takes place primarily through transpiration is not really a loss to be deducted from rainfall, as is done by Thornthwaite for finding the availability of water for plant growth. In fact, the opposite is more nearly true ; the natural evaporation from soil covered with plants represents almost entirely the water that has been used in growth with the result that places where there is high evaporation must have a luxuriant growth of vegetation, which fact is not brought about by Thornthwaite in any of his classification.

It has been already remarked that the P/E ratio is very attractive in the classification of the climates of the continents but the determination of the natural evaporation is very difficult. The only sound method for its determination is based on turbulence theory that was first formulated by Thornthwaite and Holzman (1942) and achieved its perfection in the hands of Pasquill (1949). Determination of this quantity based on the above method is very meagre. In the absence of such data we have to confine our attention to other more reasonable methods of classification rather than use some hypothetical quantity which has no real physical existence.

Temperature and plant growth

Temperature influences in one way or other every chemical and physical process connected with plants. Solubility of minerals, absorption of water, gases, mineral nutrients, diffusion, synthesis as well as the vital processes, such as growth and reproduction are all controlled by temperature. Since these processes are necessary for plants to get established and to survive, temperature controls to a considerable extent the distribution of plants on the earth and largely determines the flora of the different regions. Moreover, temperature delimits also the area of successful poduction of most agricultural crops.

Several investigators tried to find a relation between temperature and growth. All of them came to the conclusion that there is always an optimum temperature for growth, a temperature at which the growth rate is the highest. The growth rate decreases at a lower or higher temperature. This optimum temperature when the growth rate is maximum is in the vicinity of 30°C (86°F) though it is found to vary slightly with the species and length of their exposure. Lehenbaur (1914) from his investigation on the growth of maize seedling in relation to temperature found that the greatest rates of growth occur within the temperature range 29° to 32°C. Wadley (1936) from his study of Green Bugs in relation to temperature found that the rate of development was most rapid at 30°C. Similarly, there are minimum and maximum temperatures beyond which growth does not occur. These limits, though variable, are in the vicinity of 0°C for the lower value and somewhere about 40°C for the upper value.

Van't Hoff (1884) propounded the famous principle that the velocity of any chemical reaction doubles or trebles with each rise in temperature of 10°C. His equation is of the form :—

$$V = CK^t$$

where the constant K has the value 1.0718 and 1.1161 when the velocity doubles or trebles respectively for a rise of temperature of 10°C. When the growth rates as given by Lehenbaur are compared it is found that Van't Hoff's law is applicable only in a limited range of 20° to 31°C and nowhere else.

All investigations on the relation between temperature and growth have made it clear that up to 30°C there are the growth stimulating factors and beyond that the growth inhibiting factors come into operation. What these growth inhibiting factors are, is uncertain. But these relations between temperature and growth cannot be explained by the Van't Hoff's quotient which goes on increasing as the temperature increases.

A satisfactory formula for the growth index is in the form :—

$$V = \frac{pqr\, e^{rt}}{(e^{rt} + q)^2}$$

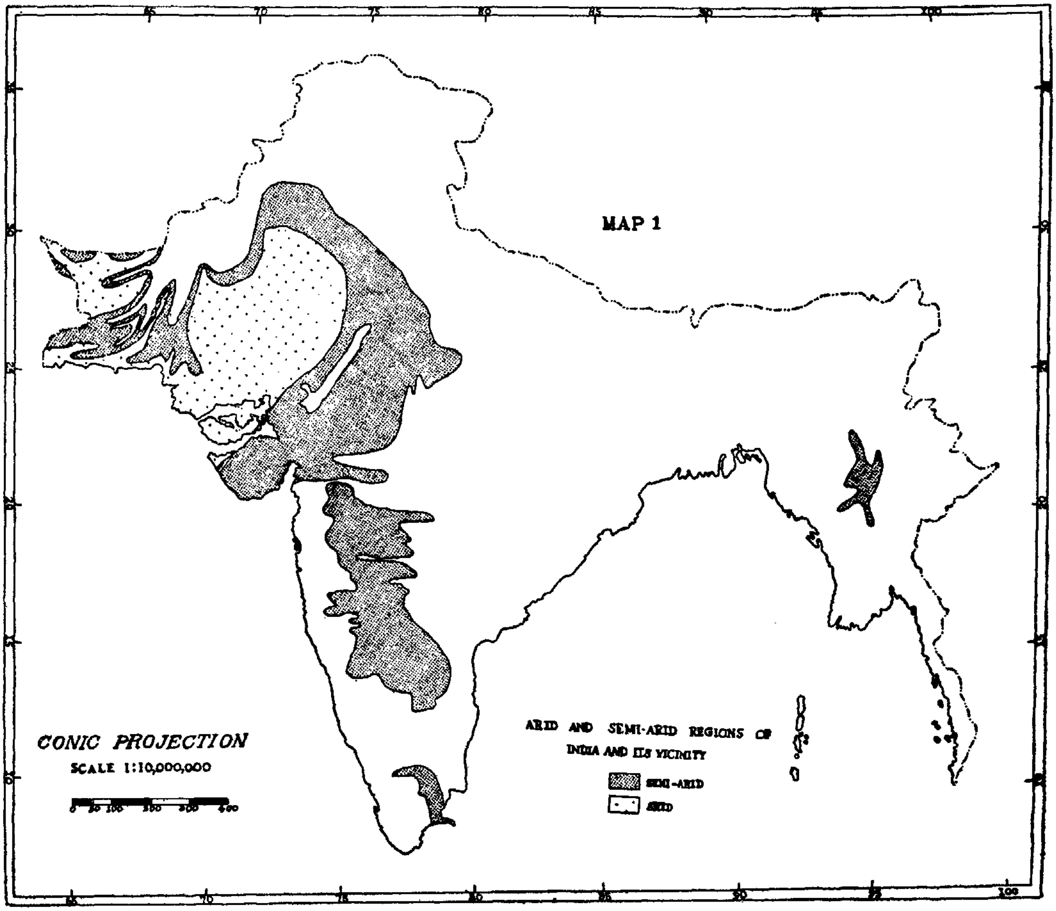
where p, q, r, are constants, t is the temperature in °C and e is the base of Napierian logarithm. In the above equation the numerator stands for growth stimulating factor while the denominator represents the growth inhibiting factor. The equation is solved in the light of the data published by Lehenbaur and the values of the constants are found out. They are :—$p = 1681.0$; $q = 1118.8$; and $r = 0.24$. Using these constants a table has been prepared by the present author (1956) to enable one to compute the growth indices for any temperature in the range 0° to 50°C.

