Meteorological sub-divisions of India : Assessment of coherence, homogeneity and recommended redelineation

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सार – भारत के मौसम उपखंडों की औसत वर्षा और औसत वर्षा विसंगतियों के आँकड़ों का उपयोग विभिन्न समय पैमानों पर मॉनसून की प्रगति की निगरानी के साथ-साथ अनुप्रयोगों और शोध के लिए विस्तृत रूप से किया जाता है। इस प्रकार, यह सुनिश्चित करना महत्वपूर्ण है कि उपखंडीय औसत उपखंडों के भीतर जिलों/स्टेशनों में वर्षा और वर्षा विसंगतियों का सार्थक चित्रण करते हैं। इसलिए, उच्च स्तरीय सुसंगतता और एकरूपता मौसम उपखंड के उपयुक्त परिसीमन के लिए संतुष्ट होने के मानदंड हैं। इस शोधपत्र में हम 1901-2015 की अवधि के लिए तमिलनाडु के जून-दिसंबर के आंकड़ों तथा शेष सभी राज्यों के ग्रीष्मकालीन मॉनसून के आँकड़ों के आधार पर जिले की मासिक औसत वर्षा के विश्लेषण से मौसमी पैमाने पर वर्षा के लिए वर्तमान मूल्यांकन और समरूपता का आकलन प्रस्तुत कर रहे हैं।

चूंकि, पूर्व के अध्ययनों से पता चला है कि कर्नाटक और महाराष्ट्र के कुछ उपखंड न तो सुसंगत हैं और न ही एकरूप, इसलिए इन राज्यों के उपखंडों के पुनर्चित्रण की समस्या पर सबसे पहले कार्य किया गया है। हमने माना कि एक राज्य में सुसंगत क्षेत्रों की संख्या वर्तमान उपखंडों की संख्या के समान है। सुसंगत उपायों के रूप में जिलों के बीच मौसमी वर्षा के सहसंबंध को समानता के एक उपाय के रूप में विचार करते हुए जिलों की मौसमी वर्षा के लिए के-मीन्स (KM) क्लस्टरिंग विधि के क्रमिक अनुप्रयोग द्वारा सुसंगत क्षेत्रों की पहचान की जाती है। इन दो राज्यों के लिए हम देखते हैं कि कुछ जिले सुसंगत और एकरूप नहीं हैं। इसलिए हमने सघन स्टेशन नेटवर्क के विश्लेषण के साथ इस अभ्यास को दोहराया। जिले के आँकड़ों और स्टेशन के आँकड़ों के विश्लेषण से पहचान किए गए सुसंगत क्षेत्रों को पूरी तरह से एकरूप भी पाया गया और हमने उन्हें राज्यों के नए उपखंड बनाए जाने की सिफारिश की। कर्नाटक के लिए सुझाए गए नए सुसंगत और एकरूप उपखंड हैं: (*i*) कर्नाटक पश्चिमी तट और घाट (जिनमें आंतरिक कर्नाटक के उपखंडों के कुछ जिलों की ही भाँति तटीय कर्नाटक के वर्तमान उपखंड में जिले/स्टेशन शामिल हैं) (*ii*) कर्नाटक उत्तरी पठार और (*iii*) कर्नाटक दक्षिणी पठार। महाराष्ट्र के वर्तमान उपखंडों में से, मराठवाड़ा और विदर्भ सुसंगतता और एकरूपता के मानदंडों को पूरा करते हैं, इसलिए इन्हें पूर्ववत बनाए रखा जा सकता है। वर्तमान मध्य महाराष्ट्र उपखंड सुसंगतता और एकरूपता के मानदंडों को पूरा नहीं करता है। हमने कोंकण और गोवा का संशोधित रूप तैयार करने के लिए मध्य महाराष्ट्र के मौजूदा उपखंडों से पश्चिमी घाट के कुछ जिलों/स्टेशनों को कोंकण और गोवा के मौजूदा उपखंडों में आबंटित करके मध्य महाराष्ट्र का संशोधित रूप तैयार किया। ये संशोधित रूप सुसंगत और एकरूप हैं। इस प्रकार महाराष्ट्र के सुझाए गए उपखंड (*i*) कोंकण और गोवा के संशोधित रूप हैं (जिनका नाम बदलकर कोंकण, घाट और गोवा किया जा सकता था लेकिन हमने पुराना नाम बरकरार रखा है) और (*ii*) मध्य महाराष्ट्र का संशोधित रूप, (*iii*) मराठवाड़ा और (*iv*) विदर्भ के वर्तमान उपखंड। हमने दिखाया कि भारत के अन्य सभी राज्यों के उपखंड, एकरूप और यथोचित सुसंगत हैं और हमारा परामर्श है कि उन्हें इसी तरह बनाए रखा जाना चाहिए।

ABSTRACT. The data on mean rainfall and mean rainfall anomaly of the meteorological sub-divisions of India, on different time-scales, is extensively used for monitoring the progress of the monsoon as well as applications and research. As such, it is important to ensure that the sub-divisional means are meaningful representations of the rainfall and the rainfall anomaly at districts/stations within the sub-division. Hence, the criteria to be satisfied for an appropriate delineation of a meteorological sub-division are high levels of coherence and homogeneity. In this paper we present an

assessment of the coherence and homogeneity of the current meteorological sub-divisions, for rainfall on the seasonal scale, by analysis of monthly district average rainfall for the period 1901-2015 during the summer monsoon for all the states, except Tamil Nadu for which June-December data are considered.

Since, earlier studies have shown that some of the sub-divisions of Karnataka and Maharashtra are neither coherent nor homogeneous, the problem of redelineation of the sub-divisions of these states is first addressed. We have assumed that the number of coherent zones in a state is the same as the number of current sub-divisions. Identification of coherent zones is achieved by successive application of the K-means (KM) clustering method to the seasonal rainfall of the districts, considering correlation of seasonal rainfall between districts as a measure of similarity. For these two states we find that some of the districts are not coherent and homogeneous. So we have repeated the exercise with analysis of a dense station network. The coherent zones identified from analysis of district data as well as station data, are found to be homogeneous as well and we have recommended that they become the new sub-divisions of the states. The new sub-divisions suggested for Karnataka, which are coherent and homogeneous, are: (*i*) Karnataka Western coast and Ghats (which includes districts/stations in the current sub-division of Coastal Karnataka as well as some from the sub-divisions of interior Karnataka) (*ii*) Karnataka northern plateau and (*iii*) Karnataka southern plateau. Of the current sub-divisions of Maharashtra, Marathwada and Vidarbha satisfy the criteria of coherence and homogeneity and can be retained as such. The current Madhya Maharashtra sub-division does not satisfy the criteria of coherence and homogeneity. We have derived a modified version of Madhya Maharashtra by allocation of some districts/stations of Western Ghats from the existing sub-division of Madhya Maharashtra to the existing sub-division of Konkan and Goa to generate a modified version of Konkan and Goa. These modified versions are coherent and homogeneous. Thus the suggested sub-divisions of Maharashtra are (*i*) modified version of Konkan and Goa (which could have been renamed as Konkan, Ghats and Goa but we have retained the old name) and (*ii*) modified version of Madhya Maharashtra, along with the current sub-divisions of (*iii*) Marathwada and (*iv*) Vidarbha. We have shown that the sub-divisions of all the other states of mainland India, are homogeneous and reasonably coherent and recommend that they should be retained as such.

Key words – K-means cluster analysis, Coherence, Homogeneity, Mean rainfall.

1. Introduction

The most important climatic element over the Indian region is the rainfall and meteorological sub-divisions are maximally used for research and monitoring as rainfall sub-divisions. A great deal of information on rainfall over the Indian region is available at the scale of meteorological sub-divisions of the different political states (Fig. 1). For example, the sub-divisional anomalies of rainfall on a day, for a week or the cumulative rainfall for a season, are regularly depicted at the India Meteorological Department (IMD) website and extensively used. It is therefore necessary to ensure that the sub-divisional average of the rainfall and its anomaly be a meaningful representation of the rainfall and anomaly of different districts/stations within the sub-division. Thus, each sub-division has to be homogeneous with respect to the mean rainfall and the variation of rainfall across each meteorological sub-division has to be coherent on the different time-scales of interest. In other words, the variation of the rainfall at any district/station has to be well correlated with the variation at the other districts/stations within the sub-division, so that the anomalies tend to be of the same sign across the sub-division.

This is also important because the all-India rainfall time series of IMD (Guhathakurta and Rajeevan, 2008; Guhathakurta *et al.*, 2011 etc.), which is available on their website, as well as the time series of Parthasarathy *et al.* (1995), which is widely used for research, are derived as weighted averages of the sub-divisional rainfall.

Rainfall sub-divisions of the region comprising, present-day India, Pakistan and Burma have been used since 1875. Homogeneity was considered to be an essential feature of the rainfall divisions, as Blanford (1877) pointed out "Partitioning of the country into in a number of rainfall provinces, partly conforming to administrative divisions, was done so as to avoid bringing together parts of the country which differ very greatly in their average". In a companion paper, Kelkar and Sreejith (2020) have discussed in detail the evolution of the rainfall/meteorological sub-divisions of India from 1875 to the present. In fact, from the early era, the climatology of the rainfall of different divisions was prepared by IMD and monthly weather review depicting the anomalies of each year were also prepared.

Walker (1924) mentions a study of 1914 in which correlations with "the monsoon rainfall in the regular 33 rainfall sub-divisions" were calculated. He further clarifies that "The 33 sub-divisions are those habitually employed in the Monthly Weather Review'. Of these 33 rainfall sub-divisions, about 30 are located in the present-day Indian region and are rather similar to the current meteorological sub-divisions. The current meteorological sub-divisions have evolved from these rainfall sub-divisions to become meteorological sub-divisions of current political states (Kelkar and Sreejith, 2020).

