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Southwest monsoon rainfall in India: Part II – Principal components in temporal domain

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सार —कालिक प्रक्षेत्र (टी. मोड) में मानसून के मूल घटकों के विश्लेषण (पी सी ए) द्वारा दक्षिणी पश्चिमी मानसून की प्रावस्थाओं के वस्तुनिष्ठ निर्धारण का प्रयास किया गया है। इस पद्धति में दक्षिणी पश्चिमी मानसून के मूल घटकों (पी सी) के साथ साप्ताहिक वर्षा की गतिविधियों के संबंध का उपयोग किया गया है। इन संबंधों के आधार पर, समान स्थानिक पैटर्न वाले सप्ताहों के उपसमूहों की पहचान की गई है। सिनॉप्टिक चार्टों की सहायता से इन उपसमूहों के सिनॉप्टिक लक्षणों पर प्रकाश डाला गया है। निम्न दाब प्रणालियों के विशिष्ट लक्षणों के प्रत्येक मूल घटक (पी सी) के अनुरूप होने की स्थिति में पहले चार महत्वपूर्ण मूल घटक (पी सी) दक्षिणी पश्चिमी मानसून की चार प्रकार की सक्रिय प्रावस्थाओं के साथ संबद्ध हैं। अतः इस अध्ययन में दक्षिणी पश्चिमी मानसून की प्रावस्थाओं के वस्तुनिष्ठ निर्धारण द्वारा सिनॉप्टिक चार्टों की सहायता से मूल घटकों (पी सी) की व्याख्या की पद्धति अपनाने का सुझाव दिया गया है।

ABSTRACT. An attempt has been made towards objective identification of phases of the southwest monsoon by principal component analysis (PCA) in temporal domain (T-mode). The method utilises the relationship of weekly rainfall activities with principal components (PCs) of southwest monsoon. Based on this relationships, subgroups of weeks with similar spatial patterns have been identified. Synoptic features of these subgroups have been brought out with the help of synoptic charts. The first four significant PCs are associated with four kinds of active phases of the southwest monsoon when the low pressure systems have typical characteristics corresponding to each PC. Thus, the study suggests a method of interpretation of PCs with the help of synoptic charts by objective identification of phases of southwest monsoon.

Key words —T-mode principal component analysis, Objective identification of phases of southwest monsoon, Interpretation of principal components, Synoptic systems and principal components of southwest monsoon.

1. Introduction

The strength of southwest (SW) monsoon over land is assessed by the associated rainfall distribution. The monsoon is said to be 'strong' when well distributed above normal rainfall occurs over major parts of the country, whereas, it is described as 'weak' when the rainfall decreases mostly over the central parts of the country. For technical details one can refer to Rao (1976). But, during the weak phase of the monsoon also some parts, *viz*., northeastern and southeastern parts of the country, receive above normal rainfall and contribute towards overall rainfall activity.

In Part I of the study (Mazumdar 1996), it was indicated that some of the dominant PCs in spatial domain have typical weak monsoon rainfall distribution. Similar patterns also appeared in earlier EOF analyses of Indian monsoon data, undertaken by a number of monsoon researchers (*e.g.*, Kripalani *et al.*, 1991). Such results suggest that increased rainfall activity in some parts of the country (for example, northeastern, southeastern, etc.) during the weak phase of the monsoon also makes significant contribution towards overall rainfall during the season.

The assessment of the rainfall activity is mainly done in a subjective manner, and the associated features are examined to explore the relationship between the two. The broad-scale synoptic features associated with the active-weak phases of monsoon have been brought out by a large number of studies (*e.g.*, Alexander *et al.*, 1978, De *et al.*, 1984, De and Vaidya 1987, etc.). These studies have used extensive data sets to reveal the mean and anomaly patterns of broad-scale circulation of southwest monsoon in a systematic manner, but the assessment of the phases of the monsoon have been subjective. There have been no attempt to obtain an objective association between the rainfall distribution and synoptic features. In this study an attempt has been made to identify the phases of the monsoon in an objective manner and obtain the broad-scale synoptic features that constitute these epochs by the application of the principal component analysis in temporal domain.

