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CLIMATIC CLUSTERS OF THE INDIAN REGION

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ABSTRACT

In this paper we derive climatic clusters of the Indian region using data on monthly mean profiles of the precipitation, the moisture index (defined as the ratio of precipitation and potential evapotranspiration) and of the minimum temperature. The delineation of regions over which the patterns of profiles of important climatic factors such as precipitation are similar is necessary for the determination of meteorological zones over which prediction can be made as well as for understanding the distribution of vegetation cover. The latter has been the major aim of the studies of climatic classification. In the traditional approach to this problem, the meteorological stations in the region are assigned to predetermined categories such as arid, semi-arid etc. on the basis of the values of the climatic factors (or of the bulk parameters derived therefrom) characterizing these stations.

Here the variation of the climatic patterns over the Indian region has been analysed to obtain climatic clusters, which represent natural grouping of the patterns and hence of the meteorological stations at which they occur, as well as the climatic boundaries separating these clusters. This analysis is facilitated by an initial reduction of dimensionality in the description of the patterns achieved by using principal component analysis. Sixteen clusters of the mean monthly profiles of the moisture index have been obtained. It is found that there is a close correspondence between these clusters and the distribution of the vegetation types in the country.

KEY WORDS Climatic classification Clustering Empirical orthogonal functions Indian climatic clusters Rainfall analysis Moisture index

1. INTRODUCTION

The identification of the spatial scales associated with the temporal scales of significant variation of climatic factors is an essential prerequisite for the determination of the subregions over which meteorological predictions for the various time-scales can be given. It is also necessary for determining the optimum network of meteorological stations over the region. At present over the Indian region, the short and medium range forecasts are issued for the meteorological subdivisions (Figure 1) whereas for the long range forecasts, the country is divided into much larger zones—northwest India, northeast India and Peninsula (Rao and Ramamurthy, 1958). Ideally, the subregions should be chosen so as to satisfy two conditions. First, the meteorological stations within any region must be characterized by similar climatic patterns. Secondly, the temporal variation over scales beginning with the subseasonal must be in phase for the stations within the subregion. In this paper we derive the climatic subregions for the Indian region which satisfy the first condition.

The delineation of the subregions which are homogeneous with respect to the values or patterns of the important climatic factors is the problem of climatic classification. Traditionally this problem has been of concern to plant geographers who sought to understand the distribution of vegetation types in terms of the variation of the climate. Consequently the climatic factors generally chosen have been the ones considered to be critical in determining the vegetation cover. In this approach, climatic zones such as arid, semi-arid etc. are specified in terms of the values of the critical climatic factors, or bulk parameters derived from them. The problem of classification then involves assigning the meteorological stations of the region to one of these predetermined categories. The result is naturally sensitive to the

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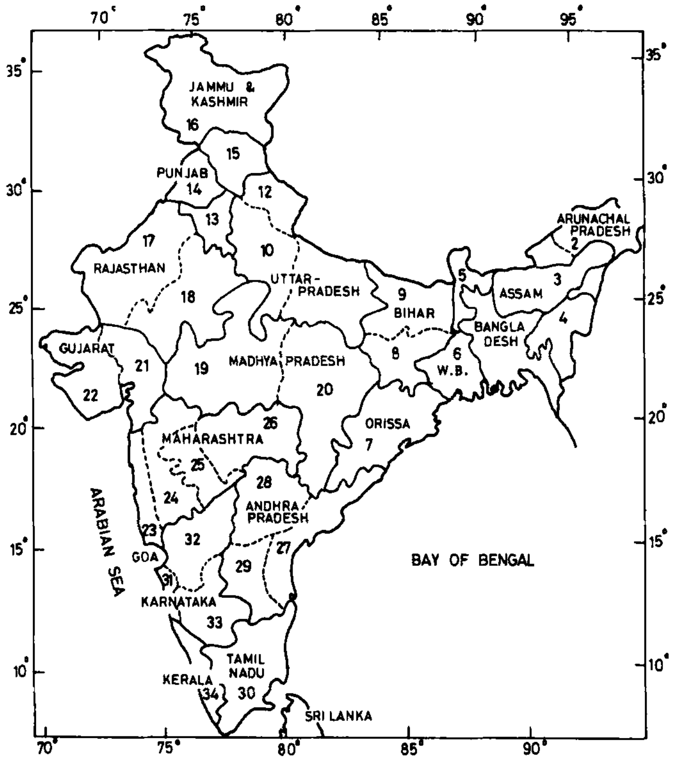

Figure 1. Meteorological sub-divisions of India (after Rao (1976))

specific choice of the climatic boundaries adopted, which are based on the observations of the vegetation types in a few regions. The more general validity of this choice for other regions of the world under the sway of different climatic conditions cannot be taken for granted. Hence the scheme of climatic classification appropriate for any given region has to be selected with reference to the vegetation cover of that region.

The subjectivity involved in the choice of climatic boundaries in such a classification scheme can be avoided by treating the problem as one of clustering of the climatic patterns rather than of classification. The aim then is to obtain natural groups or clusters of the patterns and hence of the meteorological stations at which they occur. The boundaries between these clusters are arrived at from the analysis and are not specified *a priori*.

The most significant climatic factor determining the nature and productivity of the plant cover in the tropics is the availability of moisture, and moisture availability is chosen as the major criterion in most of the climatic classifications, for example Thornthwaite and Mather (1955) and Budyko (1974). The availability of moisture depends primarily on the rainfall pattern and, not surprisingly, the most important climatic factor to be forecast is also the rainfall. This suggests that a cluster analysis of the patterns of rainfall and moisture index should provide critical information for the determination of the climatic zones for the purpose of prediction as well as for the interpretation of the distribution of vegetation types. For a large region such as India, the appropriate strategy in agriculture or forestry in terms of the choice of plant species and schedules of cultural operations can be experimentally determined at only a few field stations. In order to determine the optimum network of such stations it is necessary to have quantitative estimates of the similarity between the climatic patterns at different stations and the climatic clusters based on these estimates.

It is well known that the nature of the vegetation depends not only on the seasonal or annual means of the rainfall or the moisture index but also on its distribution within the season. For the Indian region, this was pointed out more than two thousand years ago by Kautilya, when he designated the pattern with two-thirds of the rainfall concentrated in the second month of the rainy season as the golden regime for agriculture (Kaugle, 1969). The classifications proposed by Troll (1965) and Hargreaves (1971) are also based on the distribution of the moisture index within a year. Many authors have derived a climatic classification of the Indian region based on criteria suggested by Thornthwaite (1948) and Thornthwaite and Mather (1955) (Subramanyam, 1956; Subramanyam *et al.*, 1965; Krishnan, 1968; Rao *et al.*; 1971). On a comparison of the results of several climatic classification schemes for the tropics, Virmani *et al.* (1978) concluded that the distribution of the moisture availability within a year is the most important criterion for climatic classification for agricultural applications. Thus the minimum information necessary for a useful classification appears to be the information about monthly mean patterns of moisture availability.