The Annual Conference of Relief Commissioners/ Secretaries, Department of Disaster Management of States/UTs" held on 23rd April, 2007 in New Delhi had
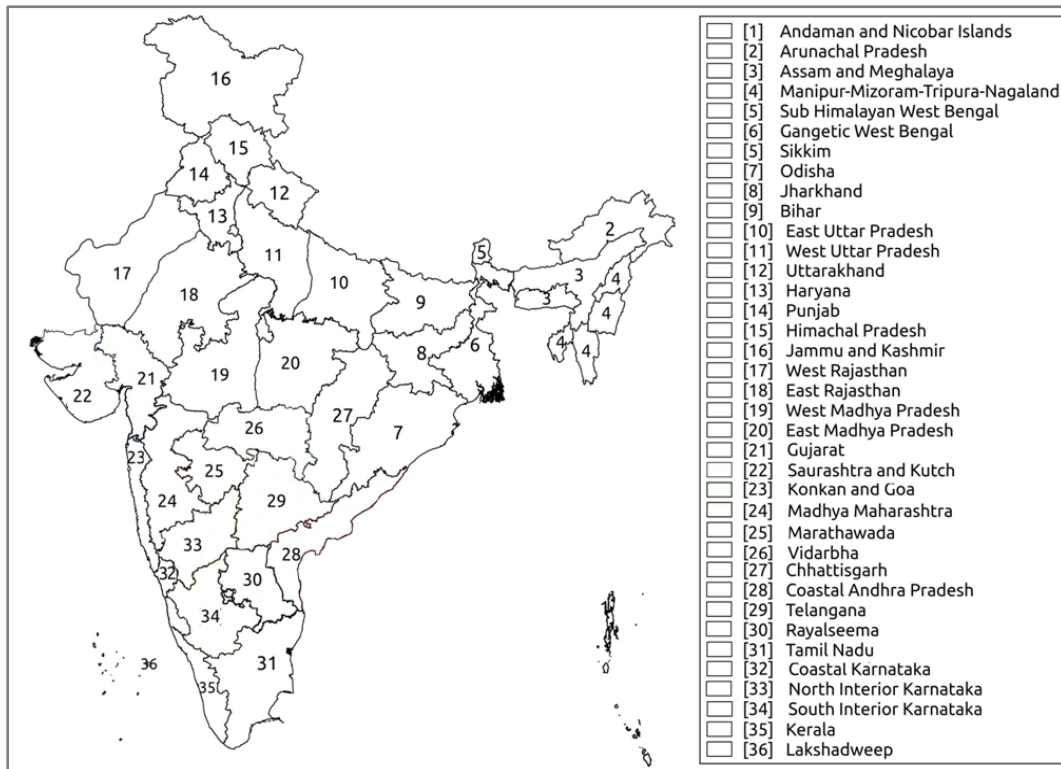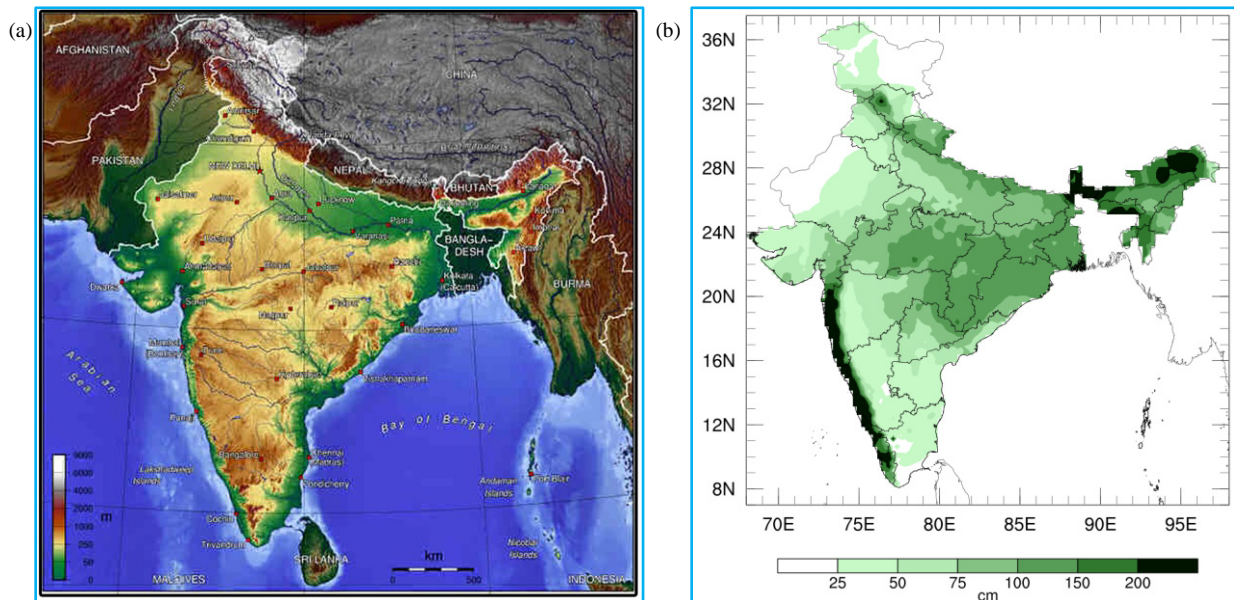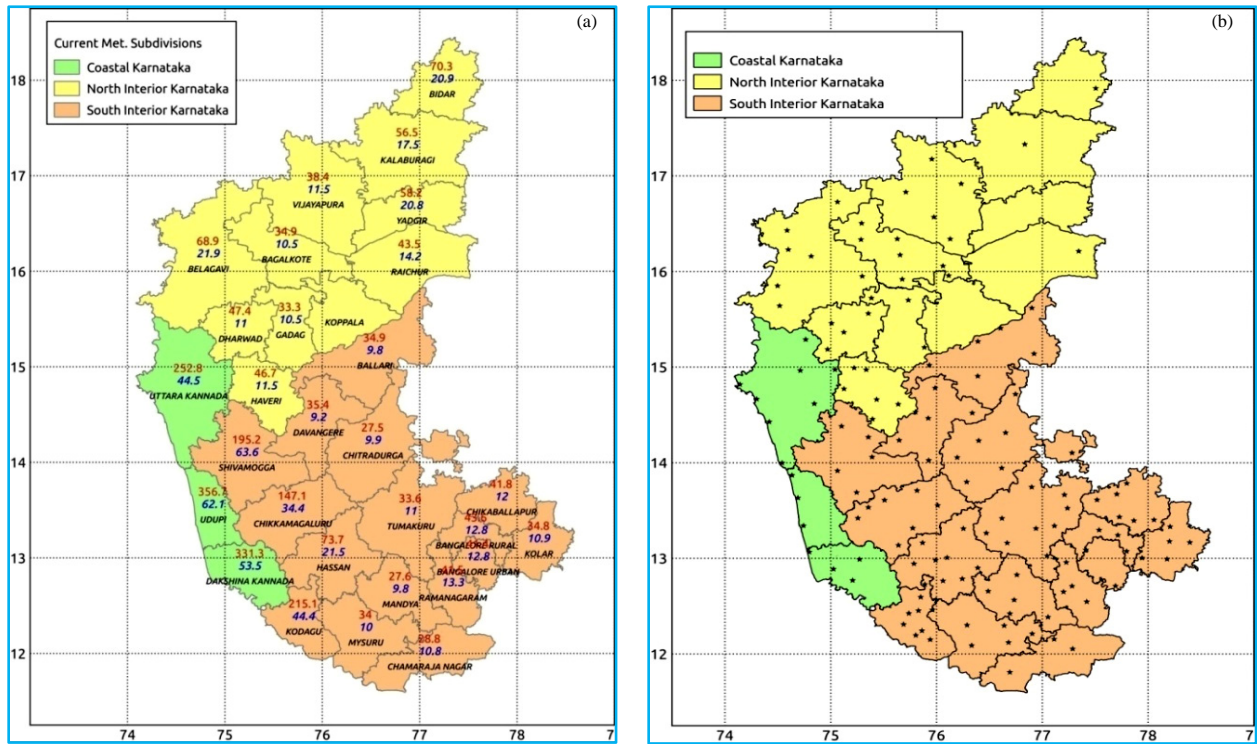
Fig. 1. Current Meteorological sub-divisions of India

Figs. 2(a&b). (a) Topography of India and (b) seasonal rainfall distribution

recommended modification of meteorological sub-divisions so that they are more homogeneous, based on past climatological data and geography of the region. In May 2016, a committee was set up by the Ministry of

Earth Sciences to review the demarcation of the existing meteorological sub-divisions and suggest changes, if required. Here we present the results of that study. More details are available in Kulkarni *et al.* (2020)

Figs. 3(a&b). Current Meteorological sub-divisions of Karnataka (a) District Mean Rainfall (cm) in red and the standard deviation (cm) in blue for the Summer Monsoon period (June-September) are also indicated and (b) the station network

Gadgil *et al*. (1988), had shown by analysis of the rainfall at 50 well distributed stations that South interior Karnataka and North interior Karnataka are not coherent with respect to variation of the summer monsoon (June-September) rainfall. Guhathakurta (2008), had come to the same conclusion by analysis of the district average rainfall data. The meteorological centre (MC) at Bangalore has formally requested for a reorganization of the meteorological sub-divisions. Analysis of the correlations for several pairs of stations in the sub-divisions of Maharashtra has clearly shown the lack of coherence within some sub-divisions such as Madhya Maharashtra as well as some districts like Satara (Guhathakurta, personal communication). In view of these studies, we have first addressed the problem of identification of coherent and homogeneous zones of Karnataka and Maharashtra located over the peninsula. Since some of the districts are also not coherent and homogeneous, the zones are identified by analysis of the district average rainfall data as well as the rainfall at dense networks of stations.

We focus here on seasonal rainfall. The summer monsoon (June-September) rainfall which contributes over 80% of the annual rainfall over the country as a whole is considered for all states except Tamil Nadu, which gets a large fraction of rainfall during the post monsoon season (October-December). Hence for Tamil Nadu the rainfall during June-December is considered. The spatial variation of the mean summer monsoon rainfall is depicted in Figs. 2(a&b) along with that of the topography.

A major factor determining the spatial variation of the rainfall over the peninsula is the topography. It is seen that the rainfall is high along the west coast and even higher over the Western Ghats which run parallel to the coast extending from Kerala in the south to Maharashtra in the north. It decreases to the east of the Ghats. Our aim is delineation of meteorological sub-divisions which are coherent at least with respect to the variation of the summer monsoon rainfall (except for the case of Tamil Nadu, for which June-December rainfall is considered). Since the mean rainfall of a sub-division is determined as the average of the rainfall at all stations/districts in the sub-division, as pointed out by Blanford (1877), it is also necessary to ensure that the mean seasonal rainfall does not vary too much across a sub-division, *i.e.*, the sub-division is homogeneous. This is because, otherwise, the mean sub-divisional rainfall will reflect primarily the rainfall at the stations characterized by heavy rainfall (such as those located on the Western Ghats).

Measures used for coherence are the correlation coefficients of the sub-divisional rainfall with the district/station rainfall as well as the pairwise
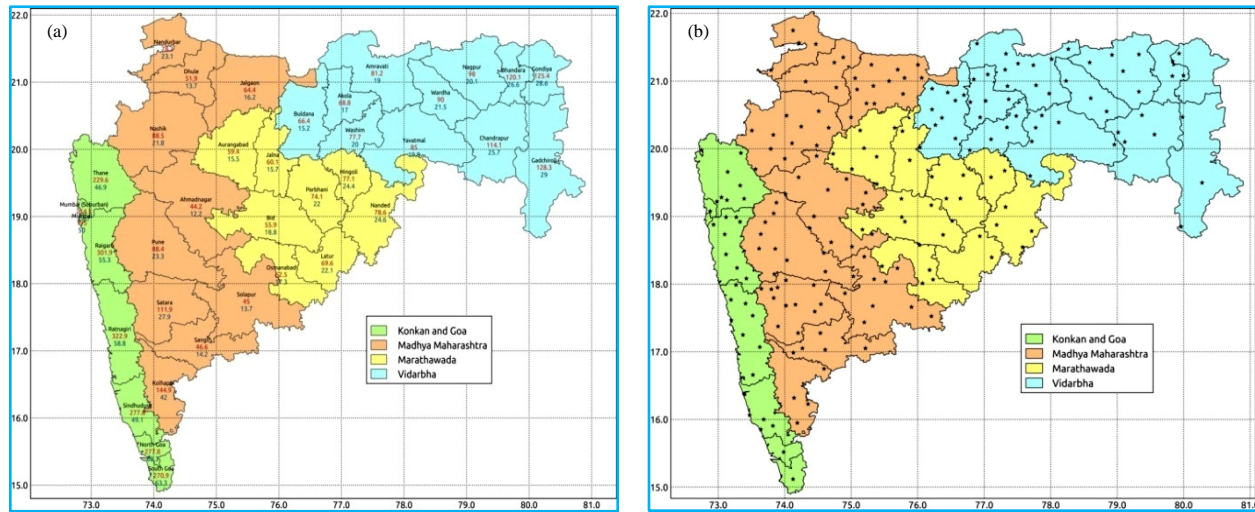
Figs. 4(a&b). Current Meteorological sub-divisions of Maharashtra along with (a) District Mean Rainfall (cm) in red and the standard deviation (cm) in blue for the Summer Monsoon period (June-September) and (b) the station network

correlations of district/station rainfall for all the districts/stations in the sub-division. The extent of the spread of the values of the climatological mean district/station rainfall around the value of the climatological sub-divisional mean rainfall, *i.e.*, the spatial standard deviation of the mean seasonal rainfall of the districts/stations in the sub-division, is taken as a measure of homogeneity.