Of late, the Principal Component Analysis (PCA) has been one of the powerful techniques to investigate the spatial and temporal variability of precipitation regime over a region. Most of the studies in recent years have applied PCA in spatial domain, *e.g.*, Bonell and Sumner (1992), Drosdowsky (1993a), etc. The application of PCA to explore features of temporal variability of rainfall has been made in a limited number of studies. Such exploration have either been attempted by analysis of the Principal Component (PC) scores obtained from S-mode PCA, *e.g.*, Eklundh and Pilesjo (1990), Murata (1990), etc., or by T-mode PCA, *e.g.*, Drosdowsky [1993 (a & b)], Richman (1983), etc.

The time series corresponding to dominant PCs, obtained from the PC scores after a S-mode analysis, have been analysed in a number of papers to study periodicity of variation of rainfall and to explore relationships between the PCs and atmospheric anomalies. Maheras (1988) and Ogallo (1989) identified principal moist and dry episodes over Western Mediterranean and East Africa, respectively, by utilising the PC scores. The time series of PC scores of southeastern Australia have been correlated with mean sea level pressure anomalies and southern oscillation by Whetton (1988). Pandzic (1988) correlated cyclone, anticyclone and frontal frequencies over Yugoslavia with time series of dominant PC scores. Opoku-Ankomah and Cordery (1993) studied the instability in southern oscillation-rainfall relationship over New South Wales (Eastern Australia) by correlating southern oscillation index with dominant PC scores. Drosdowsky (1993a) and Ogallo (1989) applied both S and T-modes of analyses over the same rainfall data of Australia and East Africa, respectively. A comparison of S and T-modes of analysis have been presented by Drosdowsky (1993a), who studied the relationship between the temporal variability of rainfall over Australia with southern oscillation and circulation anomalies (Drosdowsky 1993b). Murata (1990) applied spectral analysis on PC scores to reveal dominant periodicity of rainfall over Japan.

Utilising Indian seasonal total of southwest monsoon rainfall data, corresponding to meteorological subdivisions, Prasad and Singh (1988) analysed the time coefficient series obtained from EOF analysis in spatial domain. They correlated these time coefficients with a number of atmospheric and oceanic variables. Iyengar (1991) utilised the time coefficient series of EOFs of monthly rainfall of stations of Karnataka to group the years having similar spatial patterns.

In Part I (Mazumdar 1996), PCA was undertaken in S-mode to bring out features of spatial variability of the southwest monsoon rainfall. In this study, the same data set of weekly rainfall anomalies as utilised in Part I has been subjected to PCA in T- mode. The present work projects the differences in dominant PCs in spatial and temporal modes of analysis. The dominant PCs have been related to the broadscale synoptic patterns of SW monsoon in an objective manner and, as such, the study suggests an objective method of interpretation of PCs and an objective method of identification of phases of SW monsoon. In addition, such T-mode PCA provides necessary input to study regionalization of SW monsoon rainfall by cluster analysis which would be presented in a subsequent paper. The study would facilitate identification of the broad-scale synoptic patterns for use in statistical forecast models in the medium range.

2. Methodology

PCA can be applied in six basic operational modes depending on the manner in which the three dimensional data cube consisting of parameters, observations and variables is 'sliced' to produce a two dimensional data matrix for subsequent application of this eigen (technique (Richman 1986). Once the parameter (rainfall) is fixed, only two modes, *viz.*, S and T-modes are possible. In Part I PCA was applied in S-mode to study spatial variability of SW monsoon rainfall. In the present work it is applied in T-mode to identify dominant features of SW monsoon in the temporal domain. In this T-mode PCA, the observations (weekly rainfall anomalies) constitute the variables and the meteorological subdivisions constitute the individuals. The analysis provides a method to isolate subgroups of observations having similar spatial patterns. An outline of the mathematical theory of PCA has been given in part I.

The similarity between the spatial patterns in this T-mode analysis has been measured by utilising the correlation coefficients between the weekly rainfall anomalies. A number of methods has been suggested for the identification of number of significant PCs to be retained in PCA (Craddock and Flood 1969, Richman 1986). The sampling error test (North *et al.*, 1982) has been the method adopted for the selection of significant PCs for detailed study. In this test, the sampling errors for the eigenvectors $[d(2/N)^{1/2}]$ are compared with the separation in neighbouring eigenvalues, where '*d*' and '*n*' refer to the eigenvalue and the total number of records, respectively.

