CLASSIFICATION OF THE VEGETATION OF INDIA, PAKISTAN AND BURMA ACCORDING TO EFFECTIVE PRECIPITATION*

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Soon after Koppen's (1900) first attempt to classify the climates of the world on the basis of drainage patterns peculiar to arid regions, many attempts have been made by several investigators in different fields to improve upon his classification. Among these may be mentioned Livingston's (1913, 1916) 'temperature indices', Lang's (1915) '*P-T* ratio', De Martonne's (1926) 'index of aridity', Transeau's (1905) 'index of precipitation effectiveness', Meyer's (1926) 'le quotient hygrometrique', Emberger's (1930) 'expression synthetique du climat', Thornthwaite's (1931, 1933) '*P-E* indices' which he (1948) later modified into what is at present called the 'potential evapotranspiration'.

In the present investigation an attempt was made to find if the vegetation types of India, Pakistan and Burma as laid down by Champion (1936) could be satisfactorily explained on the basis of Koppen's (1918, 1936) and Thornthwaite's (1931, 1948) climatic classifications. As a result of this it was found that Koppen's as well as Thornthwaite's classifications would not suit the diverse climatic conditions of India, Pakistan and Burma.

Koppen (1900, 1918) published two classifications of the climates of the world, the first in 1900 and the second in 1918. In both these articles he devoted little space to the consideration of the identification of the natural climatic regions. He rather concentrated mainly in developing rules and formulae for defining De Candolle's (1856) groups in numerical terms. De Candolle (1878) proposed an original classification and proposed also six sub-divisions. Five comprise plants that are physiologically adjusted to various ranges of mean annual temperature and the sixth comprises plants that have made various physiological adaptations to drought. These are the Megistotherms, Megatherms, Mesotherms, Microtherms, Hekistotherms and Xerophytes. De Candolle made use of the symbols *A*, *B*, *C*, *D*, *E* to represent his five vegetation groups with *B* referring to the Xerophytes.

Koppen stated that he had obtained much help and inspiration from Grisebach's (1875) vegetation map and that it had given him an appreciation of the regularity and symmetry of the pattern of climate over the earth. Actually the map is far too general to have been of any direct aid in locating climatic boundaries. Furthermore, there is almost complete lack of accord except in most general terms between Grisebach's map and De Candolle's physiological groups. There is nothing inconsistent in De Candolle's use of the symbols *A*, *B*, *C*, *D*, *E* to represent his five vegetation groups since he regarded them as parallel zones but for Koppen to adapt this system to represent the climatic pattern, displayed on Grisebach's map, is quite different. Climatologists have often been puzzled by Koppen's use of the symbol *B* for the dry climate, not realizing that it traces back through De Candolle to the Greek system now pretty thoroughly discredited.

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Had Koppen used Schimper's (1903) map of vegetation formations as a basis for the identification of climates, his classification would have been very different and very much better. Schimper's vegetation formations are clearly described, easily recognized, and reasonably well mapped. Furthermore, his careful and systematic discussion of the climate corresponding to each formation supplies precisely the material that is needed to work out the general framework of a climatic classification in line with Koppen's ideas. Schimper's work, therefore, provides a basis for a natural classification of climates.

For establishing the boundaries between dry, steppe and humid climates, Koppen did not take into consideration the increase of evaporation with the increase in temperature. Trabert (1896) considers the following formula as the best expression for the rate of evaporation (R):—

$$R = C(\mathrm{I}+\alpha t)\sqrt{W}\,(E-e) \qquad \ldots \quad \ldots \quad \ldots \quad (1)$$

In this expression C is a constant depending upon the barometric pressure, W is the wind velocity, E is the maximum vapour pressure for the temperature of the evaporating surface, e is the actual vapour pressure in the air above and $\alpha = 1/273$.

When we substitute the corresponding values for the temperatures 5°, 10° and 15°C., considering C, W and e as constants for the region under consideration, we find:—

$$R_5 = C(278/273)\sqrt{W}(6\ 5-e)$$
$$R_{10} = C(283/273)\sqrt{W}(9{\cdot}2-e)$$
$$R_{15} = C(288/273)\sqrt{W}(12{\cdot}8-e)$$

This greater increase in the value of R as temperature increases is not expressed in Koppen's formula.

Thornthwaite put forward two classifications of the climate, one in 1931 which he first of all applied to North America and later to the earth, while the second one appeared in 1948. The first classification is based on the computation of P/E ratios in terms of precipitation and temperature of a station. In deriving the relation between P/E and P/T he used evaporation measurements made at twenty-one continental stations which are of one special climatic type (except one coastal station, Crowley, La of which the effect no doubt disappeared in the process of averaging) and hence its applicability elsewhere is rather doubtful. His formula $P/E = 11{\cdot}5 \left(\frac{P}{T-10}\right)^{10/9}$ when solved for E (the rate of evaporation), gives:—

$$E = 0{\cdot}087\,\frac{(T-10)^{10/9}}{(P)^{1/9}}.$$

In other words, the rate of evaporation varies directly as the approximate temperature and has a small inverse dependence upon precipitation. It is true that the rate of evaporation depends on temperature but it is also controlled by other equally important meteorological factors such as the wind velocity and the saturation deficit, neither of which is allowed for in the formula. Secondly, the presence of precipitation in the above relation is quite unjustifiable, for the rate of evaporation cannot be regarded as a function of precipitation.

As regards Thornthwaite's T-E indices, it may be said that the variations in the heat factor of climate do not generally result in the development of sharply defined boundaries between vegetation formations. As we go from the equator towards either the north or the south, we find that there is a gradual reduction in the variety of flora, with certain species being replaced by others. Thus the boundaries separating tropical, mesothermal, microthermal, taiga and tundra are vague and ill-defined and there is no indication at present that it will be possible to locate them with precision.