The data analyzed are described in the next section. We have developed an objective methodology for the delineation of coherent and homogeneous sub-divisions. This methodology and its application to the demarcation of the meteorological sub-divisions of Karnataka based on the summer monsoon rainfall is considered in section 3. The same methodology is applied for the re-delineation of some of the sub-divisions of Maharashtra and discussed in section 4. We show that the current sub-divisions of the remaining states are coherent and homogeneous by considering the indices of coherence and homogeneity for the sub-divisions of each such state in section 5. The last section comprises the summary and concluding remarks.

2.   Data

For re-delineating sub-divisions of Karnataka, we have first analyzed district average rainfall data for 29 districts [Fig. 3(a)] for the period (1901-2010). We have then analyzed the monthly rainfall data of 141 stations [Fig. 3(b)] for (1901-2012), compiled by Guhathakurta and Rajeevan, 2008 (up to 2003 and updated thereafter; for analysis of long term trends of rainfall). Daily data of this network of 141 stations has also been analyzed to assess coherence on the shorter time scale of a week.

For delineating sub-divisions of Maharashtra, we have first analyzed district average rainfall data for 38 districts [Fig. 4(a)] for the period (1901-2015). We have then analyzed the monthly rainfall data of 173 stations [Fig. 4(b)] for (1901-2014) compiled by Guhathakurta and Rajeevan, 2008 (up to 2003 and updated thereafter; for analysis of long term trends of rainfall). Daily data of this network of 173 stations has also been analyzed to assess coherence on the shorter time scale of a week.

However, with the Guhathakurta and Rajeevan (2008) constraint on the minimum period of availability of data, some districts such as Koppal in Karnataka are not represented at all and some important stations such as Mangalore and Agumbe are also not included. Also only four stations in Marathwada have been included and thus Marathwada has not been well represented. Hence for the final delineation of Karnataka, rainfall data at 13 additional observatories and Hydro stations maintained by IMD and for the final delineation of Maharashtra, rainfall data at 31 additional stations in Marathwada sub-division, which have good quality data over a period of at least 50 years (but not over a period long enough to be included in the Guhathakurta data set) are also analyzed and assigned to the appropriate zone considering the coherence and homogeneity.

3.   Delineation of the meteorological sub-divisions of Karnataka

The summer monsoon rainfall is very high in Coastal Karnataka and over the Western Ghats in the adjoining western part of Interior Karnataka [Fig. 3(a)]. The rainfall is much lower over the rest of interior Karnataka. Clearly the average sub-divisional rainfall for the South Interior

Karnataka sub-division will be totally dominated by the rainfall of these western districts and not be a meaningful representation of the rest of the districts.

The extent to which the sub-divisional rainfall anomalies are representative of the anomalies of the stations/districts in the sub-division can be assessed by the correlation coefficient of the rainfall at each district/station with the sub-divisional mean rainfall. The extent to which the anomalies at the districts/stations within a sub-division are in phase, can be assessed with the pairwise correlations of the stations/districts in the sub-division. We consider a sub-division to be coherent if all (or almost all) the pairwise correlation coefficients are positive and significant at 95% and hence the rainfall at each of the stations/districts is not just significantly but highly correlated with the sub-divisional mean rainfall. Since the summer monsoon (June-September) rainfall is the focus of attention of scientists as well as the general public, it is important to ensure that at least the June-September rainfall anomalies are coherent over each sub-division. We find that the sub-division Coastal Karnataka is coherent with the pairwise correlation for district average rainfall for the three districts in it being between 0.46 and 0.7. However, the other two sub-divisions of interior Karnataka are not coherent. For example, the correlation coefficients of the summer monsoon rainfall for the high rainfall districts of Kodagu, Chickmaglur and Shimoga are not significant at 95% with (8, 10, 10) of the 15 districts in South Interior Karnataka and correlation coefficient for Belgaum is not significant with 4 out of the 9 districts of North Interior Karnataka.

Earlier studies on coherent zones of the Indian region (Gadgil *et al.*, 1993) and climatic clusters of the peninsula and of the Indian region (Gadgil & Iyengar, 1980; Gadgil *et al.*, 1993) suggest that at least three sub-divisions of the state are necessary. In this study, we assume that three sub-divisions are adequate for the observed space-time variation of Karnataka rainfall and re-delineate the boundaries of the three so as to ensure that each new sub-division/ zone is coherent with respect to the rainfall in the summer monsoon season and homogeneous with respect to mean summer monsoon rainfall. The approach adopted involves analysis of the data of the network of stations/districts covering the entire state of Karnataka to objectively determine, the grouping into three zones/sub-divisions. We have also assessed the coherence on the shorter time scale, *i.e.*, weekly scale, because weekly averages are often used.

3.1. *Methodology*

We have seen that the existing sub-divisions of South and North Interior Karnataka are not homogeneous with respect to the annual cycle. Studies by Gadgil and

Iyengar (1980) and Gadgil and Joshi (1983) of the climatic clusters of the peninsular region and the Indian region respectively, have shown that of the first two empirical orthogonal functions (EOFs) (which explain about 88% of the variance), the first is associated with high weightage primarily during the June-September season and the second in the pre and post-monsoon seasons. In the amplitude plane of these two EOFs the high rainfall regions along the West coast form one cluster and the entire peninsular region east of the Western Ghats form the second cluster which is rather dense. Thus, if we consider the Karnataka state, the high rainfall districts along the West coast and the adjoining districts over the Western Ghats would form one homogeneous zone with respect to the climatological rainfall patterns and the rest of the districts in interior Karnataka another. The clusters/classes of the rainfall patterns within the interior region east of Western Ghats emerge in the second sorting of the districts obtained by omitting the high rainfall districts belonging to the first cluster.

It is clear that if the mean rainfall during June-September or in any month or week during that season is much larger at one or two stations/districts relative to the others in the sub-division (as seen for Kodagu and Chikmagalur districts in South Interior Karnataka in Figs. 3(a&b), the sub-divisional mean will have a disproportionately large contribution of such stations/districts and will therefore not be a meaningful representation of the other stations/districts. Since the magnitude of rainfall anomalies is also large for such stations/districts relative to anomalies at other stations, the mean sub-divisional average anomaly will also not be a meaningful representation. Hence the first step should be to identify the homogeneous, coherent zone comprising the high rainfall stations or districts. As in identification of climatic clusters, the homogeneous, coherent sub-divisions of the interior region east of Western Ghats emerge in the second step of classification of the districts/stations obtained by omitting the high rainfall districts/stations belonging to the heavy rainfall zone.

Since our aim is to ensure that at least the June-September rainfall anomalies are coherent over each sub-division, we take the primary measure of similarity between rainfall variation at any two stations/districts to be the pairwise correlation of the June-September rainfall. A sub-division/zone is considered to be coherent if all the pairwise correlation coefficients (or almost all in the case of a dense network of stations), are significant at 95% and hence the rainfall at each of the stations/districts is not just significantly but highly correlated with the sub-divisional mean rainfall. The method used is K-means (KM) clustering method (Kruizinga, 1979; Kulkarni *et al.*, 1992). We first split the state into two zones by choosing
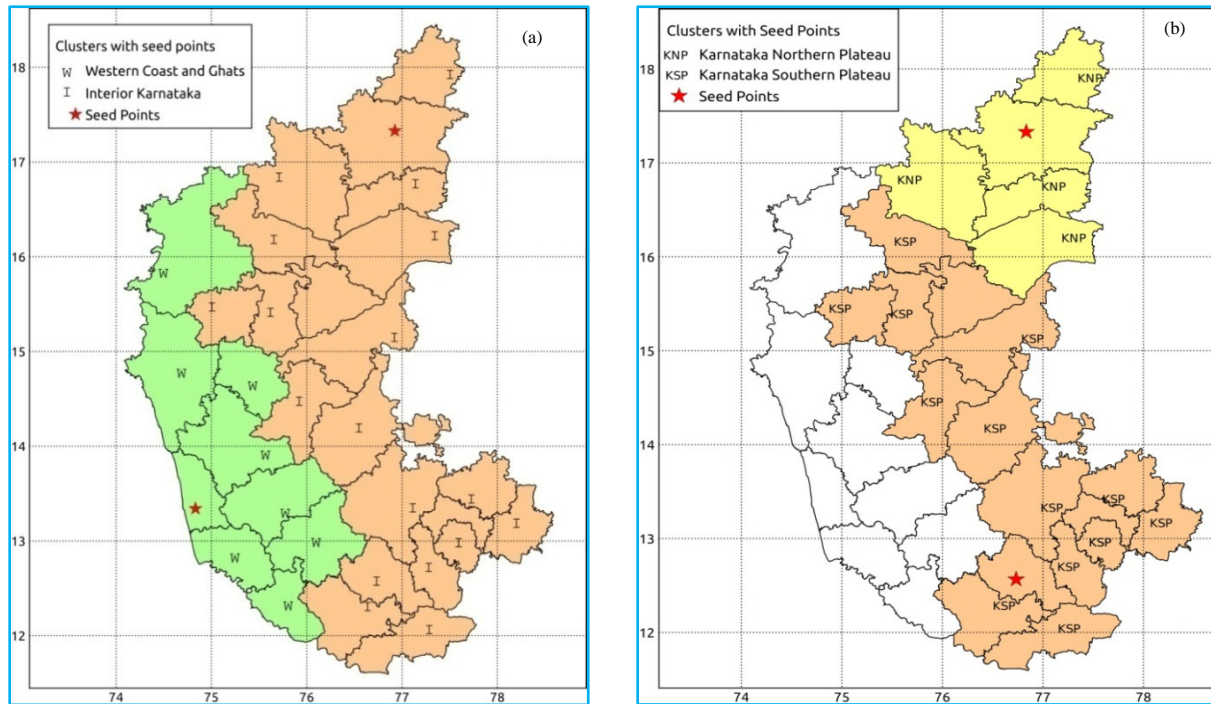
Figs. 5(a&b). Clusters of districts obtained after (a) first sorting (with the seed points shown as red stars) *viz.*, Western Coast and Ghats cluster (W) and interior Karnataka cluster (I) and (b) second sorting : Clusters obtained by analysis of all the districts except those in cluster W, *viz.*, Karnataka Northern Plateau (KNP) and Karnataka Southern Plateau (KSP)

two stations/districts as seed points which have the minimum pairwise correlation. Then each of the other stations/districts is assigned to the seed point with which the correlation coefficient of the June-September rainfall is higher and two clusters are formed. The time series of the average rainfall of the stations/districts in each cluster is then computed. At the second iteration, the correlation of the rainfall at each station/district with this average rainfall for each of the two clusters is computed and the station/district assigned to the cluster with the higher correlation with the average rainfall. This generally leads to a reassignment of some stations/districts. The procedure is continued until there are no changes in the assignment of stations/districts from that of the previous iteration.