The elements of PC loading matrix represent the correlation coefficients between the interrelated old variables and the orthogonal/independent PCs. A high/low value of PC loading could be associated with overall strong/weak monsoon rainfall activity. Assuming an arbitrary threshold value of loading, subgroups of weeks having high/low loadings have been isolated. These subgroups could be related to strong/weak phases of SW monsoon. Associated broadscale synoptic patterns have been brought out by studying the synoptic features present in these subgroups, separately, corresponding to each significant PC. This suggests a method of objective interpretation of PCs and objective identification of phases of SW monsoon. Similar method

TABLE 1

Eigenvalues cumulative proportions of total variance and sampling errors of first ten principal components

PC No.	Eigenvalue (d)	Cumulative variance	Separation between eigenvalues (Δ d)	Sampling error $d(2/N)^{1/2}$
1	20.1	18.3	–	–
2	15.6	32.3	4.6	3.7
3	9.4	40.9	6.1	2.2
4	7.2	47.4	2.2	1.7
5	6.0	52.9	1.2	1.4
6	5.0	57.4	1.0	1.2
7	4.8	61.8	0.3	1.1
8	4.2	65.6	0.5	1.0
9	3.7	69.0	0.5	0.9
10	3.3	72.0	0.4	0.8

TABLE 2

The threshold values of loadings and total number of weeks that correspond to each PC for which the synoptic features have been studied

S.No.	PC No.	Threshold value	Total No. of weeks during 1977-86 (out of 110 weeks)
1	I	more than 0.5	14
2	I	less than -0.5	18
3	II	more than 0.4	24
4	II	less than -0.4	14
5	III	more than 0.35	10
6	III	less than -0.35	13
7	IV	more than 0.35	13
8	IV	less than -0.35	10

could also be applied for interpretation of PCs in the spatial domain where the PC scores obtained after S-mode PCA could be used to identify observation having high/low scores and synoptic charts used to obtain features associated with each PC.

3. Data utilised

Weekly rainfall departures from normal (WRDN) for all the 35 meteorological sub-divisions of India, from 1977 to 1986, during the weeks when the entire country was under the grip of SW monsoon, have been utilised for the PCA. The rainfall data have been the transpose of the input data matrix utilised in Part I where the preparation of this data set has been described. The Weekly Weather Reports published by the India Meteorological Department and synoptic charts have been consulted for the identification of synoptic features associated with each PC.

4. Results and discussion

In this T-mode PCA, the PCs have been extracted from the 110 x 110 correlation matrix. The elements of correlation matrix represent the correlation coefficients between the 110 weeks' overall rainfall distribution over the Indian region during the SW monsoon period. The eigenvalue, the variance explained (VE) and sampling error of first ten PCs are shown in Table 1. The first four PCs accounting a cumulative variance of about 47% have been found to be significant as per sampling error test (North *et al.*, 1982). These four PCs have been selected for detailed study. The threshold values of the loadings and the total number of weeks having loadings of more than the threshold values corresponding to each PC are indicated in Table 2.

The PC I (VE about 18%) has a loading of more than 0.5 over a total of 14 weeks. These 14 weeks had 13 intense low pressure systems, consisting of 11 depression (D)/deep depressions (DD) and 2 cyclonic storms (CS). Out of these thirteen intense systems, ten originated from north Bay of Bengal and adjoining areas and had westerly/west-north-westerly courses across Orissa and Madhya Pradesh (MP) affecting the western parts of Indian region. One each formed over MP (with a west-north-westerly course of movement), north Bay of Bengal (with a northerly course of

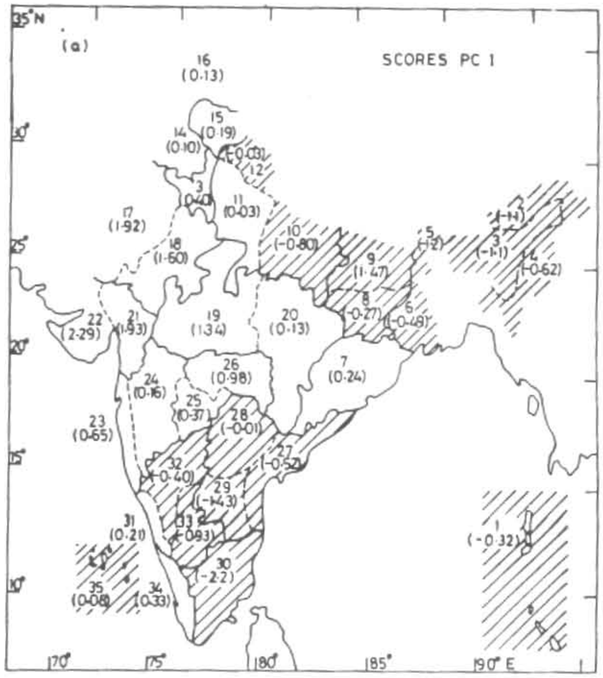

Fig.1(a). PC I scores plotted in parenthesis in each subdivision. Areas having negative scores are shaded