In this study we analyse the variation of the monthly mean patterns of moisture availability defined as the ratio of the precipitation to the potential evapotranspiration at several stations over the Indian region using the method of empirical orthogonal functions. The patterns are represented in the plane of the amplitudes of the two leading components which together explain more than 80 per cent of the variance. Thus an adequate measure of the difference between any patterns is the Euclidean distance between the points representing these patterns in this plane. An analysis of the distribution of the points representing the patterns of moisture availability by a procedure similar to that used by Gadgil and Iyengar (1980) has yielded 16 moisture index clusters for the Indian region. Since the minimum temperature is also known to be a limiting factor for plant growth (Blasco and Legris, 1973) the mean monthly profiles of the minimum temperature have also been analysed in a similar manner to obtain the thermal clusters.

The data base and the methodology are described in Sections 2 and 3. Clusters obtained by analysis of temporal profiles of rainfall and moisture index are discussed in Section 4, and by analysis of the minimum temperature profiles in Section 5. The climatic clusters so obtained are compared with the distribution of the vegetation types and with the meteorological subdivisions in Section 6.

2. DATA

The mean monthly profiles of the precipitation (P) and the minimum temperature (T) at 119 stations distributed uniformly throughout India (Figure 2), obtained from the climatological tables published by the India Meteorological Department (1967), and the mean monthly potential evapotranspiration (P_E), given by Rao *et al.* (1971) using Penman's (1948) formula, are the basic data for this study. Thus the climate at every station is specified in terms of 12 values each of the precipitation (P), the moisture index (P/P_E) and of the minimum temperature (T) implying a data matrix of the order 119×36.

3. METHODOLOGY

3.1. *Reduction of dimensionality*

The first step in the analysis is the reduction of the dimensionality of the specification of the climate at every station to the minimum possible, without significant loss of information. Since the 12 monthly mean values in the profiles of any element (such as rainfall) at a station are likely to be correlated, a more economical representation which is maximally powerful in bringing out the difference between the profiles at the different stations can be obtained by using the method of empirical orthogonal functions (Lorenz, 1956). The value of any element (say precipitation P) at a station i, in the month j can then be expressed as

$$P(i, j) = \sum_{n=1}^{12} A_n(i)B_n(j)$$

where $B_n(j)$ is the nth eigenvector of the covariance matrix and $A_n(i)$ the corresponding amplitude or

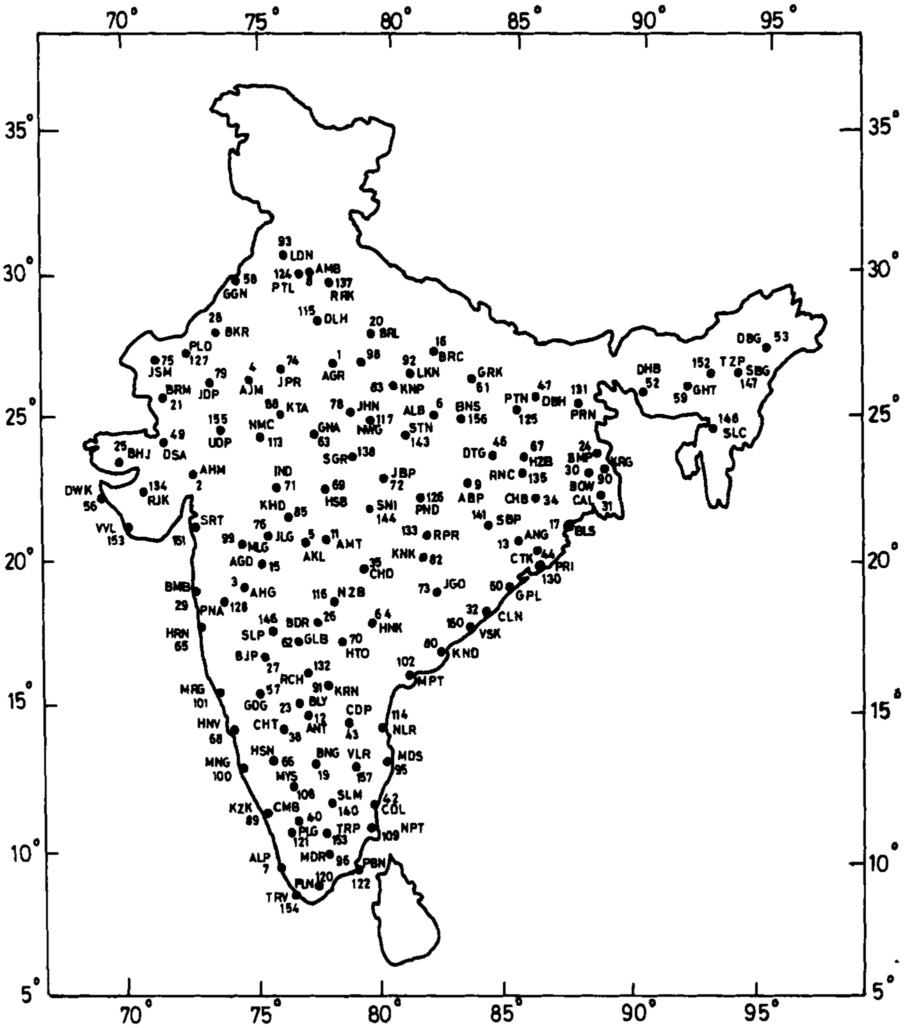

Figure 2. Meteorological stations used in the analysis

coefficient. Given the eigenvectors $B_n(j)$, every station can be represented as a point in the n-dimensional space of the amplitudes A_n.

We have analysed separately the profiles of (i) precipitation P, (ii) the moisture index P/P_E, (iii) minimum temperatures T, for all the stations. We find that in each case, the first two principal components explain more than 80 per cent of the variance. Thus the profiles of these climatic parameters at the different stations can be adequately represented as points in the plane of the amplitudes A_1, A_2 of the first two components. The Euclidean distance between points representing two stations in this plane is a direct measure of the difference between the two profiles. A small distance between two points on this plane implies that the profiles at the stations which they represent are similar and further that annual or seasonal totals have similar values. A large distance between two points can arise either from disparity in profiles or in the annual totals or a combination of both.

3.2. *Analysis of climatic patterns*

In general the points representing the patterns of any climatic element, such as rainfall, in the 12-dimensional space of their monthly values (or in any other co-ordinate space such as that of the principal components), may be assumed to form a continuum. When this distribution is either uniform or random, the logical way of classifying the patterns is by division into unit cells in this 12-dimensional space, the length of the cell being chosen appropriately.

If, on the other hand, the distribution is patchy or clumped, one can fruitfully seek clusters of these patterns. For a patchy distribution, there are clear gaps between neighbouring patches with a relatively large number of points within each patch or cluster. If the geographical distribution of the stations chosen is almost uniform (as is the case in this paper), such patchiness of the distribution of the actual patterns indicates that all the possible patterns within the observed limits are not equally probable. The probability is large within the patches and very small in the gaps between them. This suggests that natural climatic boundaries may be identified with such gaps. A classification based on climatic boundaries located in these gaps will not be unduly sensitive to the choice of the boundaries.

There are three scales which characterize a clumped or patchy distribution: (i) The typical nearest neighbour distance within a cluster, i.e. a scale which specifies the grain of the cluster; (ii) A scale measuring the separation between neighbouring clusters, i.e. the minimum distance between a point belonging to one cluster and another belonging to the neighbouring cluster; (iii) The extent of the cluster, i.e. the maximum distance between two points in a cluster.