When the state is thus split into two zones, one of the zones is the high rainfall region of the West coast and Western Ghats, the second zone which is the interior part of Karnataka, east of the first zone. It turns out that the West coast and Western Ghats is a coherent zone, satisfying the constraints regarding pairwise correlation and correlation with the zonal average rainfall. However, the zone over the interior part of Karnataka, east of the first zone is not coherent. Hence, we divide this interior region into two zones by repeating the exercise for the stations/districts obtained by omitting all the stations/districts in the first zone and thereby determine the sub-divisions of interior Karnataka.

3.2. *Zones based on district average and station data*

The long time series (1901-2010) of seasonal rainfall has been prepared for the 29 districts over Karnataka. The KM clustering algorithm is applied to these districts with the pairwise correlation of June-September rainfall as a measure of similarity. For the first sorting, the two districts which are most poorly correlated (Gulbarga and Udupi) are chosen as seed points and two clusters are obtained [Fig. 5(a)]. Cluster W consists of the districts North Kanara, South Kanara and Udupi (of the existing coastal Karnataka sub-division), along with Belgaum and Haveri from the existing North Interior Karnataka (NIK) sub-division and Shimoga, Chickmagalur, Kodagu and Hassan from the western parts of the current South Interior Karnataka (SIK) sub-division. Thus, the zone W comprises the West coast and Western Ghats region of the state. It is interesting that traditionally, from the point of view of the climate/rainfall, the state is divided into three regions: Karavali (coastal region), Malanad/ Ghatta Pradesha (Western Ghats region) and Bayaluseeme (the plateaueast of Western Ghats). Thus, the first zone identified here, W, which we will call Karnataka Western Coast and Ghats zone, comprises the traditional Karavali and Malnad/Ghatta Pradesh regions of the state.
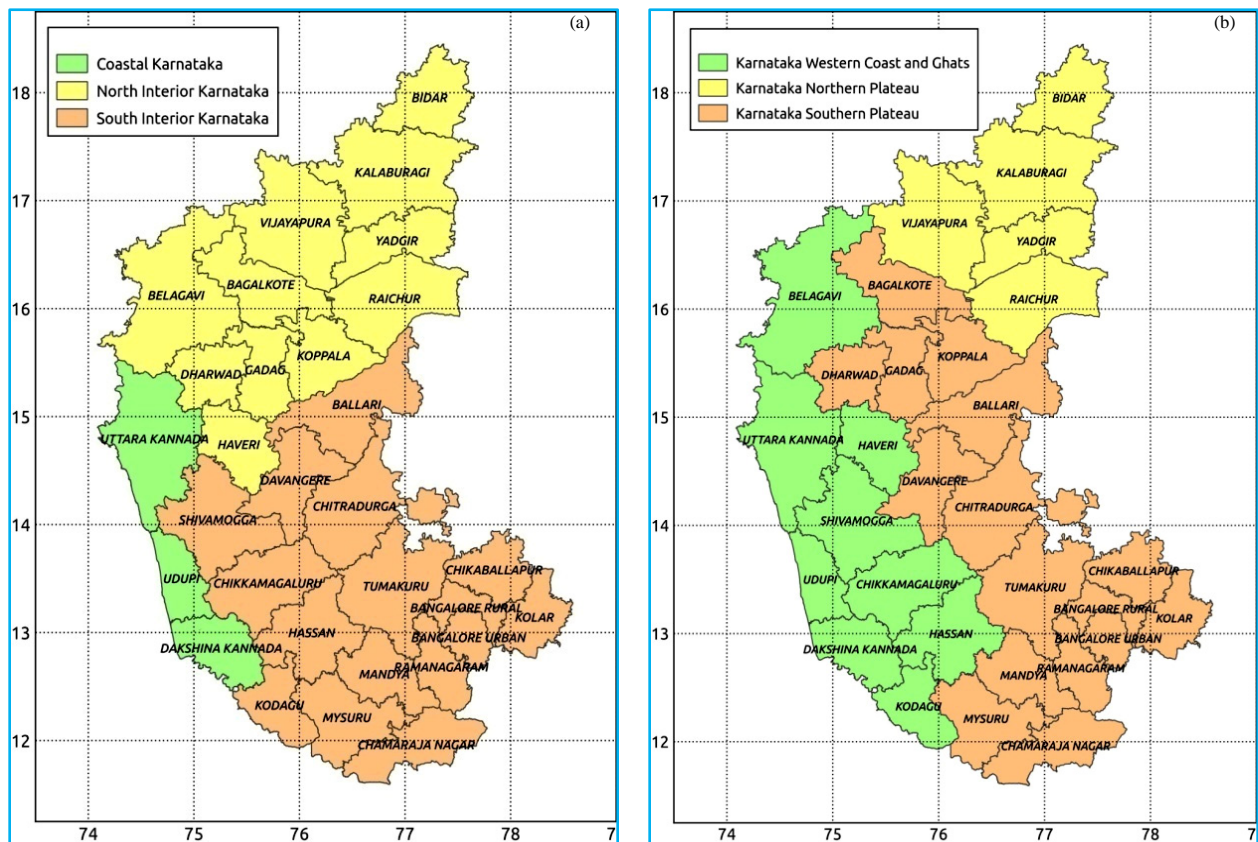
Figs. 6(a&b). (a) Current meteorological sub-divisions of Karnataka and (b) Proposed zones based on the variation of district average summer monsoon rainfall (Karnataka Western Coast and Ghats; Karnataka Northern Plateau; Karnataka Southern Plateau)

In the second sorting, all the districts except those assigned to the cluster W, *i.e*., in the plateau or the traditional 'Bayaluseeme' region of Karnataka are considered. Again, the same procedure is applied to these 20 districts with seed points as Gulbarga and Mandya (most poorly correlated), to obtain two zones of this plateau region of Karnataka which we call the Karnataka northern plateau and Karnataka Southern Plateau [Fig. 5(b)]. There are 5 districts in the northern plateau zone (NI) and 15 in the southern plateau zone (SI).

The three meteorological zones of Karnataka based on district average rainfall determined here are shown along with the current IMD sub-divisions in Figs. 6(a&b). The most important difference between the zones identified here and the existing sub-divisions is that the high rainfall districts such as Shimoga, Chickmagalur, Kodagu, Hassan, Belgaum, which belonged to the IMD sub-divisions of interior Karnataka are now assigned to the Karnataka Western Coast and Ghats zone. Another major difference between the IMD sub-divisions of north and south interior Karnataka and the northern and southern plateau zones determined here is that the districts

of Dharwad, Gadag and Bagalkote which were in the current NIK, are now in the Karnataka Southern plateau zone. However, the correlation of these districts with the neighboring districts in the current SIK are comparable to the correlations with the neighboring districts in the current NIK. Thus these districts appear to be on the border of the two classes of districts.

However, it should be noted that the summer monsoon rainfall varies considerably across the new zone of Western Coast and Ghats with districts such as Haveri with much less rainfall included along with districts such as North Kanara with high rainfall. This occurs because some stations near the western parts of the districts such as Haveri have high rainfall while a large number of stations within the same district have low rainfall. Thus, such districts cannot be considered as homogeneous.

Recognizing that districts are themselves not always homogeneous and coherent, we also analyzed the summer monsoon rainfall at a dense network of 141 stations and applied the same methodology to delineate coherent clusters. At the first step, with two seed points, 50 stations
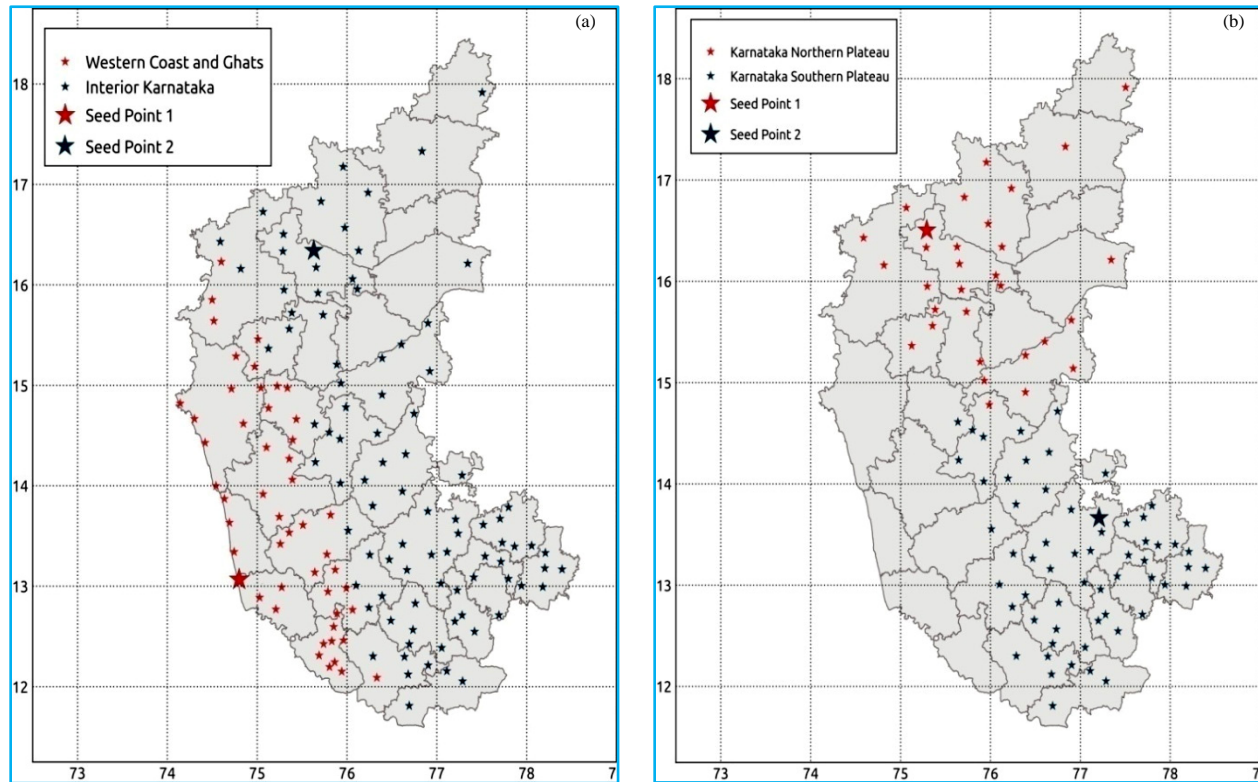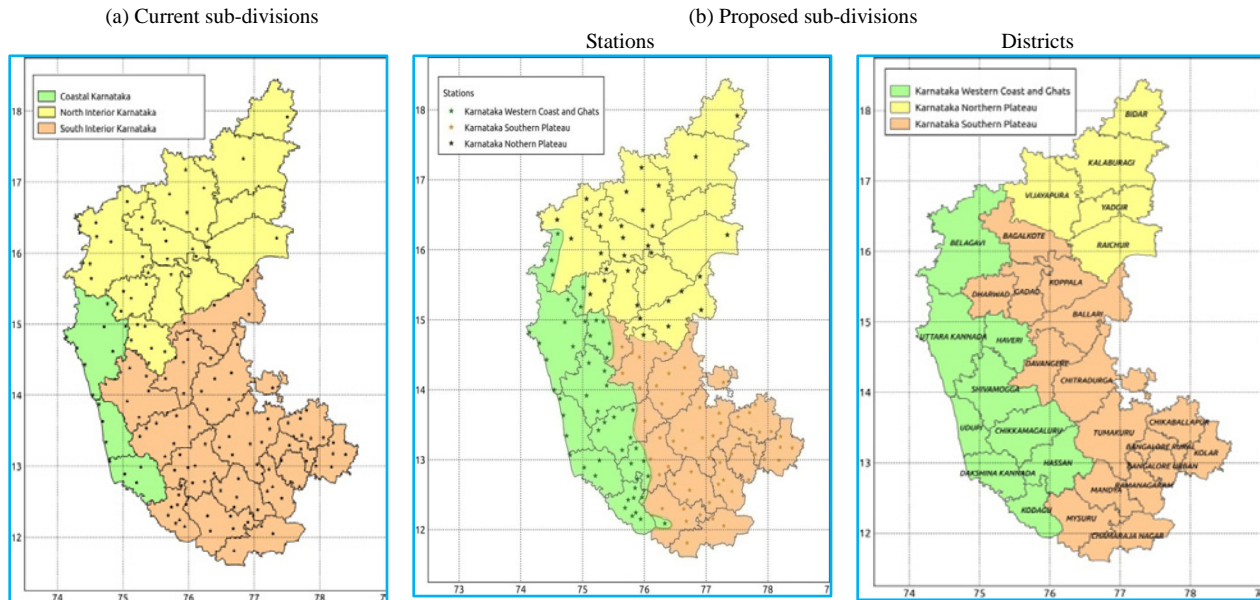
Figs. 7(a&b). Clusters obtained based on 141 stations in (a) first sorting and (b) second sorting