The second classification of Thornthwaite's (1948) is based on the computation of potential evapotranspiration by a formula which is purely empirical and according to his own words it does not accord with the newly developed law of growth. Furthermore, the equation completely lacks in mathematical elegance. It is very complicated and, without nomograms and tables as computing aids, would be quite unworkable. The chief obstacle at present to the development of a rational equation is the lack of understanding of why the potential evapotranspiration corresponding to a given temperature is not the same everywhere.

To overcome the above stated defects in the classifications of Koppen as well as those of Thornthwaite, we thought that the *P*/*E* ratios based on actual evaporation data should be computed which might enable us to explain the vegetation types of India, Pakistan and Burma according to Champion's classification. It is surprising to note that records of evaporation in various parts of the world are extremely scanty and mostly unsuitable for a comparative study. Both in the length of the records and in the apparatus used for the measurements, there is considerable variation; one may say that, barring a few exceptions, the subject has attracted only amateur attention. Systematic measurements have been started in the United States of America and Egypt; Japan and other countries are slowly following their examples.

In India there are about 3,000 rain-gauge stations, distributed more or less uniformly. The rainfall records of these stations are available generally for more than 60 to 70 years. As compared to this rainfall measurement organization, the attempts at estimating evaporation have been quite meagre owing perhaps to the difficulties of installing suitable instruments and taking observations with them. Some observations spread over a few years are available from the records of the Trivandrum and Madras Observatories. The observations made by Leather (1913) at Pusa, those made at few irrigation works on the Cauvery and at some of the agricultural stations in the Punjab and in Sind and the very detailed observations made at Colaba and discussed by Banerji and Wadia (1932) practically exhaust the scanty list of data available in India. In recent years the Agricultural Meteorological Department have started taking observations of the rate of evaporation using evaporating pans of the U.S. Weather Bureau type but the data are not yet standardized nor are they made available to the public for any investigation. Hence, it became necessary for us to calculate the mean monthly evaporation from other meteorological factors which directly control it.

Experiments carried out in the laboratories and outside have shown that the rate of evaporation increases with (*a*) the defect of saturation of water vapour, (*b*) the wind velocity, (*c*) the temperature of the water surface, and (*d*) the temperature of the air above the water surface. The effect of atmospheric pressure, judged from simultaneous observations at a few stations at different altitudes, has been found to suppress evaporation with increase of air pressure and vice versa.

There are several formulae put forward by different workers for calculating the rate of evaporation from the meteorological factors but Carl Rohwer's (1931) formula obtained from a long series of elaborate experiments with a view to find separately the influences of each factor such as (1) temperature of the water surface, (2) temperature of the air near the evaporating surface, (3) the effect of saturation, (4) wind velocity near the evaporating surface and (5) altitude of the observation station above mean sea-level has been carefully estimated by a series of experiments. Evaporation figures obtained by his formula are found to be in close agreement with observations made with several types of evaporimeters. Hence it was thought desirable to compute from his formula the mean monthly evaporation needed for our investigation.

The expression given by Rohwer for computing E, the evaporation in inches per 24 hours, is:—

$$E = (1{\cdot}465-0{\cdot}0186B)(0{\cdot}44+0{\cdot}118W)\ (e_s-e_d)$$

where B is the barometric reading in inches of mercury, W, the mean velocity of ground wind in miles per hour, e_s and e_d refer to the mean vapour pressures of the saturated air at the temperatures of the water surface and at dew point respectively, both being measured in inches of mercury. As we have no data of water surface temperatures at our meteorological stations and hence have no means of directly calculating e_s and since we are concerned with the mean daily evaporation, we may assume that the mean daily temperature of the water surface will not differ from that of the air at the same level. On the basis of this assumption Raman and Satakopan (1934) substituted:—

$$\left(\frac{100}{h}-1\right)e \text{ for } (e_s - e_d)$$

where h is the humidity percentage and e is the vapour pressure. Thus the final expression used for computing the monthly evaporation is:—

$$E = (1{\cdot}465 - 0{\cdot}0186B)(0{\cdot}44 + 0{\cdot}118W)\left(\frac{100}{h}-1\right)e.$$

The above formula could not be directly applied to the data recorded by our meteorological stations since the wind instruments of the various stations are usually exposed at the top of a building or a tower, in order to secure as free an exposure as possible. The exposure as well as the height of the instrument above the ground vary considerably from place to place while W in the above expression refers to mean velocity of ground wind in miles per hour.

The variation of wind with height had been studied by Chapman (1932) and from his data it is possible to calculate the ratio of the wind at any height to that at standard level of 4 feet which is the height of the base of the Stevenson screen. This height of 4 feet was chosen since the temperature and humidity data refer to this level and because we have no knowledge at present of the correction for reducing them to any lower level.

To test the applicability of our method, we chose a very large area, namely India, Pakistan and Burma. However, we could only select 104 stations from this vast area since complete and continuous mean monthly records for 15 years (1926–1940) of the seven meteorological elements, namely (1) temperature, (2) precipitation, (3) barometric pressure, (4) wind velocity, (5) percentage humidity, (6) vapour pressure and (7) number of rainy days, together with the characteristic vegetation of other places were not available. Table I gives the statistics regarding the 104 stations from the point of view of availability of water in their vicinity. From this table it is clear that equal importance is given to places in the interior as well as those in the proximity of large bodies of water, which is not considered by Thornthwaite in his earlier classification.

TABLE I

	Situated					
	In the interior	On the West coast	On the East coast	On the banks of the river	On the hills	Total
Number of stations ..	49	12	13	26	4	104

Table II gives the names of the stations that could be included in the present investigation, together with their characteristic vegetation according to Champion, their climatic types according Koppen's classification of 1918 and 1936, their climatic types according to Thornthwaite's classification of 1931 and 1948, and their P/E indices, which is the sum of the twelve monthly P/E ratios multiplied by 10. The P/E ratios required to get the P/E indices were obtained for each month and for each station using the monthly normals of precipitation and other monthly normal data needed to compute the evaporation from the above modified equation of Carl Rohwer. The monthly normals refer to the period of 15 years already referred to on page 188. The P/E indices in Table II are shown with a subscript outside the bracket. These subscripts refer to the number of months during which there was some measurable precipitation at the station under consideration.