If the grain-scale as well as the extent of the cluster are smaller than the separation scale, the clusters are not only well separated but also compact. Then the similarity is high between any two patterns within a cluster and low between patterns belonging to different clusters. Several methods, such as the nearest centroid method, are effective in delineating the clusters in this case (Anderberg, 1973).

However, we find that very often for meteorological patterns, even when the distribution is patchy with clear gaps between the neighbouring clusters, the extent of the patches is greater than the separation scales. This means that the clusters are sprawling rather than compact (cf. Fig. 5.1 in Anderberg, 1973). In such a case the degree of similarity between any two patterns in a cluster is not necessarily high. However, such points can be linked by a series of intermediate points within the cluster such that the degree of similarity is high between successive points. This is not true of disparate points belonging to different clusters. To identify clusters when their extent may be comparable to the separation scale, we suggest the use of grain-scale to specify a threshold value for the separation scale. Specifically we consider the clustering acceptable if and only if (i) the nearest neighbour of every point within a cluster belongs to the same cluster, (ii) the minimum distance between two points of neighbouring clusters is larger than twice the value of the smaller of the two grain-scales of these clusters.

The search for clusters satisfying the above conditions is enormously simplified because of the initial reduction of the data set to two dimensions. Because of this two dimensional representation, the human capacity for recognition of patterns (which is known to surpass, by far, that of automatic pattern recognition) can be effectively used to make an initial guess at the number and locations of the clusters. The procedure adopted here involves the following steps. First, nuclei of prospective clusters are identified by visual inspection. Then their nearest neighbours are added and initial clusters formed and their grain-scales determined. This procedure is continued until clusters satisfying the two conditions are obtained.

Finally a test is performed to ensure that the distance between any point in a cluster and its nearest neighbour is within a certain threshold. In this test the nearest neighbour distances of points in a cluster are assumed to be a sample from a normal population. The null hypothesis that the points with the highest values of nearest neighbour distances belong to the same population as the others in the cluster is tested at the 95 per cent level by the ratio test (Crow, *et al.*, 1960). Those samples for which the hypothesis is rejected, are removed from the cluster and treated as isolated points.

Having obtained this basic clustering, it may be worth while for some applications to further subdivide the clusters so as to ensure that the differences between two patterns belonging to the same group are less than an appropriate threshold. Then clear climatic boundaries would exist only between the original clusters, but the patterns would possess the desired degree of similarity within any subcluster.

4. CLUSTERS OF PROFILES OF PRECIPITATION AND MOISTURE INDEX

4.1. *First sorting*

Contours of the mean annual precipitation and moisture index are shown in Figures 3 and 4. On applying principal component analysis to the profiles of mean monthly precipitation, we find that the first two eigenvalues account for 74 and 14 per cent of the variance respectively. The first eigenvector (Figure 5) with a maximum in July and a mild trough in November can be considered to represent the southwest monsoon component. Similarly the second eigenvector with peaks in May–June and October–November and trough in July–August can be taken to represent the pre-monsoon and post-monsoon (or the northeast monsoon) component. The first two eigenvectors obtained from the monthly mean profiles of the moisture index are similar (Figure 5) to those obtained from the precipitation profiles, and the first two eigenvalues, in this case, account for 73 and 14 per cent of the variance respectively.

The distribution of the points representing the different stations in the plane of the two leading principal components for profiles of the precipitation is shown in Figure 6. Note that although the distribution of the stations is almost uniform, the distribution of the precipitation patterns is not uniform and apart from isolated points, five distinct clusters emerge. The distribution of points representing moisture index profiles is similar (Figure 6). Thus the variation in the profiles of the moisture index arises mainly from that in the precipitation, and rainfall clusters are not significantly different from moisture index clusters. Apart from isolated point clusters, there are four (five) clusters of the moisture index (precipitation) profiles. For both cases, clusters I to III (IV) consist of stations from the high rainfall region, viz. west coast and northeastern parts, whereas the large dense cluster IV (V)