get allocated to one cluster and the remaining 91 stations to another cluster [Fig. 7(a)]. We refer to the first cluster as Karnataka Western Coast & Ghats zone, since it comprises stations of coastal Karnataka and adjoining Western Ghats. The second cluster is the plateau region of Karnataka to the east of the first zone. In the second sorting, the 91 stations of the plateau region get assigned to two clusters, the northern plateau zone comprising 31 stations and southern plateau zone comprising 60 stations [Fig. 7(b)]. The zones based on district data and those based on station data are shown along with the current meteorological sub-divisions in Figs. 8(a&b).. It should be noted that the zones based on stations are more similar to the current sub-divisions than those based on district average rainfall. This is because several districts with some high rainfall stations get transferred to the Karnataka Western Coast & Ghats zone, whereas only such stations from these districts get transferred to the Karnataka Western Coast & Ghats zone. We suggest that such districts need to be split to ensure homogeneity at the district and zonal scale. Before assessing the coherence and homogeneity of the zones *vis a vis* the current sub-divisions we consider this new suggestion of the splitting of districts, *i.e.*, assignment of stations within a district to different zones.

3.3. *Assignment of stations within a district to different zones*

The delineation of zones on the basis of the district average rainfall is generally similar to that on the basis of 141 stations [Figs. 8(a&b)]. However, our analysis of the 141 stations has clearly brought out that for some of the districts, there is a large variation of the mean summer monsoon rainfall across the district and the variation of the summer monsoon rainfall is also not coherent across the district. Hence such districts have to be split into parts which are assigned to different zones. The splitting of some of the districts of the Karnataka Western coast and Ghats zone determined from district average data is clearly seen by comparison of Figs. 8(a&b). These districts are Belgaum (with 4 stations assigned to the KNP zone and 3 to the KWCG zone. Dharwad (2 in KWCG zone, 2 in KNP zone), Hassan (4 in KWCG zone, 4 in KSP zone), Haveri (5 in KWCG zone, 1 in KSP zone), Mysore (4 in KSP zone, 1 in KWCG zone) and Chickmagalur (6 in KWCG zone, 1 in KSP zone).

The K-means clustering method we have used is based on the correlation of the rainfall of the station to be assigned with the mean rainfall of the stations in the cluster. A more stringent criterion of coherence is the

(a) Current sub-divisions   (b) Proposed sub-divisions
                                                    Stations   Districts

Figs. 8(a&b). (a) Current meteorological sub-divisions of Karnataka, the locations of the 141 station network, in each subdivision are shown and (b) KWCG, KNP and KSP zones determined from the variation of the summer monsoon rainfall at 141 stations (left) and from 29 districts (right)

pairwise correlation of all the stations within a cluster. For the districts for which some stations are assigned to one zone and others to a different zone, we have assessed whether the assignment made is justified, by comparison of the frequency distributions of correlation coefficients of each station with each of the stations in the two zones. We find that parts of Belgaum and Dharwad districts get assigned to different zones, as also parts of as Chickmagalur-Hassan and Haveri-Mysore. We find that the correlation coefficients for almost all the stations are higher with the stations in the zone to which they have been assigned, relative to the stations in the other zone (original assignment) (Figures in Kulkarni *et al*., 2020). Only Hukeri in Belgaum and Hubli in Dharwad district appear to be on the borderline with comparable correlations with both the zones. And Alur in Hassan district also appears to be on the borderline with comparable correlations with stations in KWCG and KSP.

The assignment of parts of some districts to different zones has had an impact on the assignment of some other districts. For example, one part of Belgaum and Dharwad districts is now assigned to the KWCG zone and the other to the KNP zone. With this, districts of Gadag, Bagalkoteand Bellary, which were assigned to KSP in the zones based on district average rainfall, get assigned to KNP [Figs. 8(a&b)] due to the higher correlations (of the order of 0.3-0.7) with the stations in KNP of the divided districts, Belgaum and Dharwad.

3.4. *Coherence*

3.4.1. *Seasonal scale*

The frequency distributions of the correlation coefficients of all the districts/stations in each of the three zones as well as each of the current sub-divisions with the zonal/sub-divisional mean are shown in Figs. 9(a&b). The frequency distributions of the pairwise correlation coefficients between the rainfall of the districts/stations in the current sub-divisions and proposed zones is shown in Figs. 10(a&b). The correlation of the districts/stations in the Karnataka plateau zones with the zonal mean is higher than that of the districts/stations in the sub-divisions of interior Karnataka with the sub-divisional means [Figs. 9(a&b)]. It is seen that whereas for the current sub-divisions of interior Karnataka, the inter-correlation between the districts/stations is insignificant for well over 10% of the pairs and is even negative in some cases, for the proposed zones of the Karnataka plateau, the inter-correlation between the rainfall of the districts is significant and substantially higher [Figs. 10(a&b)].

Thus, the zones identified for the Karnataka plateau region are coherent whereas the current sub-divisions are not and zonal means are more representative of the districts/stations within the zones than the sub-divisional means of the districts within the sub-divisions. However,
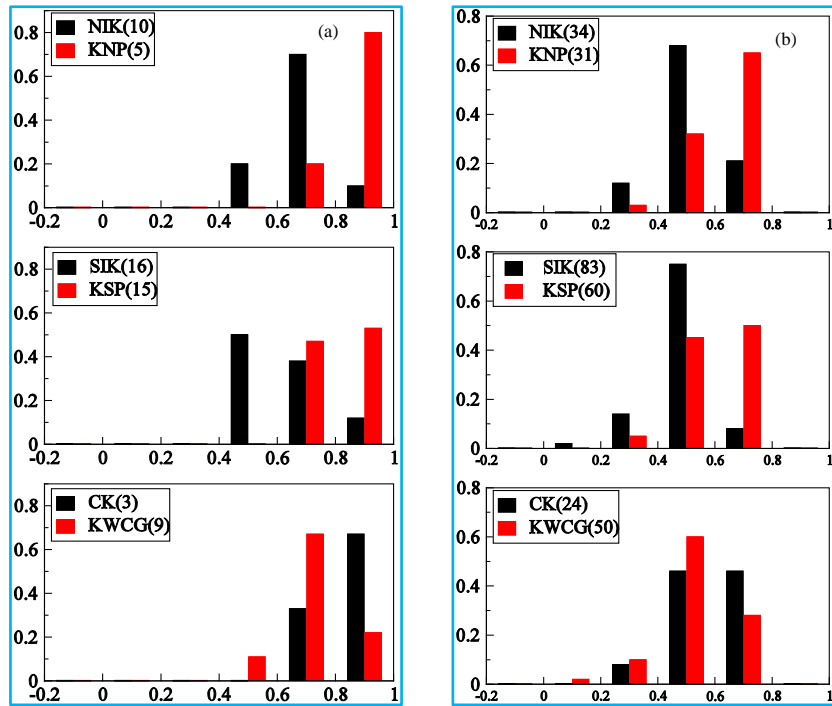
Figs. 9(a&b). Frequency distribution of the correlation coefficients of the June-September rainfall at each of the (a) districts and (b) stations in the subdivision/zone with the sub-divisional/zonal (black/red) mean rainfall
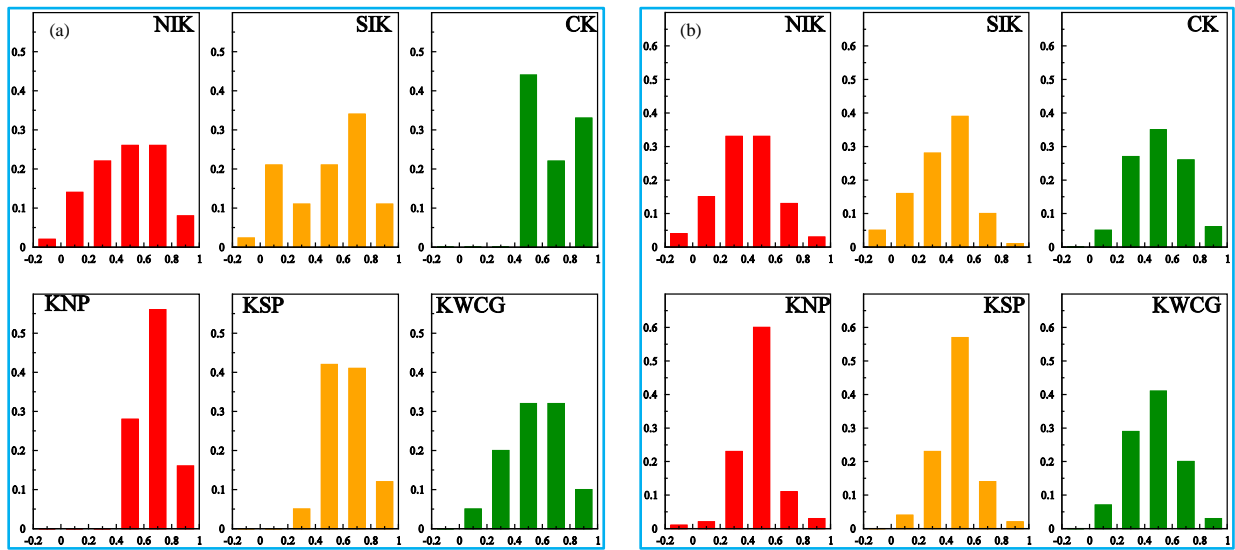
Figs. 10(a&b). Frequency distribution of the inter correlation coefficients of (a) districts and (b) stations in a sub-division (top)/zone (bottom)

with the addition of several districts/stations to make up the KWCG zone from the Coastal Karnataka sub-division, the inter-correlation is somewhat smaller and for a few cases not significant. Also, the correlations of the districts in the Coastal Karnataka sub-division with the sub-divisional mean are somewhat higher than the correlation of the districts in the KWCG zone with the zonal mean because the latter has three times as many districts.