A close examination of Table II shows that both classifications of Koppen's and Thornthwaite's fail to place the same stations having the same characteristic vegetation in the same category of climate. Thus, for example, the first 25 stations in Table II with thorn forest as their characteristic vegetation belong to the semi-arid region of India, Pakistan and Burma. Koppen's classification of 1918 places only 18 of them into the category of 'semi-arid' while the remaining seven fall into three different categories, viz. arid, periodically dry savanna and warm temperate rainy climate with dry winter. His later classification, however, places 22 stations out of these 25 into the semi-arid type whereas the remaining three fall into two different types, viz. desert and periodically dry savanna. Thornthwaite's classifications of 1931 and 1948 place only 17 and 20 of these stations into the semi-arid type while the remaining 8 and 5 stations fall into 4 and 2 different types respectively. Thus, Koppen's classification of 1936 fits better to the semi-arid regions of India, Pakistan and Burma but it does not give satisfactory results when we consider stations in the other groups.

The P/E indices given in Table II of all the stations from Hyderabad (Sind) to Chitaldurg whose climate is akin to that of semi-arid and which have similar vegetation, viz. tropical thorn forest, range between 1 and 5. Places from Madura to Bombay having tropical dry deciduous as their characteristic vegetation have P/E indices which fall in the range from 5 onwards to 15; while stations from Daltonganj to Naya-Dumka having the same characteristic tropical moist deciduous (sal) forest fall in the range of 15 to 20. The tropical semi-evergreen group of stations come in the range of 20 to 50 and places having tropical wet evergreen vegetation have P/E indices above 50. The exceptions to this rule are Port Blair, Kodaikanal and Sagar Island which have tropical wet evergreen, sub-tropical wet and tidal forests respectively as their characteristic vegetation. On the basis of P/E indices these places should have tropical semi-evergreen, moist deciduous (sal) and dry deciduous forests respectively as their natural vegetation but it is not so owing to the peculiar micro-climates of these places. Thus with the exception of the vegetation of these three stations, the vegetation of the remaining 101 stations can be explained on the basis of the calculated P/E indices and grouping them in the way stated below. P/E indices 1–5 thorn forest, 6–15 tropical dry deciduous, 16–20 tropical moist deciduous (sal), 21–50 tropical semi-evergreen, 51 onwards tropical wet evergreen.

These P/E indices have some advantages compared with the aridity factor given by Gorczynski (1942, 1945) and the P/E indices of Thornthwaite. They are:

1. The P/E indices are simple climatic factors and are easier to determine as compared to the aridity index of Gorczynski.

2. The calculation of the P/E indices does not require many years of observations as it is the case with the aridity factor. On the contrary, it can be determined for short periods consecutively, showing interesting fluctuations of climate.

3. Besides precipitation and temperature which are used by Thornthwaite in his computation of the P/E indices, they take into consideration other climatic

TABLE II

Station	Characteristic vegetation according to Champion	Climatic type according to Koppen's classification of		Climatic type according to Thornthwaite's classification of		Computed P/E indices
		1918	1936	1931	1948	
1	2	3	4	5	6	7
Hyderabad (Sind)	Tropical thorn forest	Arid (desert) climate (BWhw)	Arid (desert) climate (BWhw)	Mesothermal desert climate (EB′ wa)	Megathermal, arid climate (EA′ da′)	$(1{\cdot}187)_{12}$
Gulburga ..	,,	Periodically dry savanna climate (Aw)	Semi-arid (steppe) climate (BShw)	Tropical grassland (CA′ wa)	Megathermal semi-arid (DA′ da′)	$(4{\cdot}085)_{12}$
Bhuj ..	,,	Semi-arid climate (steppe) (BShw)	Semi-arid (steppe) (BShw)	Tropical semi-arid (steppe) (DA′ wa)	Megathermal arid climate (EA′ da′)	$(1{\cdot}957)_{11}$
Jodhpur ..	,,	,,	Arid (desert) climate (BWhw)	Mesothermal semi-arid (steppe) (DB′ wa)	,,	$(2{\cdot}052)_{12}$
Dwarka ..	,,	,,	Semi-arid (steppe) (BShw)	Tropical semi-arid (DA′ wa)	,,	$(2{\cdot}577)_{12}$
Malegaon ..	,,	,,	,,	Mesothermal semi-arid (DB′ wa)	Megathermal semi-arid (DA′ da′)	$(2{\cdot}598)_{12}$
Bellary ..	,,	,,	,,	Tropical semi-arid (DA′ wa)	,,	$(2{\cdot}824)_{12}$
Ahmadnagar ..	,,	,,	,,	Mesothermal forest (DB′ wa)	,,	$(2{\cdot}944)_{11}$
Rajkot ..	,,	,,	,,	Tropical semi-arid (DA′ wa)	,,	$(3{\cdot}071)_{12}$
Jhansi ..	,,	Warm temperate rainy climate with dry winter (Cwa)	,,	Tropical grassland (CA′ wa)	Megathermal semi-arid (DA′ db′$_4$)	$(4{\cdot}256)_{12}$
Sholapur ..	,,	Semi-arid (steppe) (BShw)	,,	Tropical semi-arid (DA′ wa)	Megathermal semi-arid (DA′ da′)	$(3{\cdot}325)_{12}$