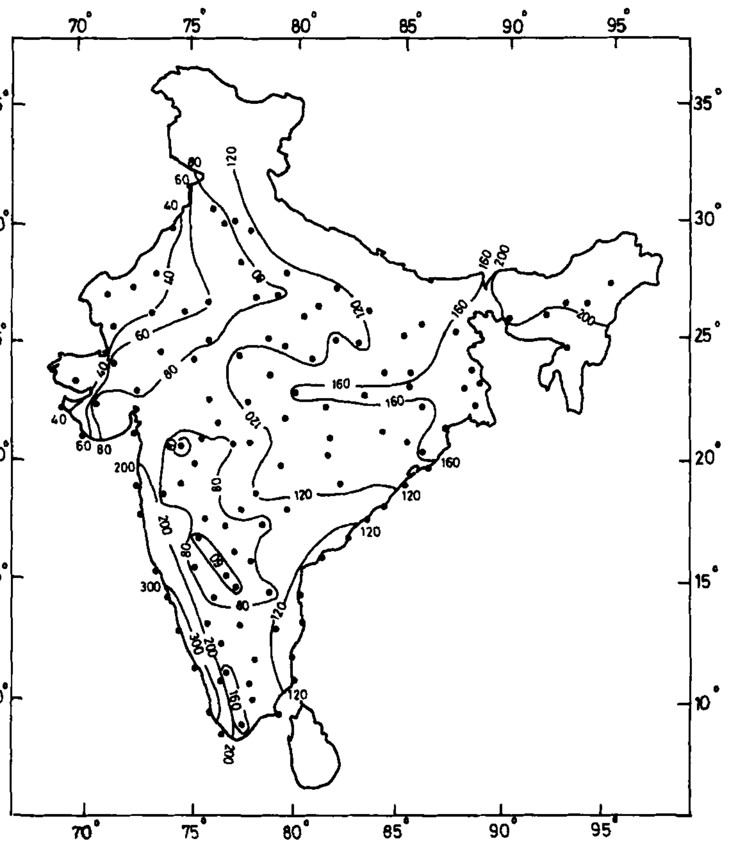

Figure 3. Mean annual rainfall (P) in cm

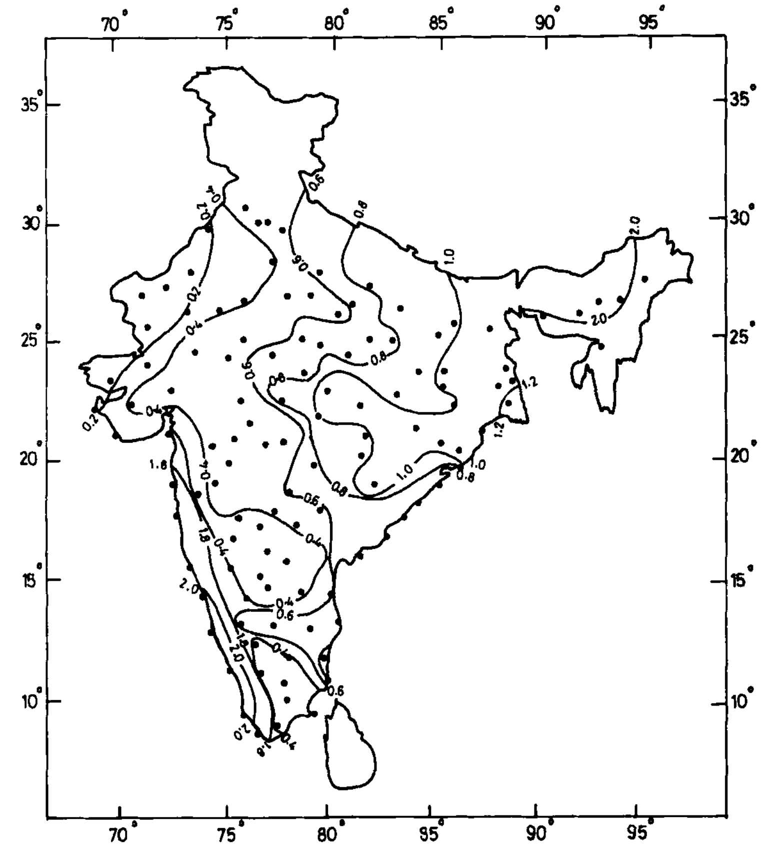

Figure 4. Mean annual moisture index (P/P_E)

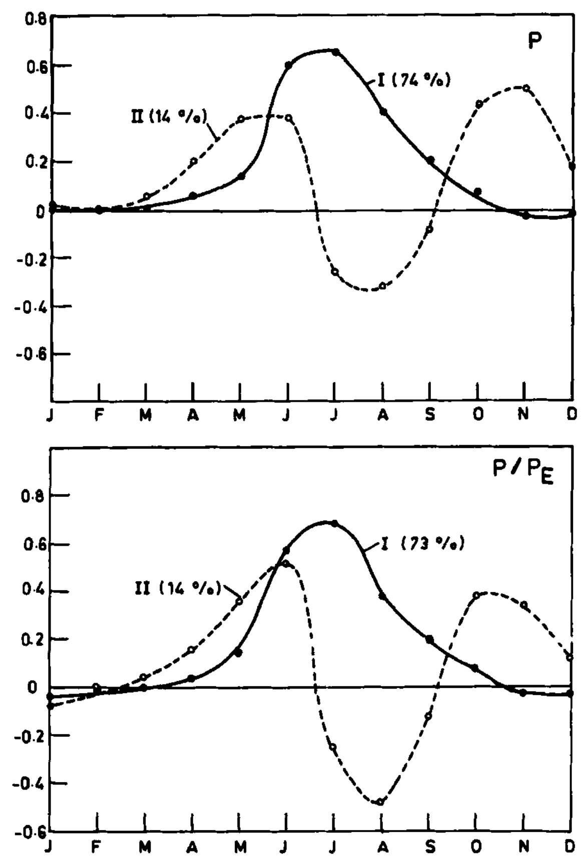

Figure 5. Eigenvectors from analysis of precipitation profiles (above) and from the profiles of moisture index (below).

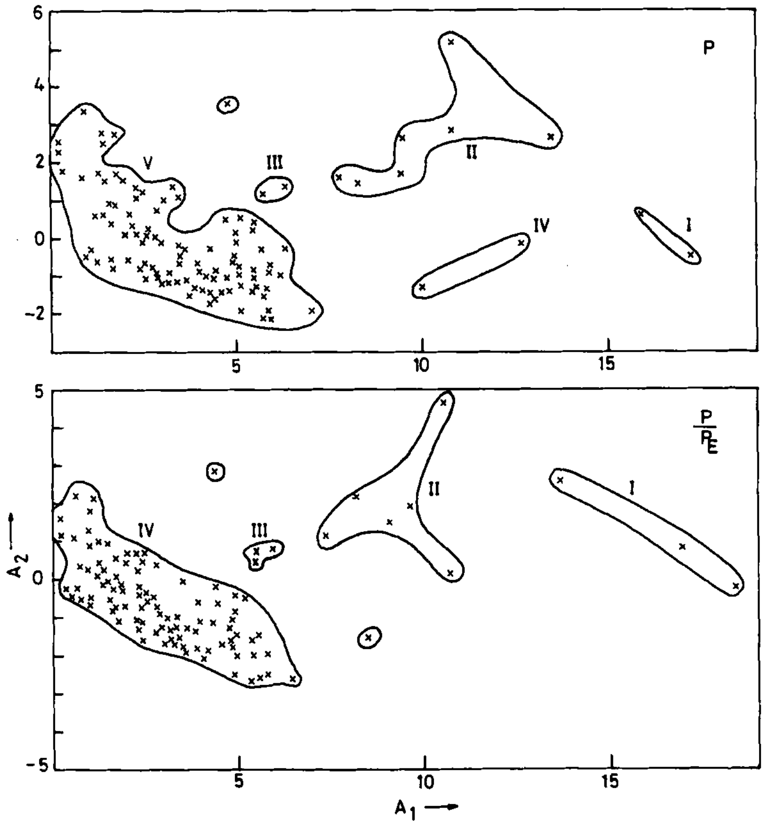

Figure 6. Distribution of the profiles at the different stations in the amplitude space A_1–A_2 of the leading eigenvectors in Figure 5 for precipitation (above) and for moisture index (below)

consists of stations from the rest of India. The high rainfall regions have prominent orographic features and, over some parts, there is considerable variation of the profiles of the moisture index even over distances comparable to the typical separation between stations. Hence the clusters obtained are sensitive to the choice of the grid of stations, and we expect more clusters to emerge and existing clusters to become better-defined if a finer grid is used. The geographical location of the clusters of Figure 6 is shown in Figure 7. The mean moisture index profiles are shown in Figure 8. It is seen from the figure that for any month, the ratio of the standard deviation to the mean is much higher in the dense cluster, compared to the other clusters. This indicates that the dense cluster is less homogeneous, and the moisture index patterns of the stations in it may differ considerably from each other.

4.2. *Second sorting*

In order to bring out the differences, if any, between the stations belonging to the dense cluster of stations spread over most of India, we repeated the principal component analysis separately for this dense cluster, after omitting the other stations. The first two eigenvectors for this second sorting of the profiles of the precipitation as well as of the moisture index are shown in Figure 9. Again the first eigenvector represents the southwest monsoon component and the second the northeast component with the two leading eigenvalues together accounting for at least 85 per cent of the variance. The distribution of the points representing the profiles of the moisture index at different stations in the plane of the amplitudes of the leading components and the clusters that emerge are shown in Figure 10. As in the first sorting, this is similar to the result obtained from rainfall profiles. The geographical locations of the clusters of Figures 7 and 10 are shown in Figure 11. It is important to note that all the clusters are