The monthly precipitation (P) of a station when divided by the growth index corresponding to the mean monthly temperature of that station and multiplied by 100 (to save the inconvenience of fractions) gives what is called the "monthly effective growth index" and its summation for all the months of the year gives what is termed as the "Effective Growth Index" and is represented symbolically as E.G.

The formula for getting the "Effective Growth Index" is :—

$$E.G. = \sum_{n=1}^{n=12} \left\{ \frac{100(P)[e^{0.24t} + 1118.8]^2}{(1681.0)(1118.8)(0.24)(e^{0.24t})} \right\}_n$$

This formula was first of all applied to study the arid and semi-arid regions of India and vicinity. The $E.G.$ was calculated for sixty stations in and around our arid and semi-arid regions. These stations had temperature and precipitation records extending over a period of 30 years or more. The computed effective growth indices were plotted on a map of scale 1 : 5,000,000 and the *E.G.* isopleths were drawn. Through the study of vegetation, soil and landscape it was found that if the *E.G.* of a station falls between 0 and 20 its climate is arid, while, if it lies between 20 and 40, it is of the semi-arid type (See Map I, reduced copy of the original).



Examples of computation for five stations of the arid type and five of the semi-arid type are given in Table I.

TABLE I

Item	Jan.	Feb.	Mar.	Apr.	May	Jun.	July	Aug.	Sep.	Oct.	Nov.	Dec.	Sum	Climatic type
BIKANER, LAT. 28°N, LONG. 73°E.														
T	16.7	18.9	25.0	31.1	35.0	35.6	33.3	31.7	31.1	28.3	22.2	16.7	..	
P	0.31	0.31	0.20	0.20	0.71	1.50	3.11	3.39	1.50	0.31	—	0.20	11.74	
G.I.	18.1	28.7	78.7	96.0	64.6	59.1	80.3	92.6	96.0	99.6	53.0	18.1	784.8	
R	1.7	1.1	0.2	0.2	1.1	2.5	3.9	3.7	1.6	0.3	—	1.1	17.4	Arid.
DWARKA, LAT. 22°N, LONG. 69°E.														
T	18.5	20.3	23.5	26.3	28.3	29.3	28.1	26.8	26.7	26.8	24.4	19.7	..	
P	0.05	0.10	0.83	0.12	0.01	3.62	8.14	2.11	1.25	0.07	0.01	0.08	16.39	
G.I.	26.5	37.8	64.9	89.4	99.6	100.0	99.0	92.6	92.0	92.6	73.1	33.6	901.1	
R	0.2	0.3	1.3	0.1	0.01	3.62	8.2	2.3	1.4	0.8	0.01	0.2	18.44	Arid.
JAMNAGAR, LAT. 23°N, LONG. 70°E.														
T	18.9	20.6	25.0	28.3	30.6	31.1	29.4	27.8	27.2	26.2	24.4	20.0	..	
P	0.00	0.20	0.20	0.00	0.00	1.89	7.80	7.01	2.01	0.00	0.00	0.08	19.19	
G.I.	26.7	40.0	78.7	99.6	98.3	96.0	100.0	97.9	95.0	98.3	73.1	35.7	939.3	
R	—	0.5	0.2	—	—	2.0	7.80	7.2	2.1	—	—	0.2	20.0	Arid.
KARACHI, LAT. 25°N, LONG. 67°E.														
T	18.3	20.0	23.3	26.1	28.9	30.0	28.9	27.8	27.2	26.7	22.8	19.4	..	
P	0.51	0.39	0.31	0.20	0.08	0.91	2.91	1.69	0.39	—	—	0.20	7.59	
G.I.	25.1	35.7	63.6	87.4	100.0	100.0	100.0	97.9	95.0	92.0	58.4	31.8	886.9	
R	2.0	1.1	0.5	0.2	0.08	0.91	2.91	1.70	0.4	—	—	0.6	10.4	Arid.
SAKKAR, LAT. 28°C, LONG. 69°E.														
T	14.8	18.6	23.2	28.8	34.2	35.7	34.3	32.8	32.0	28.1	22.3	16.9	..	
P	0.20	0.28	0.24	0.12	0.16	0.16	0.16	0.10	0.04	—	—	0.04	2.5	
G.I.	11.8	27.0	62.1	100.0	72.1	58.6	71.2	84.3	90.5	99.0	53.8	18.8	749.2	
R	1.7	1.0	0.4	0.1	0.2	0.3	0.2	1.3	—	—	—	0.2	5.4	Arid.