The implications of the lack of coherence of the sub-divisions of interior Karnataka are rather serious in some years since they lead to even the sign of the sub-divisional rainfall anomalies not being representative of the rainfall anomalies over large parts of the sub-division. We note that the sub-divisions of interior Karnataka differ from the zones of Karnataka plateau primarily in the absence of the high rainfall stations along the western boundary in the

TABLE 1

Frequency distribution of the number of years in various categories of rainfall anomalies in KNP versus NIK and KSP versus SIK

	KNP Rainfall Anomaly(Based on stations)					
	–30 - –20	–20 - –10	–10 - 0	0 - 10	10 - 20	20 - 30
NIK Rainfall Anomaly (Based on stations) –30 - –20	1	1	-	-	-	-
–20 - –10	-	8	4	-	-	-
–10 - 0	-	3	32	**6**	-	-
0 - 10	-	**1**	**7**	28	5	-
10 - 20	-	-	**1**	5	7	1
20 - 30	-	-	-	-	1	1

	KSP Rainfall Anomaly(Based on stations)						
	-	–30 - –20	–20 - –10	–10 - 0	0 - 10	10 - 20	20 - 30
SIK Rainfall Anomaly (Based on stations) –30 - –20	-	-	3	-	-	-	-
–20 - –10	-	-	10	6	-	-	-
–10 - 0	-	-	5	26	**10**	-	-
0 - 10	-	-	-	**7**	19	3	-
10 - 20	-	-	-	**2**	6	12	2
20 - 30	-	-	-	-	-	1	-

TABLE 2

Number of stations, mean rainfall and spatial standard deviation for original sub-divisions and proposed zones of Karnataka

SD/Zone (# stations)	NIK (34)	KNP (31)	SIK (83)	KSP (60)	CK (24)	WCGK (50)
Mean RF (cm)	46.8	38.3	55.5	35.4	251.0	178.9
SD (cm)	23.9	8.2	57.7	6.7	91.0	111.9

plateau zones. These stations are generally not well correlated with the stations retained in the plateau zones. However, they dominate the sub-divisional rainfall anomalies.

The frequency distribution of the number of years in classes of magnitude of anomalies in northern (southern) plateau *vis a vis* north (south) interior Karnataka (Table 1). Note that in the period of 112 years considered, the sign of the average rainfall anomaly of the north interior Karnataka sub-division is opposite to the sign of the average anomaly of KNP (*i.e.*, Karnataka northern plateau) in 15 years whereas the sign of the average anomaly of south interior Karnataka is opposite to the sign of the average anomaly of KSP (*i.e.*, Karnataka southern plateau), in 19 years. Such misrepresentation of the anomalies of seasonal rainfall of sub regions of sub-divisions will lead to major consequences in applications.

3.4.2. *Coherence on the weekly scale*

We have also derived the frequency distributions of the correlation coefficient of the stations with the zonal mean rainfall on the weekly scale based on the 17 weeks of the summer monsoon season, for the three zones (Kulkarni *et al*., 2020). We find that for the KNP and KSP zones, the correlation coefficient is larger than 0.4 for all but one station and higher than 0.6 for close to 80% of the stations for the KNP zone. For the KWCG zone more than 70% of the stations are significantly positively correlated with the zonal mean. Also, over 60% of the stations have correlation coefficients more than 0.6. Hence on the whole, the weekly mean rainfall of each of the three zones can be considered to a meaningful representation of most of the stations within the zone.

3.5. *Homogeneity*

We have noted that the coherent zones of the Karnataka plateau differ from the sub-divisions of interior Karnataka primarily in the absence of the relatively high rainfall stations near the western boundary of the sub-divisions. This has led to a decrease in the average rainfall of the zones *vis a vis* the sub-divisions (Table 2). The average rainfall of the coastal sub-division also decreases with the formation of the Western Coast and Ghats zone because several stations with somewhat lower rainfall also get added.

We consider a zone to be homogeneous if the spatial variation of the mean summer monsoon, *i.e.*, variation of the mean rainfall between the included stations is not very large, *i.e.*, standard deviation is much smaller than the
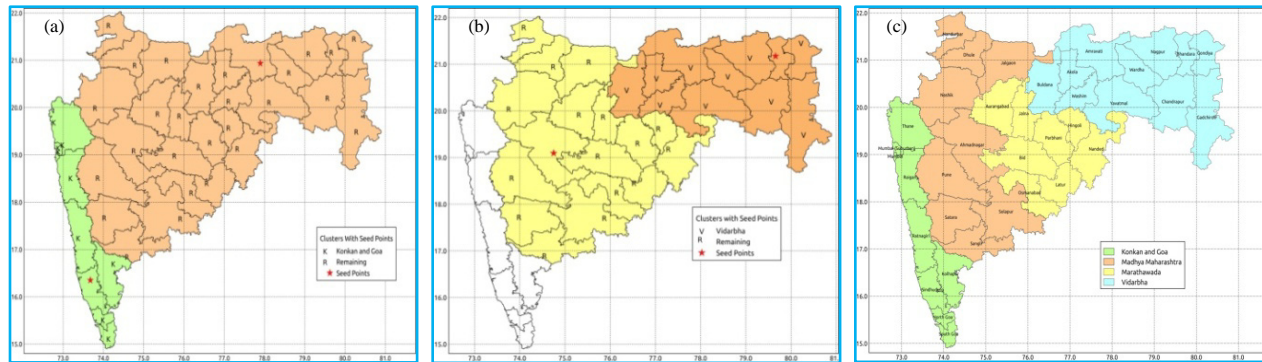
Figs. 11(a-c). (a) Clusters of districts obtained after first sorting, *viz.*, Konkan and Goa (K) and remaining Maharashtra (R), (b) Vidarbha and remaining Maharashtra clusters obtained by analysis of all the districts except those in the new Konkan and Goa region denoted by K in (a) and (c) proposed zones of Maharashtra, based on the variation of district average summer monsoon rainfall

zonal mean. In Table 2, in addition to values of the overall mean rainfall of each zone/sub-division, values of a measure of the spread of the mean rainfall values of the stations within a zone/sub-division, *viz.*, the spatial standard deviation derived from the mean rainfall of the stations in each zone/sub-division are given.

It is seen that the standard deviations of the zones of the plateau are much smaller than the mean whereas the standard deviation of the sub-division of south interior Karnataka is comparable to the mean and that of north interior Karnataka is almost 50% of the mean rainfall suggesting a far larger spread in the mean rainfall of the stations in the sub-divisions of interior Karnataka relative to that in the zones of the Karnataka plateau. While the standard deviation for the stations in KWCG region is a little larger than that of original coastal Karnataka, (although it is still much smaller than the mean) because some stations with lesser rainfall were added.

In fact the zones are also found to be more homogeneous for the annual cycle than the sub-divisions (details in Kulkarni *et al.*, 2020).

3.6. *Final delineation of zones for Karnataka*

We have noted that some districts such as Koppal are not represented at all in the 141 station network and some important stations such as Mangalore and Agumbe are also not included. Hence the rainfall data for additional 13 observatories and Hydro stations maintained by IMD, which have good quality datafor at least 50 years (but not over a period long enough to be included in the Guhathakurta data set for examining long term trends), were considered. Each of these stations were assigned to one of the three zones determined by the analysis of the 141 stations [Figs. 9(a&b)] based on their correlations with zonal average rainfall. The list of all the stations in each of the three zones, *viz.*, Karnataka Western Coast and

Ghats, Karnataka Northern plateau and Karnataka Southern plateau is given in Annexure 2 of Kulkarni *et al.*, 2020. The same approach will be adopted if it is decided to define the zones for higher resolution data, such as Taluk average data, as well.

4. Delineation of the meteorological sub-divisions of Maharashtra

The annual mean rainfall and its standard deviation for the different districts in each of the current IMD meteorological sub-divisions of Maharashtra is depicted in Figs. 4(a&b). It is seen that the rainfall is very high throughout Konkan and Goa, rather high in Kolhapur, high in Satara in Madhya Maharashtra and eastern districts of Vidarbha and is much lower over the rest of Maharashtra. With the rainfall over Satara being more than twice that of several districts in Madhya Maharashtra and that of Kolhapur even higher, it is clear that contribution of these two districts to the average rainfall of Madhya Maharashtra will be disproportionately high.

4.1. *Delineation of meteorological sub-divisions by analysis of district average data and station data*

We first consider delineation of sub-divisions by analysis of district average monthly rainfall for the period 1901-2015 for Maharashtra and Goa. The methodology used (described in section 3.1) is K-means (KM) clustering (Kruizinga, 1979; Kulkarni *et al.*, 1992). The result of the first sorting is shown in Fig. 11(a). When we followed the procedure for second sorting outlined in section 3.1, by dropping districts belonging to the new Konkan and Goa sub-divisions and analyzing the district rainfall of the remaining districts (denoted by R in Fig. 11(a) we found that that the eastern zone is identical to the meteorological sub-division of Vidarbha while the other zone (with districts denoted by R in Fig. 11(b)

Proposed Sub-divisions

(a) Existing Subdivisions   (b) Stations   (c) Districts
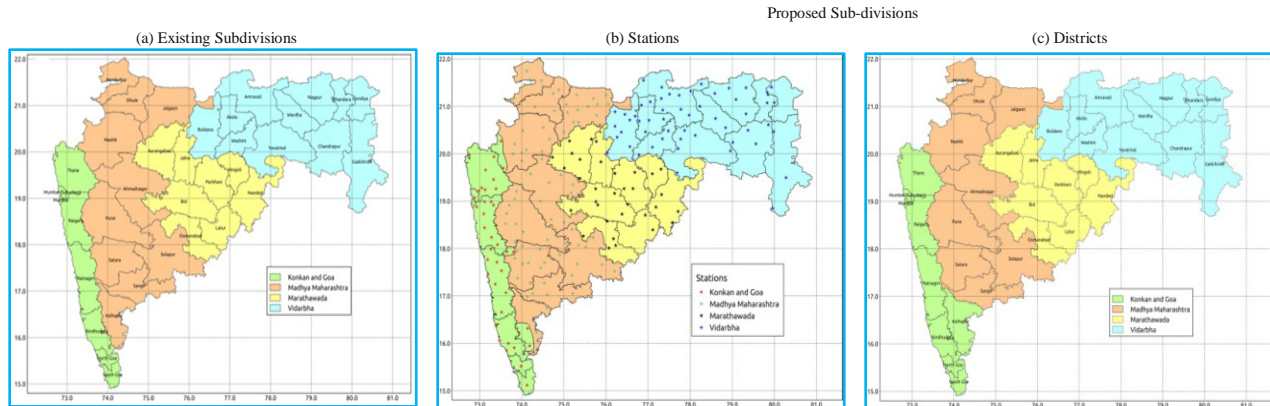
Figs. 12(a-c).   (a) Current meteorological sub-divisions of Maharashtra, proposed zones based on the variation of (b) station and (c) district summer monsoon rainfall

comprises the current Madhya Maharashtra sub-division (without Kolhapur) and the Marathwada region. When we followed the same procedure for dividing the remaining region [shown as R in Fig. 11(b)] to derive the new sub-divisions of Madhya Maharashtra and Marathwada, we found that the sub-division of Marathwada thus determined was not superior in terms of coherence or homogeneity to the existing sub-division. Hence, we decided that only the boundary between Konkan and Goa and Madhya Maharashtra needs to be changed as shown in Fig. 11(a). The sub-divisions of Marathwada and Vidarbha are retained as the current ones. The final delineation of the sub-divisions based on district average rainfall is shown in Fig. 11(c).

Since some of the districts are not coherent with respect to the variation of the summer monsoon rainfall, we have also analyzed the rainfall at 173 stations [Fig. 4(b)], using the same methodology of applying the K-means algorithm and sorting into clusters in two steps. This again yielded a new delineation of Konkan & Goa with reallocation of some stations which were in the current Madhya Maharashtra state, while the sub-division of Vidarbha which was identical to the current one. The remaining stations of Madhya Maharashtra and those belonging to Marathwada were the residual stations. Again, since applying the K-means algorithm to this residual set did not yield a new sub-division of Marathwada which was significantly more coherent than the current sub-division, we decided to retain the current sub-division of Marathwada as in the case of the districts. The delineation of the sub-divisions obtained by analysis of station data is shown in Fig. 12(b) along with that obtained by analysis of the district data [Fig. 12(c)]. The current sub-divisions are also shown in Fig. 12(a) for comparison.