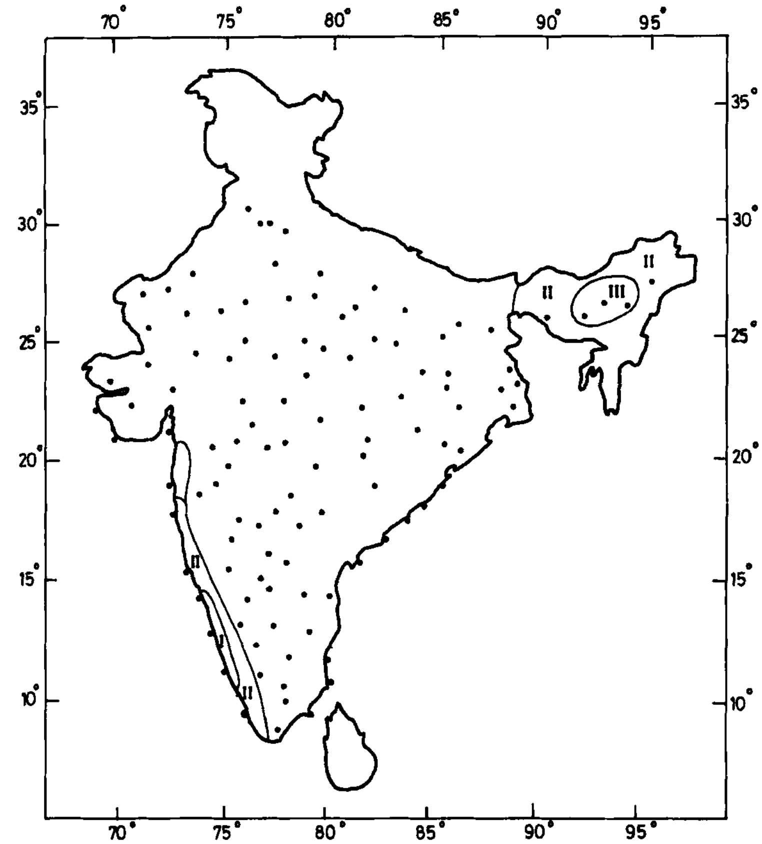

Figure 7. Geographical location of the moisture index clusters of Figure 6

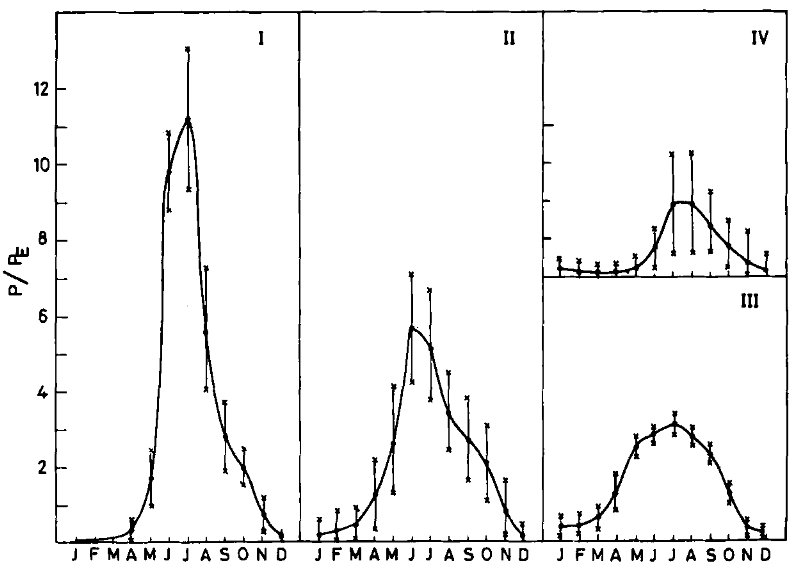

Figure 8. Mean moisture index profiles of the clusters in Figure 6. The standard deviations for each month are also shown

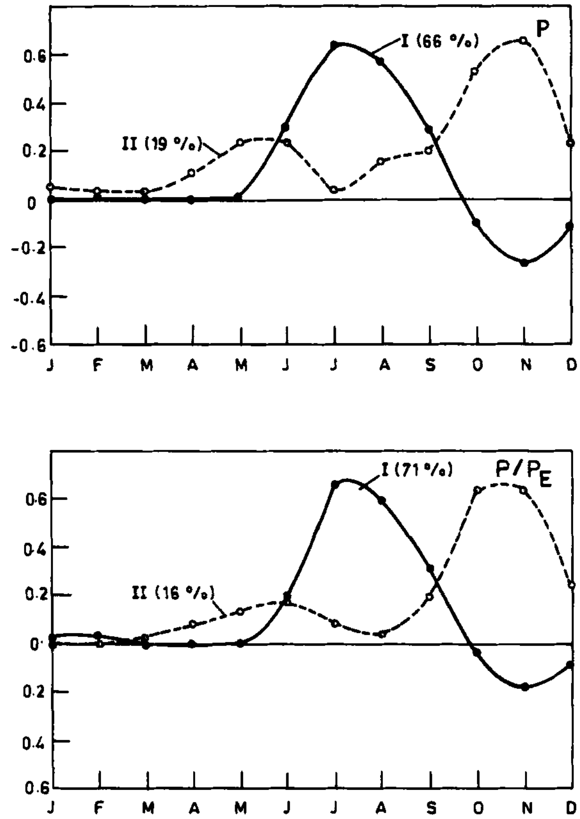

Figure 9. Eigenvectors from analysis of precipitation profiles (above) and for moisture index (below) for the second sorting

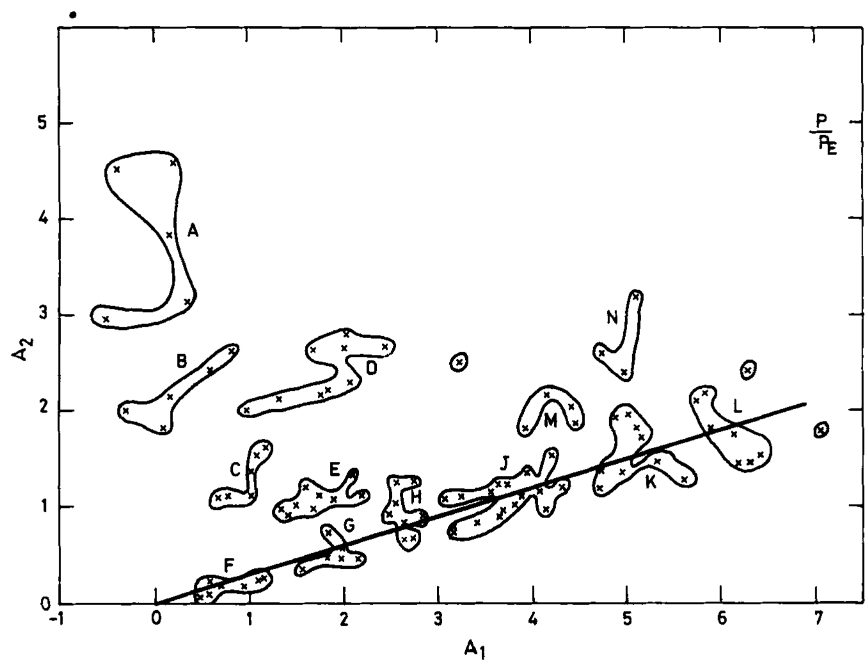

Figure 10. Distribution of profiles of moisture index at the stations retained for second sorting in the amplitude space of the eigenvectors shown in Figure 9