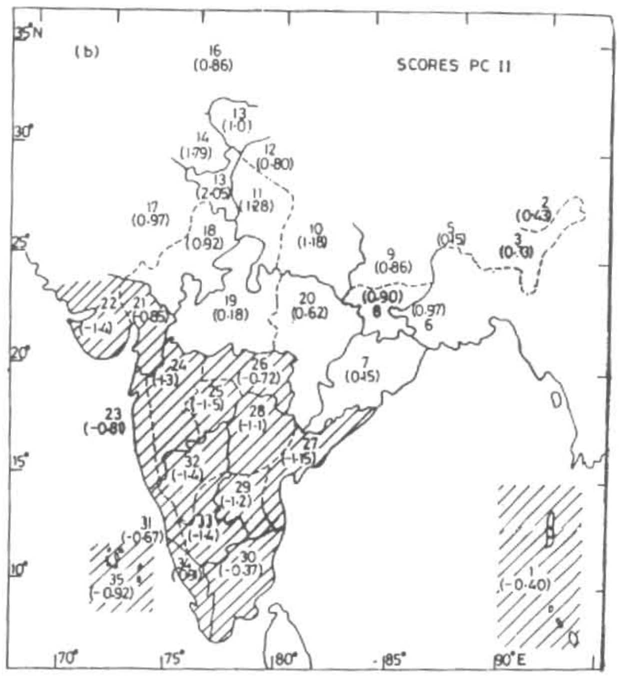

Fig.1(b). PC II scores plotted in parenthesis in each subdivision. Names of meteorological subdivisions are indicated in Fig.1(a). Areas having negative scores are shaded movement) and Saurastra region. These fourteen weeks also had eighteen low pressure areas (LOPARs). Twelve LOPARs formed over north Bay of Bengal and adjoining areas and had west-north- westerly courses. Three LOPARs formed over western parts of the country and one LOPAR each formed over MP (with a westerly course), Bangladesh and north eastern parts of the country. There were a total number of 32 cyclonic circulations (CCs) that affected the western and northwestern parts of Indian region. A synoptician identifies these as either Mid-Tropospheric Cyclones (MTC) or small circulation embedded in the westerlies over northwest India. Most of these CCs were formed *in-situ* over the western parts of the country and had northeasterly movements. In addition, the low level trough off the west coast of India had been active in almost all of these weeks.

There have been 18 weeks having PC I loading of less than -0.5. These negatively correlated weeks' correspond to the weak phase of the monsoon. Examination of synoptic systems present during these weeks confirm the same. On a number of occasions the western half of the monsoon trough was absent or was close to the foothills and the eastern half was lying close to the foothills of the Himalayas. There were a large number of westward moving systems in lower and middle tropospheric levels affecting southern parts of peninsular India and eastward moving systems in westerlies affecting northern parts of the country.

The distribution of scores of PC I (Fig.1a) conform with the general synoptic patterns as described above. The high scores are noticed over the subdivisions located in the western part of the country which are low rainfall areas. The movement of systems from east, *in-situ* formation and systems in westerlies have been the low pressure systems affecting these region. Enhanced rainfall activity resulting from these systems in these regions dominated the overall rainfall activity during the SW monsoon. Low scores in the southeastern parts of the peninsula and northeast India could be noticed which are the regions receiving less than normal rainfall during active monsoon epochs with intense synoptic systems generally moving along the monsoon trough in westerly/west-northwesterly courses.

The PC II (VE about 14%) has a loading of more than 0.4 over 24 weeks. There were 11 D/DD during these weeks. Five D/DD, formed over the north Bay of Bengal and adjoining areas with four having northwesterly courses and one a westnorthwesterly course of movement. Out of remaining six D/DD, three formed over Uttar Pradesh (UP), two over north MP and one over south MP. A total of 25 LOPARs were found in these weeks. Thirteen LOPARs formed over the north Bay of Bengal and adjoining land areas with northwesterly courses. The remaining LOPARs formed over the land areas of MP, Bihar and UP. A large number of CCs in westerlies (64) also affected the northwestern parts of the country.