An important point to note is that, like in the case of Karnataka, for some districts there is a large variation of

the mean rainfall at stations within the same district, *e.g.*, in Kolhapur Gadhinglaj (75.7 cm) and Shirol (40.5 cm) have substantially less rainfall as compared to Chandgad (251.5 cm) and Gargoti (131.2 cm). Chandgad and Gargoti are more homogeneous and coherent with the stations in Konkan-Goa. In Nasik district Igatpuri (309.9 cm) and Peint (210.4 cm) are very heavy rainfall stations which lead to the mean rainfall of Nasik district being much higher than if these stations were not included. In Satara district, Mahabaleshwar (565.7 cm) and Panchgani (168.6 cm) are more coherent with stations in Konkan-Goa than with the other stations in Satara. The mean rainfall of Satara district *i.e.*, 120.3 cm, is mainly influenced by these stations. So some of the stations of such districts have been assigned to a different sub-division. Comparison of the frequency distribution of pairwise correlations of such stations with other stations in the current sub-division with that of the correlation with stations in the sub-division to which they are newly assigned, shows that it is more appropriate to assign the stations to the new sub-division rather than retaining them along the with other stations in the district in the current sub-division (details Kulkarni *et al.*, 2020).

4.2.   *Coherence*

4.2.1. *Seasonal scale*

We consider next how representative is the sub-divisional mean rainfall anomaly of the rainfall anomaly at the different districts/stations in the sub-division. The frequency distributions of the correlation of the rainfall of each district/station with the sub-divisional mean rainfall in the current and proposed sub-divisions of Konkan & Goa and Madhya Maharashtra are shown in Figs. 13(a&b) respectively. Figs. 13(a&b) also show the correlation of district/station rainfall with current sub-divisional mean rainfall in Marathwada and Vidarbha since these two
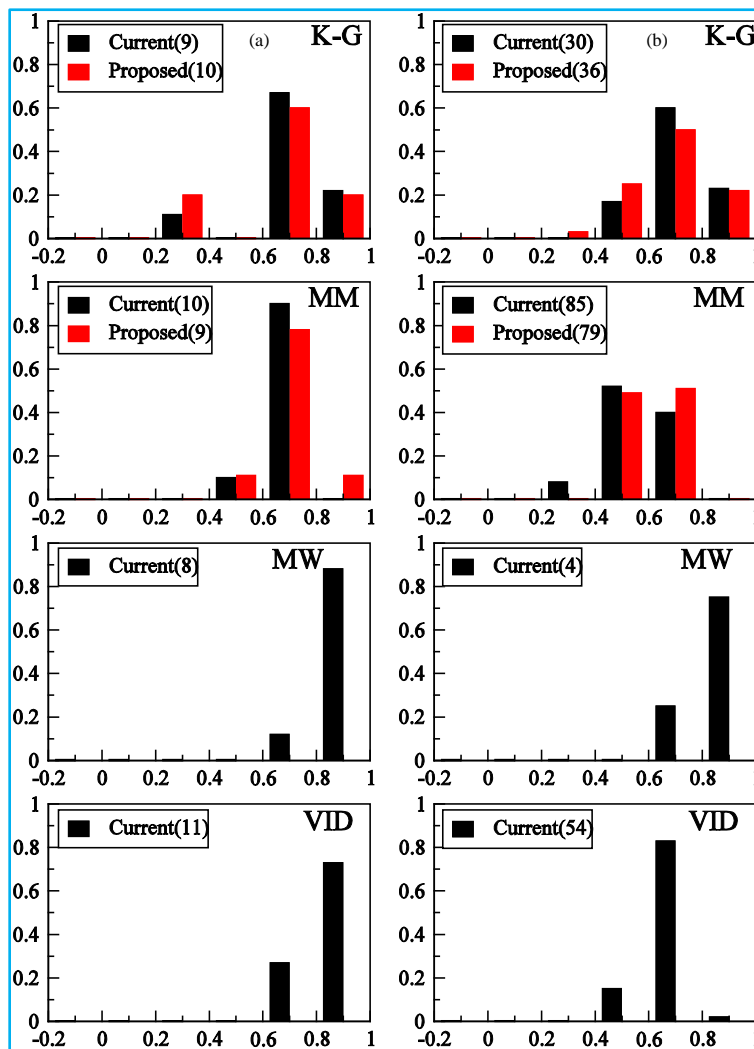
Figs. 13(a&b). Frequency distribution of the correlation coefficients of (a) each district and (b) station in modified and original four subdivisions of Maharashtra, Konkan-Goa (k-G), Madhya Maharshtra (MM), Marathwada (MW) and Vidarbha (VID) with the sub-divisional mean rainfall; the number of districts/stations in the current and proposed sub-divisions are also indicated

sub-divisions are not modified. It is seen that there is an improvement in the correlation with the mean of the proposed Madhya Maharashtra sub-division relative to the current one, while that for the proposed Konkan and Goa is slightly worse because of the addition of stations from Madhya Maharashtra.

The frequency distributions of the pairwise correlations of the district/station rainfall in the current and proposed sub-divisions of Konkan & Goa and Madhya Maharashtra and current sub-divisions of Marathwada and Vidarbha are shown in Figs. 14(a&b). The pairwise correlations of the districts in the proposed Konkan & Goa sub-division are comparable with those in

the current sub-division while those of the districts in proposed Madhya Maharashtra sub-division are slightly better than that in the current sub-division.

4.2.2. *Coherence on the weekly scale*

The frequency distributions of the correlation coefficient of the stations with the mean rainfall of proposed zones on the weekly scale based on the 17 weeks of the summer monsoon season, shows that all the stations are positively significantly correlated with their respective sub-divisional mean rainfall and the correlation coefficient is larger than 0.4 for both the proposed zones, (details in Kulkarni *et al.*, 2020). More than 60% of the stations in Madhya Maharashtra
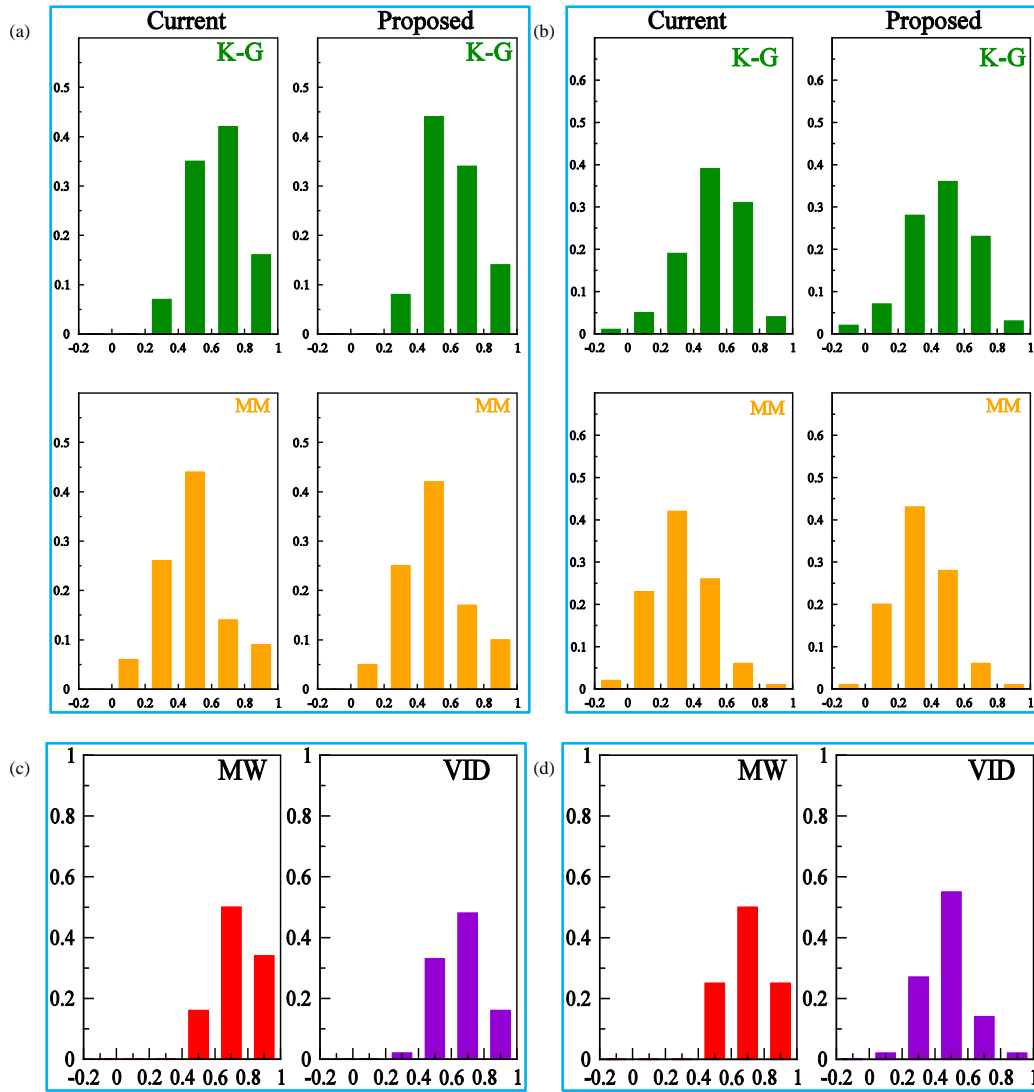
Figs. 14(a-d). (a) Frequency distribution of the pairwise correlation coefficients of districts in current and proposed sub-divisions of Konkan and Goa (K-G) and Madhya Maharashtra (MM) based on analysis of district data, (b) same as (a) but based on analysis of station data, (c) for the sub-divisions of Marathwada and Vidarbha based on district and (d) station data

have correlations more than 0.6. For Konkan-Goa, 60% of the stations have correlation coefficients of more than 0.8 with the mean. Hence on the whole, the weekly mean rainfall of both the proposed zones can be considered to be a meaningful representation of most of the stations within the zone.

4.3. *Homogeneity*

We consider a sub-division to be homogeneous if the variation of the mean summer monsoon rainfall between the included stations is not very large *i.e.*, the standard deviation is much smaller than the mean. The values of the mean June-September rainfall of the current and proposed sub-divisions of Konkan & Goa and Madhya

Maharashtra based on station rainfall are given in Table 3. It is seen that while the mean rainfall in proposed Konkan & Goa sub-division is slightly reduced due to the addition of several stations of the current Madhya Maharashtra sub-division, this reallocation has led to a large reduction of the mean rainfall of the proposed Madhya Maharashtra sub-division from that of the current one.

Table 3 also shows the spread of the mean rainfall values of the stations within a zone/sub-division *viz*., the spatial standard deviation derived from the mean rainfall of the stations in each zone/sub-division. The standard deviation of the current as well as proposed sub-divisions of Konkan and Goa are seen to be much smaller than the mean. However, that of the proposed

TABLE 3

Number of stations, mean rainfall and spatial standard deviations for current and proposed sub-divisions of Maharashtra

SD	Konkan - Goa		Madhya Maharashtra	
	Current	Proposed	Current	Proposed
# Stations	30	36	85	79
Mean Rainfall (cm)	285.7	283.5	73.3	58.1
SD (cm)	61.9	81.3	70.7	23.8

Madhya Maharashtra is much smaller than the mean whereas the standard deviation of the current sub-division is comparable to the mean suggesting a far larger spread in the mean rainfall of the stations in the current sub-division of Madhya Maharashtra relative to the proposed one. Although the standard deviation of the proposed Konkan & Goa sub-division is a little higher than that of the current one, it is still only 28% of the mean. Thus, the proposed sub-divisions of Maharashtra can be considered to be homogeneous as well as coherent.