TABLE II—*contd.*

Station	Characteristic vegetation according to Champion	Climatic type according to Koppen's classification of		Climatic type according to Thornthwaite's classification of		Computed P/E indices
		1918	1936	1931	1948	
1	2	3	4	5	6	7
Kurnool ..	Tropical thorn forest	Semi-arid (steppe) (BShw)	Semi-arid (steppe) (BShw)	Tropical semi-arid (DA′ wa)	Megathermal semi-arid (DA′ da′)	$(3{\cdot}502)_{12}$
Ajmer ..	,,	,,	,,	Mesothermal semi-arid (DB′ wa)	,,	$(3{\cdot}500)_{12}$
Agra ..	,,	,,	,,	,,	,,	$(3{\cdot}874)_{12}$
Poona ..	,,	Warm temperate rainy climate with dry winter (Cwa)	,,	Mesothermal grass-land (CB′ wa)	Megathermal dry sub-humid ($C_1B'_4$ da′)	$(4{\cdot}605)_{11}$
Kotah ..	,,	,,	,,	Tropical semi-arid (DA′ wa)	Megathermal semi-arid (DA′ db'_4)	$(4{\cdot}115)_{12}$
Khandwa ..	,,	Semi-arid (steppe) (BShw)	,,	Mesothermal grassland (CB′ wa)	Megathermal semi-arid (DA′ da′)	$(4{\cdot}323)_{12}$
Akola ..	,,	Warm temperate rainy climate with dry winter (Cwa)	,,	Tropical grass-land (CA′ wa)	,,	$(4{\cdot}355)_{12}$
Veraval ..	,,	Semi-arid (steppe) (BShw)	,,	Tropical semi-arid (DA′ wa)	,,	$(4{\cdot}339)_{10}$
Bhavnagar ..	,,	,,	,,	,,	,,	$(4{\cdot}330)_{12}$
Jaipur ..	,,	,,	,,	Mesothermal semi-arid (DB′ wa)	,,	$(4{\cdot}187)_{12}$
Deesa ..	,,	,,	,,	,,	,,	$(4{\cdot}520)_{12}$
Raichur ..	,,	,,	,,	Tropical semi-arid (DA′ wa)	,,	$(2{\cdot}869)_{12}$
Chitaldurg ..	,,	,,	,,	Mesothermal semi-arid (DB′ wa)	,,	$(4{\cdot}946)_{12}$
Hanamkonda ..	,,	Periodically dry savanna climate (Aw)	Periodically dry savanna climate (Aw)	Tropical grassland (CA′ wa)	,,	$(4{\cdot}601)_{12}$
Madura ..	(Tropical dry deciduous)	,,	,,	,,	,,	$(5{\cdot}519)_{12}$

TABLE II—*contd.*

Station	Characteristic vegetation according to Champion	Climatic type according to Koppen's classification of		Climatic type according to Thornthwaite's classification of		Computed P/E indices
		1918	1936	1931	1948	
1	2	3	4	5	6	7
Neemuch ..	(Tropical dry deciduous)	Warm temperate rainy climate with dry winter (Cwa)	Warm temperate rainy climate with dry winter (Cwa)	Mesothermal grassland (CB′ wa)	Megathermal dry sub-humid (C_1A′ wa′)	$(5{\cdot}565)_{12}$
Pamban ..	,,	Periodically dry savanna climate (Awi)	Periodically dry savanna climate (Awi)	Tropical grass-land (CA′ sa)	Megathermal semi-arid (DA′ da′)	$(5{\cdot}801)_{12}$
Trichinopoly ..	,,	,,	Semi-arid (steppe) (BShw)	Tropical grass-land (CA′ wa)	,,	$(6{\cdot}037)_{12}$
Amraoti ..	,,	,,	Periodically dry savanna climate (Awi)	,,	,,	$(6{\cdot}139)_{12}$
Ahmadabad ..	,,	Warm temperate rainy climate with dry winter (Cwa)	Semi-arid (steppe) (BShw)	,,	,,	$(6{\cdot}239)_{11}$
Hyderabad (Deccan)	,,	,,	Warm temperate rainy climate with dry winter (Cwa)	Mesothermal grassland (CB′ wa)	Megathermal dry sub-humid (C_1A′ wa′)	$(6{\cdot}406)_{12}$
Mainpuri ..	,,	,,	Semi-arid (steppe) (BShw)	,,	Megathermal semi-arid (DA′ da′)	$(6{\cdot}981)_{12}$
Indore ..	,,	,,	,,	,,	,,	$(7{\cdot}532)_{12}$
Allahabad ..	,,	,,	Warm temperate rainy climate with dry winter (Cwa)	,,	Megathermal dry sub-humid (C_1A′ da′)	$(7{\cdot}821)_{12}$
Mandalay ..	,,	,,	,,	Tropical grass-land (CA′ wa)	Megathermal semi-arid (DA′ da′)	$(7{\cdot}817)_{12}$

TABLE II—*contd.*

Station	Characteristic vegetation according to Champion	Climatic type according to Koppen's classification of		Climatic type according to Thornthwaite's classification of		Computed P/E indices
		1918	1936	1931	1948	
1	2	3	4	5	6	7
Nizamabad ..	(Tropical dry deciduous)	Warm temperate rainy climate with dry winter (Cwa)	Warm temperate rainy climate with dry winter (Cwa)	Tropical grassland (CA′ wa)	Megathermal dry sub-humid (C_1A' wa′)	$(8{\cdot}117)_{12}$
Cawnpur ..	,,	,,	,,	Mesothermal grassland (CB′ wa)	Megathermal semi-arid (DA′ da′)	$(8{\cdot}697)_{12}$
Salem ..	,,	Periodically dry savanna climate (Awi)	Periodically dry savanna climate (Awi)	Tropical grassland (CA′ wa)	,,	$(8{\cdot}848)_{12}$
Gaya ..	,,	Warm temperate rainy climate with dry winter (Cwa)	Warm temperate rainy climate with dry winter (Cwa)	Tropical grassland (CA′ wa)	Megathermal dry sub-humid (C_1A' wa′)	$(9{\cdot}251)_{11}$
Bangalore ..	,,	,,	,,	Mesothermal grassland (CB′ wa)	Mesothermal dry sub-humid ($C_1B'_4$ wa′)	$(9{\cdot}177)_{12}$
Chanda ..	,,	,,	,,	Tropical forest (BA′ wa)	Megathermal moist sub-humid (C_2A' s_2a')	$(9{\cdot}302)_{12}$
Ambala ..	,,	Warm temperate rainy climate without dry season (Cfa)	Warm temperate rainy climate without dry season (Cfa)	Mesothermal grassland (CB′ wb)	Megathermal semi-arid (DA′ db'_4)	$(9{\cdot}515)_{12}$
Nagpur ..	,,	Warm temperate rainy climate with dry winter (Cwa)	Warm temperate rainy climate with dry winter (Cwa)	Tropical grassland (CA′ wa)	Megathermal dry sub-humid (C_1A' $w_2b'_4$)	$(9{\cdot}926)_{12}$
Surat ..	,,	,,	,,	,,	Megathermal dry sub-humid (C_1A' wa′)	$(10{\cdot}116)_{11}$