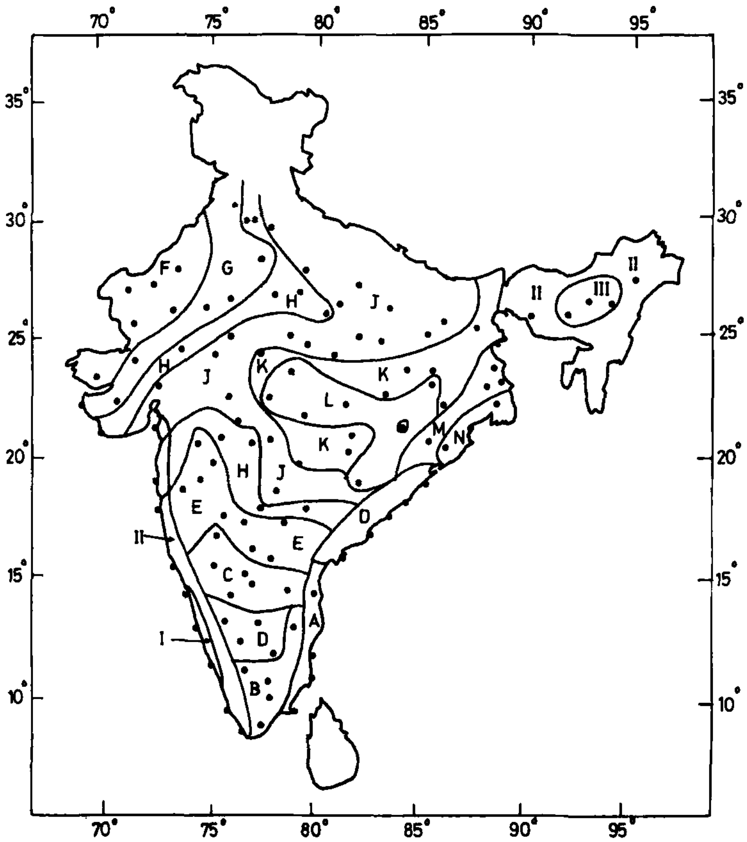

Figure 11. Geographical locations of the clusters of profiles of moisture index from the first and the second sorting

geographically contiguous although no information about geographical location of the stations was used in the analysis.

The peninsular clusters A–E are similar to those obtained by Gadgil and Iyengar (1980). The mean moisture index profiles of these clusters are shown in Figure 12. Note that the contribution of the southwest monsoon increases with increasing latitude along the east coast as well as in the central part of the peninsula.

The most remarkable feature of the distribution of the clusters of moisture index profiles shown in Figure 10 is the alignment of the clusters F–L about the line

$$A_2 = 0{\cdot}3A_1$$

Consequently the mean profiles of these clusters are similar (Figure 13) and the clusters differ mainly in the quantum of rainfall received. The clusters M and N have a disproportionately large amplitude of the second component relative to these clusters.

4.3. *Meteorological interpretation*

As pointed out by Gadgil and Iyengar (1980), the amplitude of the second principal component (representing the pre-monsoon and northeast monsoon) decreases monotonically with latitude north of about 10°N over the peninsula. This suggests that the second component is a manifestation of some system located equatorward of 10°N. It is interesting to note in this context that the ITCZ is located in this equatorial region in the pre-monsoon and post-monsoon seasons. Further, even in the summer monsoon an ITCZ appears intermittently over this region (Sikka and Gadgil, 1980). Thus the pattern of

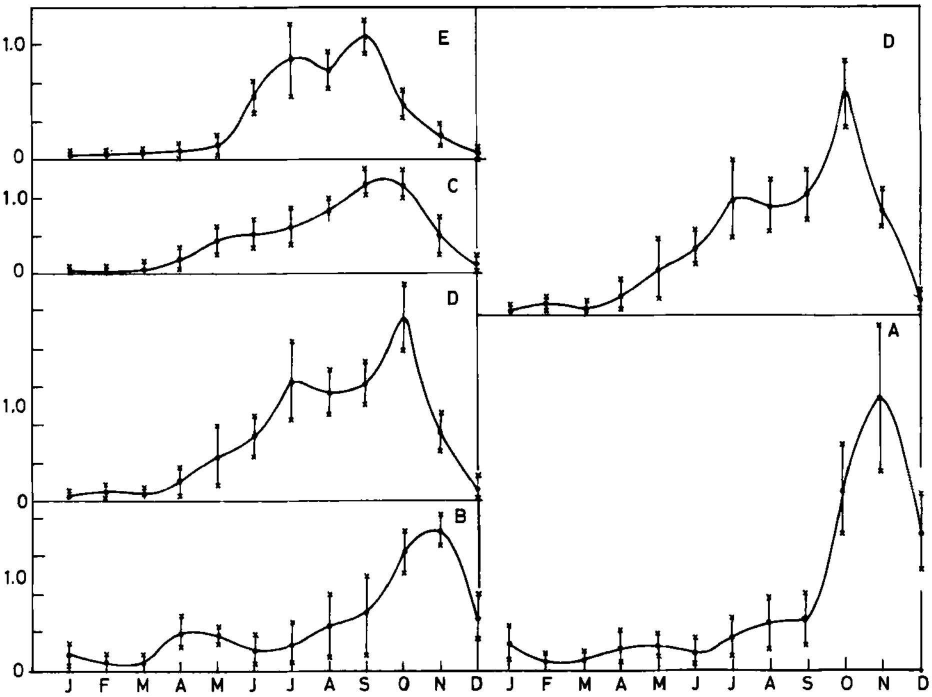

Figure 12. Mean moisture index profiles for the peninsular clusters along the east coast (to the right) and along a central longitude. Standard deviations for each month are also shown

the second component may be looked upon as an empirically derived rainfall pattern associated with the oceanic ITCZ.

In the monsoon trough zone, the rainfall pattern in the clusters F–L has been shown to be similar with the amount of rainfall increasing from F to L. Thus as one moves southeastward in the trough zone from the arid region in the northwest, the amplitude increases and the pattern remains the same along the monsoon trough until the coastal clusters with a disproportionately large amount of rainfall in the

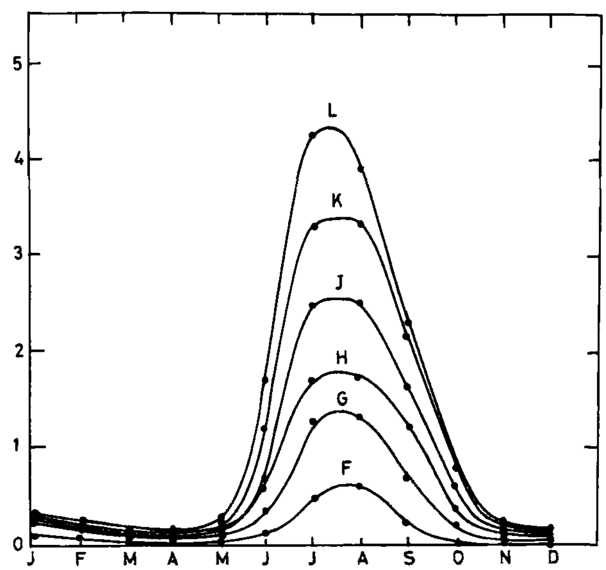

Figure 13. Mean moisture index profiles for the clusters in the monsoon trough zone

pre- and post-monsoon season are encountered. The pattern of the clusters along the trough zone, obtained by a linear superposition of the first two eigenvectors in the proportion implied by the equation in Section 4.2, can thus be interpreted as the empirically derived rainfall pattern associated with the monsoon trough or the continental ITCZ.