The current sub-division of Marathwada (which is also the proposed) has mean rainfall 69.6 cm and spatial standard deviation 8.6 cm. For Vidarbha, the mean rainfall is 87.1 cm and spatial standard deviation 22.2 cm. Thus, Marathwada and Vidarbha are homogeneous with respect to the mean summer monsoon rainfall.

5.   Meteorological sub-divisions of the other states

In this section, we assess the coherence and homogeneity of the seasonal rainfall of the meteorological sub-divisions of all the remaining states. For all the states except Tamil Nadu, the seasonal rainfall considered is the rainfall during Jun-Sep. Since for Tamil Nadu, the contribution of the Jun-Sep rainfall is 33% while that during Oct-Dec is almost 50%, we consider the rainfall during Jun-Dec. We could not include analysis for Puducherry, since no long period rainfall data is available.

As in the cases of Karnataka and Maharashtra, we have used as measures of coherence (*i*) correlation of the time series of the seasonal rainfall of each district with that of the sub-divisional mean rainfall (*ii*) pairwise correlations of seasonal rainfall for all the districts within the sub-division. In order to assess homogeneity of the sub-divisions, we consider a measure of the spread or the spatial variation of the district seasonal mean rainfall across the sub-division, *viz.*, the spatial standard deviation of the seasonal mean rainfall at all districts within the sub-division, A small standard deviation compared to the mean rainfall of sub-division suggests that the values of the mean rainfall at all the districts are closely clustered

about the sub-divisional mean. This implies that the sub-divisional mean can be considered to be a meaningful representation of the district mean values and the sub-division can be considered to be homogeneous.

Detailed information of these measures of coherence and homogeneity is given in Kulkarni *et al.*, 2020. We find that the spatial standard deviation of the mean summer monsoon rainfall of the districts in each sub-division is very small as compared to the mean sub-divisional rainfall for all the sub-divisions and hence all the sub-divisions of the states considered here can be considered to be homogeneous. For all the 25 sub-divisions considered here, the correlation of the seasonal rainfall at each district with sub-divisional mean rainfall is high for all sub-divisions, ranging from 0.46 for Assam to 0.9 for Rayalseema, being larger than 0.6 for several sub-divisions. We find that there is not a single case of negative correlation coefficient and the rainfall for each member district is significantly correlated with the sub-divisional rainfall for all the sub-divisions except for West Rajasthan. It is intriguing that for that sub-division, the correlation coefficient is higher than 0.6 for 90% of the districts. Hence, the mean correlation of the district rainfall with sub-divisional rainfall is high (0.75). This needs to be explored further.

We find that that for 19 out of the 25 sub-divisions, the correlation coefficients of all the districts are higher than 0.4. For the states of Bihar and Tamil Nadu, only 3% of the districts have correlation coefficient less than 0.4 whereas, for Assam and Meghalaya, Jammu and Kashmir, Orissa and Gangetic West Bengal, the correlation coefficient is less than 0.4 for over 10% of the districts, perhaps because of the presence of topography and our assumption that the number of sub-divisions in each state will not change. Thus, we may conclude that the sub-divisional mean anomaly is a meaningful representation of the anomalies of the districts in each of the sub-divisions.

The pair wise correlations among the district average rainfall for almost all the sub-divisions are found to be positive. For some fraction of the districts of Assam and Meghalaya and Gangetic West Bengal and a small fraction of the districts in Bihar, West Rajasthan and Jammu and Kashmir, the correlation coefficients are negative. The pairwise correlations of the vast majority of districts in each sub-division (except Assam and Meghalaya) are significant (5% level). Thus, on the whole, we can consider that the variation of the seasonal rainfall for districts within the sub-divisions of these states is coherent.

We may thus conclude that the sub-divisions of the states considered are homogeneous and reasonably coherent.
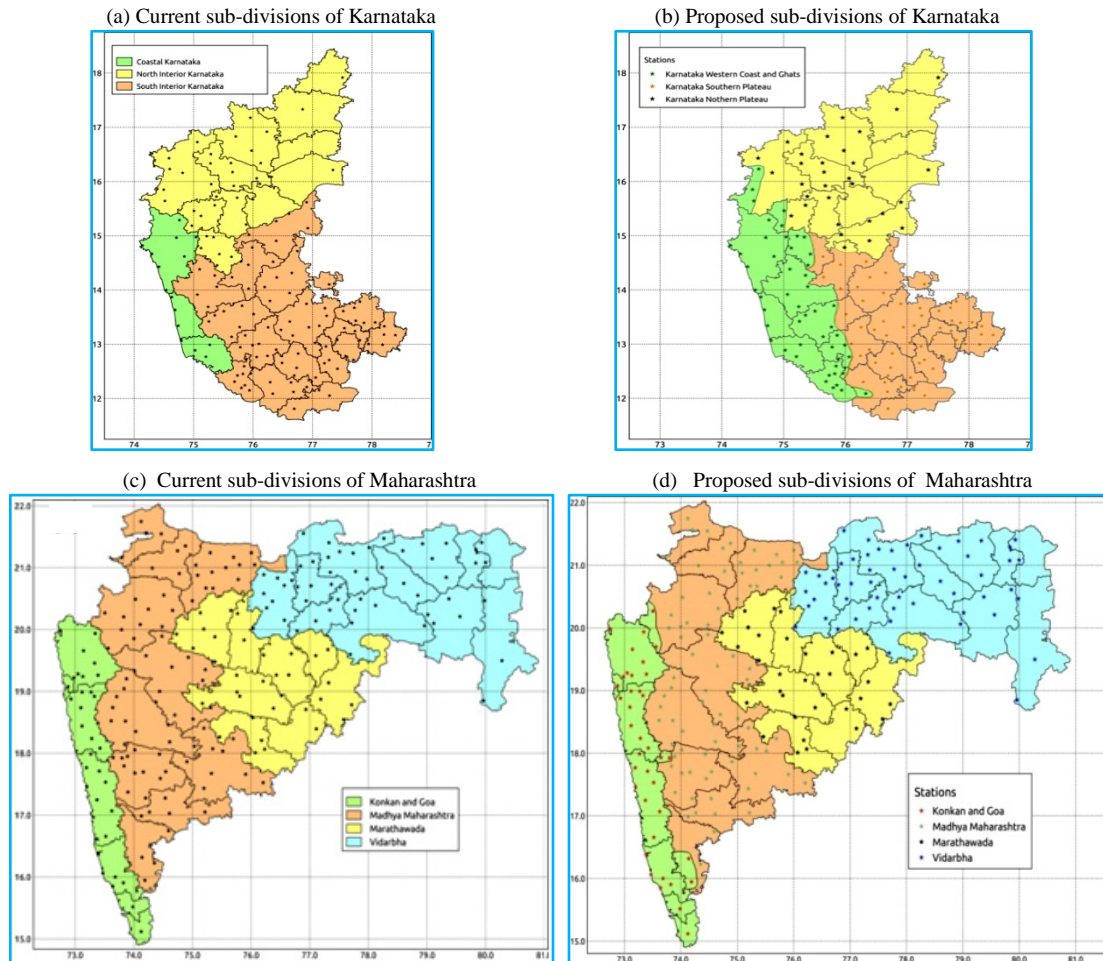
(a) Current sub-divisions of Karnataka

(b) Proposed sub-divisions of Karnataka

(c) Current sub-divisions of Maharashtra

(d) Proposed sub-divisions of Maharashtra

Figs. 15(a-d). Current and proposed sub-divisions of Karnataka (a and b) and Maharashtra (c and d)

6. Summary and conclusions

The mean rainfall and rainfall anomaly of the meteorological sub-divisions of India, on different time-scales, which is readily available from IMD, is extensively used for monitoring the progress of the monsoon as well as applications and research. As such, it is important to ensure that the sub-divisional mean rainfall and rainfall anomaly are a meaningful representation of the rainfall and the rainfall anomaly at districts/stations within the sub-division. Hence, the criteria to be satisfied for an appropriate delineation of a meteorological sub-division are high levels of coherence & homogeneity. Earlier studies have suggested that some sub-divisions of Karnataka and Maharashtra are neither coherent nor homogeneous. A committee was set up by the Ministry of Earth Sciences to review the demarcation of all the currently used meteorological sub-divisions and suggest changes, if required. The results of addressing this problem of determining new sub-divisions which are coherent and homogeneous, in place of those current ones which are not, are presented in this paper.

Coherence implies that the temporal variation of the seasonal rainfall at each district/station within the sub-division tends to be in phase so that the sub-divisional mean rainfall anomaly is at least similar in sign as the anomalies at most of the districts/stations within the sub-division. In this study, we have focused on seasonal rainfall, *i.e.*, June-September rainfall for all states except Tamil Nadu, for which June-December rainfall is considered. Measures of coherence are taken as (*i*) correlation of the time series of the seasonal rainfall of each district/station with that of the sub-divisional mean rainfall and a stricter measure, *i.e.*, (*ii*) pair wise correlations of seasonal rainfall for all districts/stations within the sub-division. In order to assess homogeneity of the sub-division with respect to the seasonal mean rainfall at each district/station in the sub-division, we consider the standard deviation of the climatological seasonal mean rainfall at all districts/stations within the sub-division, which is a measure of the spread or the spatial variation of the climatological seasonal mean rainfall across the sub-division. A small standard deviation relative to the

of Madhya Maharashtra to the modified version of Konkan and Goa, is coherent and homogeneous. Thus the suggested sub-divisions of Maharashtra are (*i*) modified version of Konkan and Goa (which could have been renamed as Konkan, Goa and Ghats but we have retained the old name) and (*ii*) modified version of Madhya Maharashtra and the current sub-divisions of (*iii*) Marathwada and (*iv*) Vidarbha. The current and proposed sub-divisions of Karnataka and Maharashtra (based on station data) are shown in Figs. 15(a-d).

It is important to note we recommend the use of coherent zones derived from station data rather than district data because, some districts, particularly along the eastern boundary of the current Konkan and Goa and coastal Karnataka sub-divisions, cannot be considered to be homogeneous and coherent. In objective determination of coherent zones, some stations of such districts get assigned to the coastal zone while others to interior region east of the Western Ghats. We recommend splitting of such districts into homogeneous coherent units for advice and action regarding the monsoon. In fact, in earlier era, the ghats region was included in the rainfall division along the West coast of present day Maharashtra and the division was named Konkan and the Ghats (Kelkar & Sreejith, 2020).

We find that the current meteorological sub-divisions of the other states are homogeneous and reasonably coherent with respect to seasonal rainfall and hence we suggest that they be retained as such. Thus, the proposed sub-divisions of the Indian region are as shown in Fig. 16. That most of the current meteorological sub-divisions are found to be homogeneous and reasonably coherent is remarkable since many of them closely correspond to the rainfall sub-divisions used by IMD since 1875 for Monthly weather review and Indian Daily Weather Report (Kelkar and Sreejith, 2020). That they have stood the test with modern measures of homogeneity and coherence is evidence of the tremendous insight into space-time variation of the rainfall over the Indian region of the pioneers such as Blanford and his successors, despite the scanty data available to them.

Acknowledgements

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