TABLE II—*contd.*

Station	Characteristic vegetation according to Champion	Climatic type according to Koppen's classification of		Climatic type according to Thornthwaite's classification of		Computed P/E indices
		1918	1936	1931	1948	
1	2	3	4	5	6	7
Lucknow ..	(Tropical dry deciduous)	Warm temperate rainy climate with dry winter (Cwa)	Warm temperate rainy climate with dry winter (Cwa)	Mesothermal grassland (CB′ wa)	Megathermal dry sub-humid (C_1A' da′)	$(10{\cdot}132)_{12}$
Nellore ..	,,	Periodically dry savanna climate (Aw)	Periodically dry savanna climate (Aw)	Tropical grassland (CA′ sa)	Megathermal semi-arid (DA′ da′)	$(10{\cdot}488)_{12}$
Hazaribag ..	,,	Warm temperate rainy climate with dry winter (Cwa)	Warm temperate rainy climate with dry winter (Cwa)	Mesothermal forest (BB′ wa)	Megathermal humid (B_1A' w_2a')	$(11{\cdot}247)_{12}$
Benares ..	,,	,,	,,	Tropical forest (BA′ wa)	Megathermal dry sub-humid (C_1A' da′)	$(11{\cdot}247)_{12}$
Monywa ..	,,	,,	,,	Tropical grassland (CA′ wa)	Megathermal semi-arid (DA′ da′)	$(11{\cdot}428)_{10}$
Sutna ..	,,	,,	,,	Mesothermal grassland (CB′ wa)	Megathermal dry sub-humid (C_1A' wb'_4)	$(11{\cdot}845)_{12}$
Cuddalore ..	,,	Periodically dry savanna climate (Awi)	Periodically dry savanna climate (Awi)	Tropical forest (BA′ sa)	Megathermal dry sub-humid (C_1A' s_2a')	$(12{\cdot}672)_{12}$
Bhagalpur ..	,,	,,	,,	Tropical forest (BA′ wa)	Megathermal dry sub-humid (C_1A' wa′)	$(12{\cdot}956)_{11}$
Patna ..	,,	,,	,,	,,	Megathermal moist sub-humid (C_2A' wa′)	$(12{\cdot}973)_{12}$
Raipur ..	,,	,,	,,	Mesothermal forest (BB′ wa)	Megathermal moist sub-humid (C_2A' $w_2b'_4$).	$(13{\cdot}483)_{12}$

TABLE II—*contd.*

Station	Characteristic vegetation according to Champion	Climatic type according to Koppen's classification of		Climatic type according to Thornthwaite's classification of		Computed P/E indices
		1918	1936	1931	1948	
1	2	3	4	5	6	7
Seoni ..	(Tropical dry deciduous)	Periodically dry savanna climate (Awi)	Periodically dry savanna climate (Awi)	Mesothermal forest (BB′ wa)	Megathermal moist sub-humid (C_2A' $w_2b'_4$)	$(13{\cdot}741)_{12}$
Madras ..	,,	,,	,,	Tropical forest (BA′ sa)	Megathermal dry sub-humid (C_1A' sa′)	$(13{\cdot}703)_{12}$
Bahraich ..	,,	Warm temperate rainy climate with dry winter (Cwa)	Warm temperate rainy climate with dry winter (Cwa)	Mesothermal grassland (CB′ wa)	Megathermal dry sub-humid (C_1A' wa′)	$(13{\cdot}922)_{12}$
Hosangabad ..	,,	,,	,,	,,	Megathermal moist sub-humid (C_2A' $s_2b'_4$)	$(14{\cdot}099)_{12}$
Yamethin ..	,,	,,	,,	Tropical grassland (CA′ wa)	Megathermal semi-arid (DA′ da′)	$(14{\cdot}676)_{12}$
Bombay ..	,,	Periodically dry savanna climate (Awi)	Periodically dry savanna climate (Awi)	Tropical forest (BA′ wa)	Megathermal humid (B_1A' w_2a').	$(14{\cdot}760)_{11}$
Daltonganj ..	Tropical moist deciduous (sal)	Warm temperate rainy climate with dry winter (Cwa)	Warm temperate rainy climate with dry winter (Cwa)	Mesothermal grassland (CB′ wa)	Megathermal dry sub-humid (C_1A' da′)	$(15{\cdot}167)_{12}$
Sambalpur ..	,,	,,	,,	Tropical forest (BA′ wa)	Megathermal moist sub-humid (C_2A' s_2a')	$(15{\cdot}557)_{12}$
Ranchi ..	,,	,,	,,	Mesothermal forest (BB′ wa)	Megathermal humid (B_1A' sa′)	$(15{\cdot}587)_{12}$
Darbhanga ..	,,	,,	,,	,,	Megathermal moist sub-humid (C_2A' sa′)	$(16{\cdot}199)_{12}$