5. THERMAL CLUSTERS

The first two eigenvectors obtained from principal component analysis of the monthly mean of the minimum daily temperature are shown in Figure 14, and the distribution of stations in the amplitude space of the two leading components is shown in Figure 15. It is seen that the first component with a maximum during the winter explains 81 per cent of the variance whereas the second one with a maximum in the summer explains about 14 per cent. The amplitude associated with the second

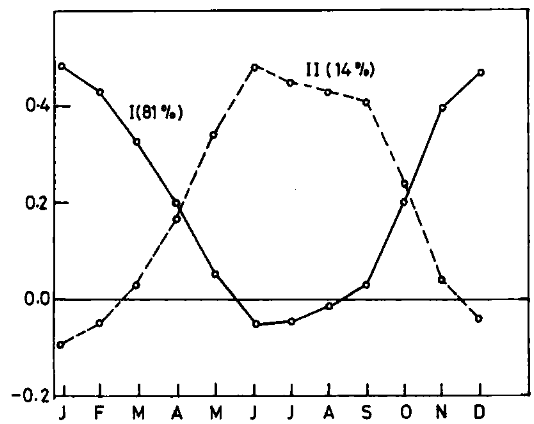

Figure 14. Eigenvectors obtained from the analysis of profiles of mean monthly minimum temperature

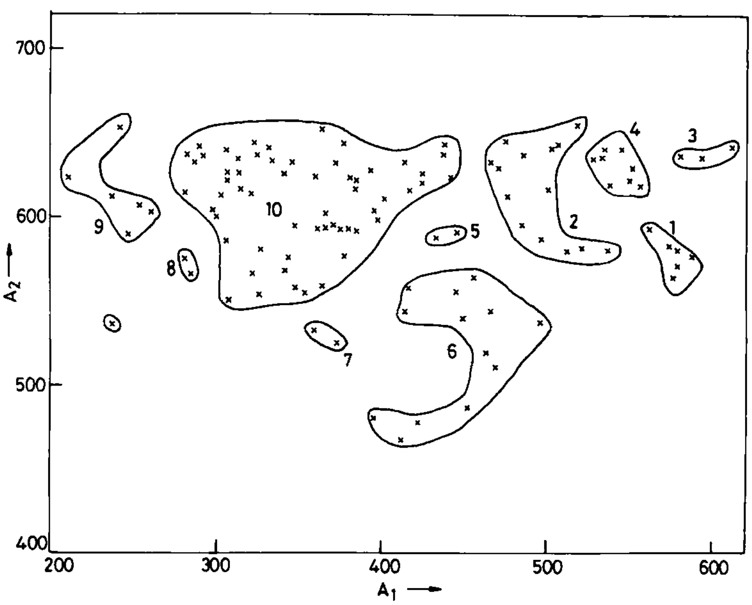

Figure 15. Distribution of the minimum temperature profiles at the different stations in the amplitude space A_1–A_2 of the eigenvectors of Figure 14

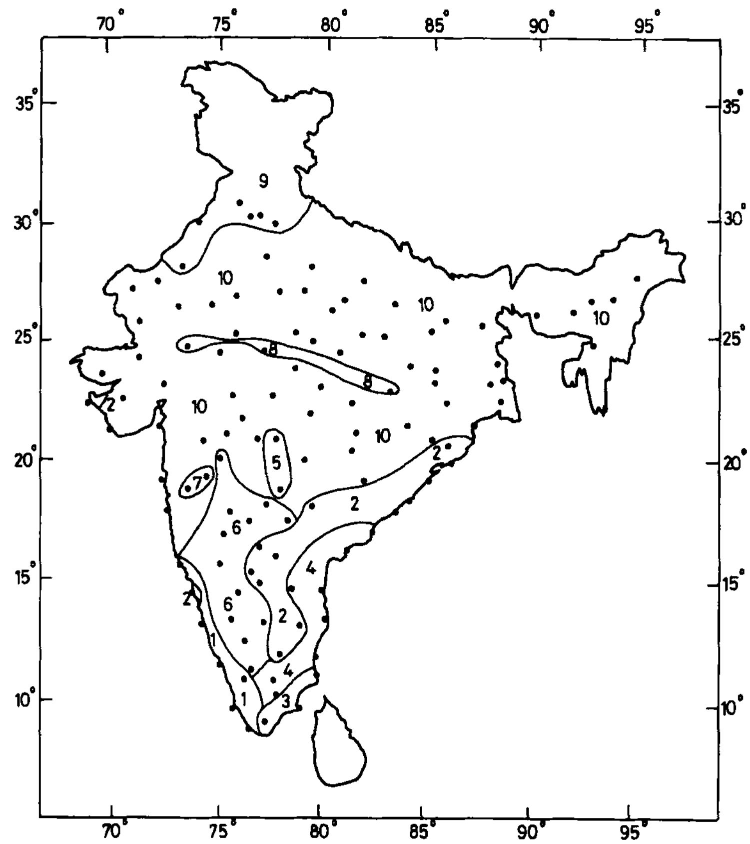

Figure 16. Geographical locations of the clusters of Figure 15

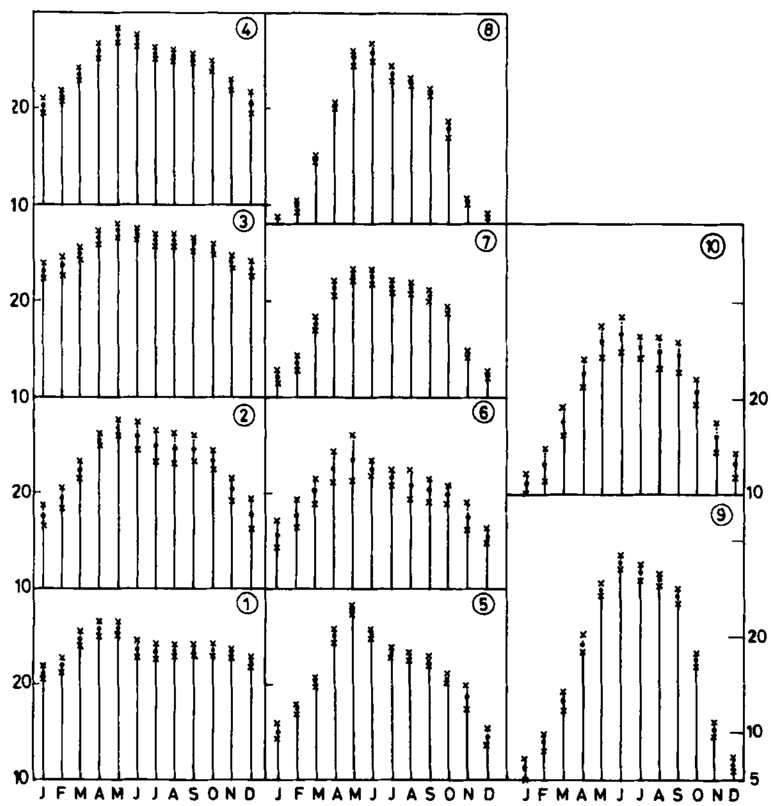

Figure 17. Mean minimum temperature profiles for the clusters of Figure 16. The standard deviations for each month are also shown

component is larger than that with the first for most of the stations, yielding the familiar temperature profiles with a maximum in the summer. The geographical locations of the clusters of Figure 15 are shown in Figure 16. It can be seen from Figure 15 that a vast majority of the clusters occur along a line parallel to the A_1 axis, with the value of A_1 varying from a minimum in the northeasternmost region, to a maximum in the coastal regions of the peninsula. As expected, the value of A_1 is largely determined by the latitude. The mean profiles of the clusters are shown in Figure 17.