TABLE I—Contd.

Item	Jan.	Feb.	Mar.	Apr.	May	Jun.	July	Aug.	Sep.	Oct.	Nov.	Dec.	Sum	Climatic type
AHMADABAD, LAT. 23°N, LONG. 72°E.														
T	21.1	23.3	27.8	31.7	33.9	32.8	29.4	28.3	28.9	29.4	26.1	22.8	..	
P	—	0.08	—	—	0.51	3.78	12.28	8.19	4.29	0.51	0.20	—	29.84	
G.I.	43.9	63.6	97.9	92.6	74.9	84.5	100.0	99.6	100.0	100.0	87.4	58.4	1002.8	
R	—	0.13	—	—	0.70	4.48	12.28	8.22	4.29	0.51	0.23	—	30.84	Semi-arid.
AHMADNAGAR, LAT. 19°N, LONG. 74°E.														
T	20.3	21.7	27.2	29.4	30.3	27.8	25.0	25.6	25.0	25.0	20.3	19.7	..	
P	0.20	0.08	0.20	0.39	0.91	5.20	3.78	2.72	6.50	2.21	1.10	0.59	23.88	
G.I.	37.8	48.7	95.0	100.0	99.3	97.9	78.7	83.7	78.7	78.7	37.8	33.6	869.9	
R	0.54	0.16	0.21	0.39	0.92	5.31	4.80	3.25	8.26	2.81	2.91	0.18	29.74	Semi-arid.
MONYWA, LAT. 22°N, LONG. 95°E.														
T	21.2	23.7	28.1	31.4	32.1	30.4	30.4	29.9	29.4	28.1	25.1	21.4	..	
P	0.04	0.08	0.12	0.91	4.76	4.65	2.95	4.65	5.98	5.20	1.58	0.32	31.24	
G.I.	44.7	66.6	99.0	94.5	89.9	98.9	98.9	100.0	100.0	99.0	79.5	46.2	1017.2	
R	0.09	0.12	0.12	0.96	5.29	4.70	2.98	4.65	5.98	5.25	1.99	0.69	32.82	Semi-arid.
PAMBAN, LAT. 9°N, LONG. 79°E.														
T	25.9	26.6	28.2	29.7	30.2	29.6	29.1	28.9	28.9	28.2	27.1	26.9	..	
P	2.56	0.87	0.71	1.85	0.98	0.16	0.47	0.59	1.14	8.54	11.73	7.60	37.20	
G.I.	86.2	91.3	99.3	100.0	99.7	100.0	100.0	100.0	100.0	99.3	94.6	93.2	1163.6	
R	2.97	0.95	0.72	1.85	0.98	0.16	0.47	0.59	1.14	8.60	12.37	8.15	38.95	Semi-arid.
RAJKOT, LAT. 22°N, LONG. 71°E.														
T	19.7	21.4	25.8	29.7	32.2	31.7	28.6	27.5	27.8	27.8	24.2	20.6	..	
P	—	0.08	0.08	—	0.51	4.41	10.39	5.59	3.90	0.59	0.31	0.08	25.94	
G.I.	33.6	46.2	85.4	100.0	89.2	92.6	100.0	96.6	97.9	97.9	71.4	40.0	950.8	
R	—	0.17	0.09	—	0.57	4.76	10.39	5.79	3.98	0.60	0.43	0.20	26.98	Semi-arid.

Note :—T — Temperature in °C, P — Precipitation in inches, G.I. — Monthly Effective Growth Index, R — Ratio P/G. I.

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