TABLE II—*contd.*

Station	Characteristic vegetation according to Champion	Climatic type according to Koppen's classification of		Climatic type according to Thornthwaite's classification of		Computed P/E indices
		1918	1936	1931	1948	
1	2	3	4	5	6	7
Bareilly ..	Tropical moist deciduous (sal)	Warm temperate rainy climate with dry winter (Cwa)	Warm temperate rainy climate with dry winter (Cwa)	Mesothermal grassland (CB′ wa)	Megathermal dry sub-humid (C_1, A′ wb′$_4$)	$(16{\cdot}847)_{12}$
Jubbulpur ..	,,	,,	,,	Mesothermal forest (BB′ wa)	Megathermal moist sub-humid (C_2A′ s_2b′$_4$)	$(18{\cdot}084)_{12}$
Gorakhpur ..	,,	,,	,,	Mesothermal grassland (CB′ wa)	Megathermal moist sub-humid (C_2A′ sa′)	$(18{\cdot}339)_{12}$
Balasore ..	,,	,,	,,	Tropical forest (BA′ wa)	,,	$(18{\cdot}419)_{12}$
Naya-Dumka ..	,,	,,	,,	Mesothermal forest (BB′ wa)	,,	$(19{\cdot}612)_{12}$
Ratnagiri ..	Tropical semi-evergreen	Periodically dry savanna climate (Awi)	Periodically dry savanna climate (Awi)	Tropical rain forest (AA′ wa)	Megathermal humid (B_3A′ w_2a′)	$(20{\cdot}540)_{12}$
Trivandrum ..	,,	,,	,,	Tropical forest (BA′ wa)	Megathermal humid (B_1, A′ sa′)	$(20{\cdot}631)_{12}$
Cuttack ..	,,	Warm temperate rainy climate with dry winter (Cwa)	Warm temperate rainy climate with dry winter (Cwa)	,,	Megathermal moist sub-humid (C_2A′ sa′)	$(21{\cdot}279)_{12}$
Belgaum ..	,,	Periodically dry savanna climate (Awi)	Periodically dry savanna climate (Awi)	Mesothermal forest (BB′ wa)	Mesothermal humid (B_2B′$_4$ s_2a′)	$(21{\cdot}389)_{11}$
Berhampore ..	,,	Warm temperate rainy climate with dry winter (Cwa)	Warm temperate rainy climate with dry winter (Cwa)	,,	Megathermal humid (B_1, A′ ra′)	$(22{\cdot}146)_{12}$

TABLE II—*contd.*

Station	Characteristic vegetation according to Champion	Climatic type according to Koppen's classification of		Climatic type according to Thornthwaite's classification of		Computed P/E indices
		1918	1936	1931	1948	
1	2	3	4	5	6	7
Narayanganj ..	**Tropical semi-evergreen**	Warm temperate rainy climate with dry winter (Cwa)	Warm temperate rainy climate with dry winter (Cwa)	Tropical forest (BA′ wa)	Megathermal humid (B_2 A′ ra′)	$(26{\cdot}778)_{12}$
Cochin ..	,,	Periodically dry savanna climate (Awi)	Periodically dry savanna climate (Awi)	Tropical rain forest (AA′ wa)	Megathermal humid (B_4 A′ ra′)	$(29{\cdot}884)_{12}$
Purnea ..	,,	Warm temperate rainy climate with dry winter (Cwa)	Warm temperate rainy climate with dry winter (Cwa)	Mesothermal forest (BB′ wa)	Megathermal humid (B_1 A′ ra′)	$(30{\cdot}546)_{12}$
Marmagao ..	,,	Periodically dry savanna climate (Awi)	Periodically dry savanna climate (Awi)	Tropical rain forest (AA′ wa)	Megathermal humid (B_3 A′ s_2 a′)	$(31{\cdot}691)_{10}$
Bogra ..	,,	Warm temperate rainy climate with dry winter (Cwa)	Warm temperate rainy climate with dry winter (Cwa)	Mesothermal forest (BB′ wa)	Megathermal humid (B_2 A′ ra′)	$(31{\cdot}973)_{12}$
Gauhati ..	,,	,,	,,	,,	Megathermal humid (B_1, A′ ra′)	$(34{\cdot}354)_{12}$
Shillong ..	,,	Warm temperate rainy climate with dry winter (Cwb)	Warm temperate rainy climate with dry winter (Cwb)	Mesothermal rain forest (AB′ wa)	Microthermal per humid (AB′$_2$ ra′)	$(37{\cdot}368)_{12}$
Dhubri ..	,,	Warm temperate rainy climate with dry winter (Cwa)	Warm temperate rainy climate with dry winter (Cwa)	,,	Megathermal per humid (AA′ ra′)	$(41{\cdot}722)_{12}$
Karwar ..	,,	Monsoon type of tropical climate (Ami)	Monsoon type of tropical climate (Ami)	Tropical rain forest (AA′ wa)	Megathermal per humid (AA′ s_2 a′)	$(45{\cdot}292)_{10}$

TABLE II—*contd.*

Station	Characteristic vegetation according to Champion	Climatic type according to Koppen's classification of		Climatic type according to Thornthwaite's classification of		Computed P/E indices
		1918	1936	1931	1948	
1	2	3	4	5	6	7
Tezpur ..	(Tropical semi-evergreen)	Warm temperate rainy climate with dry winter (Cwa)	Warm temperate rainy climate with dry winter (Cwa)	Mesothermal forest (BB′ wa)	Mesothermal humid ($B_3B'_4$ ra′)	$(45{\cdot}287)_{12}$
Mangalore ..	,,	Monsoon type of tropical climate (Ami)	Monsoon type of tropical climate (Ami)	Tropical rain forest (AA′ wa)	Megathermal per humid (AA′ s_2a′)	$(48{\cdot}630)_{12}$
Toungoo ..	Tropical wet evergreen	Warm temperate rainy climate with dry winter (Cwa)	Warm temperate rainy climate with dry winter (Cwa)	,,	Megathermal humid (B_3A′ ra′)	$(52{\cdot}537)_{12}$
Rangoon ..	,,	Monsoon type of tropical climate (Ami)	Monsoon type of tropical climate (Ami)	,,	Megathermal per humid (AA′ ra′)	$(53{\cdot}863)_{12}$
Chittagong ..	,,	Warm temperate rainy climate with dry winter (Cwa)	Warm temperate rainy climate with dry winter (Cwa)	Mesothermal rain forest (AB′ wa)	,,	$(55{\cdot}358)_{12}$
Myitkina ..	,,	,,	,,	Mesothermal forest (BB′ wa)	Mesothermal humid ($B_4B'_4$ ra′)	$(60{\cdot}665)_{12}$
Cox's Bazar ..	,,	,,	,,	Tropical rain forest (AA′ wa)	Megathermal per humid (AA′ ra′)	$(60{\cdot}237)_{12}$
Sibsagar ..	,,	,,	,,	Mesothermal rain forest (AB′ wa)	Mesothermal per humid (AB′$_4$ ra′).	$(61{\cdot}840)_{12}$
Silchar ..	,,	,,	,,	,,	Megathermal per humid (AA′ ra′)	$(71{\cdot}407)_{12}$