Rao's (1972) analysis of the thermal regime on the basis of the annual values of the potential evapotranspiration yielded only two classes. Most of the country came under the megathermal type. Mesothermal regions were confined to the western Himalayas and a few pockets in the northeast. However, our analysis of the mean monthly profiles of minimum temperature has yielded ten thermal clusters. Where the minimum temperature is known to be also important for determining the nature of the vegetation, the temperature clusters obtained here can be used in conjunction with the moisture index clusters.

6. DISCUSSION

Our analysis has two major advantages over the earlier classifications. First, the classification criteria are objectively determined. Secondly, we have been able to use the detailed distribution of the moisture index and the minimum temperature within a year (instead of bulk parameters derived therefrom) owing to the efficiency of principal component analysis in the reduction of the dimensionality. With this, clusters which are homogeneous not only with respect to the seasonal or annual totals but also with the detailed shape of the profile have been obtained. As a result, marked variations within zones deduced

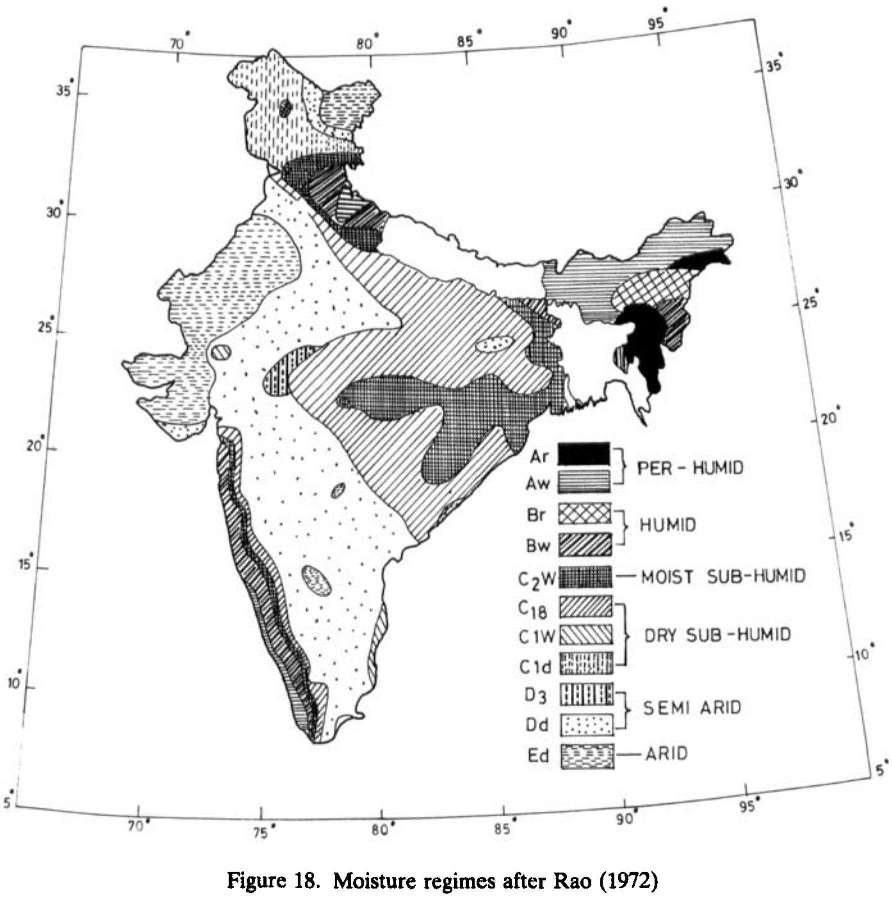

Figure 18. Moisture regimes after Rao (1972)

to be homogeneous in earlier classifications have become manifest. For example in the classification of the moisture regime obtained by Rao *et al.* (1972) based on Thornthwaite's method (Figure 18), there is a prominent semi-arid zone extending from the northwest down to the peninsula. However, as expected, the mean monthly moisture index profiles vary considerably in this zone, and about eight distinct clusters emerge from our analysis in this zone alone (Figure 11). Given the sensitivity of the vegetation to the detailed distribution of the moisture index within a year, the clusters obtained here are likely to be more pertinent for understanding the distributions of vegetation.

Indeed, there is a close correspondence between the climatic clusters based on moisture index profiles and the distribution of vegetation types (Meher-Homji, 1980; Gadgil and Meher-Homji, 1982). The nature of the vegetation types characterizing each climatic zone is given in Table I.

A comparison of the meteorological subdivisions of India (Figure 1) and the climatic clusters of Figure 11 indicates that they are generally similar, although there are some important differences. For example, the cluster A along the southern part of the coast is clubbed with the interior cluster B and part of D in the meteorological subdivision Tamilnadu (30). Similarly the three clusters C, E and H are clubbed in the subdivision North interior Karnataka (32). Since the division into the various states is necessary for administrative convenience, we suggest that the climatic divisions for India be obtained by a superposition of the statewise map on the climatic cluster map.

Table I

Climatic clusters	Vegetation types
First sorting	Vegetation containing evergreen plant species
West coast region I	*Dipterocarpus–Mesua palaquium* evergreen forest of Malabar
West coast region II	Other wet evergreen forest types of Malabar
Northeastern region II	Tropical moist deciduous forest of eastern Himalayas and northeastern Hills
Northeastern region III	Wet evergreen forest of northeastern Hills
Second sorting (Cluster IV)	Vegetation lacking evergreen plant species
A	*Manilkara–Chloroxylon* zone of Coromandal coast
B	*Albizzia amara–Acacia* zone
C	*Hardwickia binata–Anogeissus latifolia* zone
D	*Anogeissus latifolia–Chloroxylon–Albizzia amara* zone
E	*Acacia–Anogeissus latifolia* zone + part of *Anogeissus latifolia–Terminalia–Tectona* zone
F	*Prosopis–Capparis–Ziziphus* zone of Indian desert
G	*Acacia–Capparis* zone of Indian desert
H	*Anogeissus pendula* zone of Rajputana + part of *Anogeissus latifolia–Terminalia–Tectona* zone
J	*Tectona–Terminalia* zone + part of *Anogeissus latifolia–Terminalia–Tectona* zone
K L M	*Shorea robusta* zone
N	*Shorea–Dillenia–Pterospermum* zone

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