TABLE II—*concld.*

Station	Characteristic vegetation according to Champion	Climatic type according to Koppen's classification of		Climatic type according to Thornthwaite's classification of		Computed P/E indices
		1918	1936	1931	1948	
1	2	3	4	5	6	7
Bassein ..	Tropical wet evergreen	Monsoon type of tropical climate (Ami)	Monsoon type of tropical climate (Ami)	Mesothermal rain forest (AB′ wa)	Mesothermal per humid (AB'_4 ra′)	$(70{\cdot}151)_{12}$
Bhamo ..	”	Warm temperate rainy climate with dry winter (Cwa)	Warm temperate rainy climate with dry winter (Cwa)	Mesothermal forest (BB′ wa)	Mesothermal humid ($B_4B'_4$ ra′)	$(91{\cdot}180)_{12}$
Mergui ..	”	Monsoon type of tropical climate (Ami)	Monsoon type of tropical climate (Ami)	Tropical rain forest (AA′ wa)	Megathermal per humid (AA′ ra′)	$(130{\cdot}218)_{12}$
Tavoy ..	”	”	”	”	Megathermal per humid (AA′ sa′)	$(188{\cdot}551)_{12}$
Dibrugar ..	”	Warm temperate rainy climate with dry winter (Cwa)	Warm temperate rainy climate with dry winter (Cwa)	Mesothermal rain forest (AB′ wa)	Mesothermal per humid (AB'_4 ra′)	$(145{\cdot}571)_{12}$
Akyab ..	”	”	”	Tropical rain forest (AA′ wa)	Megathermal per humid (AA′ ra′)	$(190{\cdot}265)_{12}$
Mercara ..	”	Warm temperate rainy climate with dry winter (Cwb)	Warm temperate rainy climate with dry winter (Cwb)	Mesothermal rain forest (AB′ wa)	Microthermal per humid (AB'_2 ra′)	$(241{\cdot}743)_{12}$
Cherrapunji ..	”	”	”	”	”	$(447{\cdot}342)_{12}$
Port Blair ..	”	Monsoon type of tropical climate (Ami)	Monsoon type of tropical climate (Ami)	Tropical rain forest (AA′ ra)	Megathermal humid (B_3A' ra′).	$(25{\cdot}582)_{12}$
Kodaikanal ..	Sub-tropical wet forest	Warm temperate rainy climate without dry season (Cfbi)	Warm temperate rainy climate without dry season (Cfbi).	Mesothermal forest (BB′ ra)	Microthermal per humid (AB'_1ra′)	$(17{\cdot}563)_{12}$
Sagar Island ..	Tidal ..	Warm temperate rainy climate with dry winter (Cwa)	Warm temperate rainy climate with dry winter (Cwa)	Tropical forest (BA′ wa)	Megathermal moist sub-humid (C_2A' wa′)	$(12{\cdot}841)_{12}$

factors such as humidity, barometric pressure, wind velocity, etc. The objection that there are not many evaporation data available is not serious, since the evaporation capacity of the air may be easily calculated by a formula using temperature, humidity and wind velocity. Another objection may be raised that the evaporation data are not comparable in the same degree as the rainfall values. Several different methods of evaporation measurements are used indeed, but if we exclude observations executed by means of floating pans for hydrologic purposes and confine ourselves to pans set over the ground, then the difference will not be too great. One should also hope that sooner or later the methods of determining evaporation rates will be standardized to a certain degree.

In our present attempt of explaining the natural vegetation of India, Pakistan and Burma on the basis of P/E ratios, we were required to calculate the evaporation figures of each station for each month of the year. Thus the total number of evaporation figures as well as the P/E ratios amounted to 1,248 (104×12) groups. Hence, it was thought that such a large body of data should first of all be used to test as to whether the relation deduced by Thornthwaite:—

$$P/E = 11{\cdot}5\left(\frac{P}{T-10}\right)^{10/9}$$

using only 1,100 groups of P/E ratios, is true in the case of Indian data or not. The procedure adopted to test the validity of the above formula is the same as suggested by Thornthwaite. The calculated P/E ratios were arranged in such a manner that all having similar P/E ratios were put together, the dates and the locations of the P/E ratios being ignored while grouping. In this way 63 groups of P/E ratios whose values varied from 0·01 to 5·4 were obtained. The data were then represented on a graph, where the monthly normal temperature expressed in degree Fahrenheit was plotted along the ordinate and the monthly normal precipitation along the abscissa. Thus 63 separate graphs, one for each group of P/E ratios, were obtained. Instead of drawing a straight line through each of these plots by visual judgement as was done by Thornthwaite, a straight line equation of the form $T = A + BP$ was computed by the method of least squares using the temperature and precipitation data in each plot. In this way 60* straight line equations were computed for the various P/E ratios.

This method of computing a straight line equation is not subjected to criticism as is the case with the method adopted by Thornthwaite. Whereas Thornthwaite's method is a visual one, i.e. to draw a straight line passing through the maximum points in each plot and hence an approximate one, for the nature of the straight line will depend much upon the investigator, the method here is a statistical one and hence the nature of the straight line will not vary with the investigator.

The 60 different equations obtained by the method stated above showed that none of the straight lines which they represent would cut the ordinate at 10°F. as was found to be the case by Thornthwaite. The values of the constants A in the equation which represents the point of intersection of the straight lines with the Y axis and which can be obtained by putting $P = O$ in each one of the 60 equations were found to vary from a minimum of 19·12°F. in the case of the plot having a P/E ratio 5·1 to a maximum of 95·55°F. in the case of the plot of P/E ratio 5·2. The mean value of these 60 different intercepts was found to be 68·09. Thus it was found that the result obtained by Thornthwaite, viz. that in the case of each plot a straight line cutting the ordinate at 10°F. fitted the data satisfactorily, was found to be no longer valid with the present data.

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* There were in all 63 plots having P/E ratios ranging from 0·01 to 5·4. Therefore there should be 63 straight line equations but as there was only one observation in each one of the plots having P/E ratios 4·7 and 4·8 and no observation in the plot with P/E ratios equal to 5·3, no equation could be fitted for these plots. Therefore, we got only 60 equations for 63 plots.

Lastly, from these several equations and proceeding on the lines suggested by Thornthwaite, an attempt was made to formulate a single equation which expressed the relation of P/E ratios to the easily available meteorological elements, precipitation and temperature alone. As a result of this investigation it was found that there cannot be a simple relation between P/E and P/T, namely

$$P/E = (11{\cdot}5)\left(\frac{P}{T-10}\right)^{10/9}$$

deduced by Thornthwaite on the visual judgement that the temperature against precipitation curves would be straight lines cutting the ordinates at 10°F.

The computation of the P/E ratios, which explains satisfactorily the vegetation types of India, Pakistan and Burma, from other meteorological factors is very laborious and hence an attempt was made to obtain these P/E ratios in terms of P/T on the lines suggested by Thornthwaite but the attempt did not prove to be successful. Therefore, in our further attempt we proceeded to find out as to whether there is any other easily available meteorological factor which could be correlated with the P/E ratios.

Nearly a century ago De Candolle (1856) had advocated that the number of rainy days are the best expressions for denoting the humidity or aridity of a country. He said, 'the number of days of rain seemed to me to be the best expression of the conditions of humidity or dryness of a country as relating to the vegetation. I prefer this figure to that of the quantity of rain, and it is easier to obtain, I would not know how to recommend it too highly to the meteorological societies, and amateur scientists scattered in every country. Nothing is easier than marking on an almanac (calendar) each twenty-four hour day in which some rain or some snow has fallen. After ten or fifteen years, one can draw upon the data very advantageously to learn the mean number of natural rainfalls per month, or better yet, per decade, the mean duration and extreme of droughts, the mean duration and extreme of precipitation in certain seasons. No instrument is needed for this; good will and exactitude suffices'.

Koppen (1900) while discussing the moisture factor with reference to dry climate said, 'precipitation alone is of little help in determining the moisture content of the soil and especially in distinguishing a moist or dry climate. Here the time and character of the precipitation and the amount of evaporation are decisive. Equal amounts of rainfall, for example, produce primeval forest in Siberia and pronounced desert plants in Africa. This is one reason why I prefer tabulation of the number of rainy days. Actually the boundary between forest and steppe is in general defined climatologically more readily by means of the number of rainy days than by the rainfall amount'.

It is well known that the same amount of rainfall produces a great difference in the vegetation as the rain falls uniformly throughout a long period or falls for only a very short time in the form of heavy storms. The number of rainy days is, therefore, of greater importance than the amount of rain. In the former case the rain is capable of being much more beneficial to the vegetation; in the later case the parched soil is not in a condition to absorb all the water, most of which flooding and denuding the soil, flows over its surface or percolates to its depths. Under the former conditions we find growth-forms and plant communities quite different from those under the later. Hence the number of rainy days appeared to us to be the best and easily available meteorological element which could be used to explain the vegetation of any locality. Therefore, with a view to find out as to whether a relationship exists between the P/E indices and the number of rainy days of a station, the mean annual (mean of fifteen years) number of rainy days (D) were plotted along the ordinate and the P/E indices along the abscissa. A study of the graph showed that a parabola passing through the origin could be fitted to the data. Hence using the P/E indices and the mean annual number of rainy days of 98* stations a formula of the type

$$P/E = aD + bD^2$$

was computed by the method of least square. The final equation for the data was

$$P/E = (-0{\cdot}065251)D + (0{\cdot}004691)D^2$$

which enables one to get the P/E indices and hence the vegetation type of a station from the mere knowledge of its annual number of rainy days.

In conclusion the authors express their acknowledgement to Professor C. Troll of the University of Bonn, W. Germany, for his suggestions.

Abstract

Comparison of the vegetation types of India and vicinity as laid down by Champion with those obtained from theoretical consideration using Koppen's and Thornthwaite's formulae revealed that both the formulae cannot satisfactorily explain the varied natural vegetation types of the Indian subcontinent. A satisfactory explanation of the natural vegetation types could, however, be made on the basis of P/E (mean monthly precipitation/mean monthly evaporation from the free water surface) ratios. The mean monthly evaporation from the free water surface for 104 stations used in the present investigation was calculated from the mean monthly barometric pressure, wind velocity, relative humidity and vapour pressure using Carl Rohwer's formula as modified by Raman and Satakopan. The P/E index which is the sum of the twelve monthly P/E ratios of a station, when grouped in the following way:—indices 1–5—thorn forest, 5–15—tropical dry deciduous, 15–20—tropical moist deciduous, 20–50—tropical semi-evergreen, 50 onwards—tropical wet evergreen, were able to explain the real distribution of the vegetation types. It was further shown that the P/E index of a station, which is very laborious to compute in the usual way, could easily be obtained from the mean annual number of rainy days of that station.

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* Out of 104 stations the data of 98 stations alone was used to compute the equation of the parabola since the co-ordinates of the points of the following six stations showed considerable deviation from the parabola. These stations are:—(1) Sagar Island, (2) Port Blair, (3) Cherrapunji, (4) Mercara, (5) Tavoy and (6) Akyab.

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