Fourteen weeks have PC II loadings of less than -0.4. During these weeks the western half of the monsoon trough remained close to the foothills of the Himalayas on a number of occasions. There were also a number of low pressure systems which formed off Orissa/Andhra Pradesh (AP) coasts with a short life spans and troughs in lower levels off the coasts of AP and Tamil Nadu (TN).

The scores of PC II (Fig.1b) have a general north-south pattern. High positive values are seen over UP, Bihar, Punjab, Haryana, and Himachal Pradesh. Low scores are in the southern states of AP, Karnataka and Maharashtra. The general distribution of these scores matches well with the synoptic patterns described above. The general north-westerly movement of low pressure systems originating from the Bay of Bengal and systems in the westerlies affecting the northern/northwestern parts of the country resulted in positive scores in the northern half of the country.

The PC III (VE 9%) shows high loading of more than 0.35 over 10 weeks. Six D/DD and ten LOPARs were noticed in these weeks. Most of these low pressure systems formed over the land areas of UP and MP. These showed either very little movement or were stationary. Trough off the west coast of India were also present on a number of occasions. The thirteen weeks associated with low loadings of less than -0.35 had a large number of systems in westerlies affecting the northern and northwestern parts and westward moving troughs affecting southern parts of the country. The monsoon trough had been close to the foothills of the Himalayas on many days.

The distribution of PC III scores shows high scores over the central parts of the country, UP, Bihar and over the western coast of the country and low scores over northern, northwestern and northeastern parts of the country and over the southeastern parts of peninsula (Fig.1c). This distribution is also in conformity with the general synoptic features outlined above. *In- situ* formation of low pressure areas over the land areas of UP and MP along with off-shore (west coast) troughs have resulted in producing such distribution of the PC III scores. Shorter track of the disturbances and *in-situ* development/dissipation of system in this type distinguish it from PC I and II, as yet another mode of active monsoon epoch.

The thirteen weeks having PC loading of more than 0.35 for PC IV (VE 7%) had nine D/DD and seventeen LOPARs. Most of these low pressure systems formed over the north Bay of Bengal and adjoining areas and had short life spans. These systems had appreciable southward tilt with height. There were also a large number of systems in the westerlies affecting the northern parts of the country.

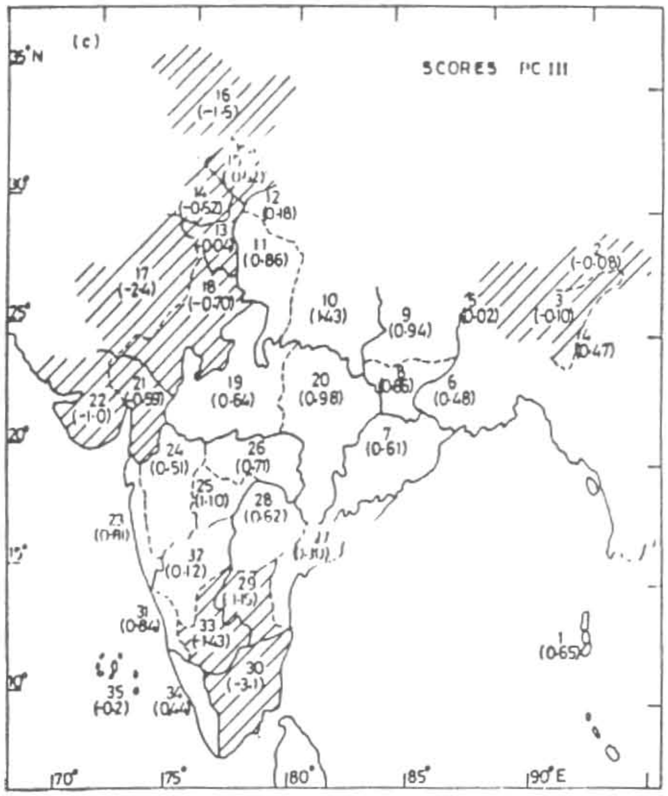

Fig.1(c). PC III scores plotted in parenthesis in each subdivision. Names of meteorological subdivisions are indicated in Fig.1(a) Areas having negative scores are shaded

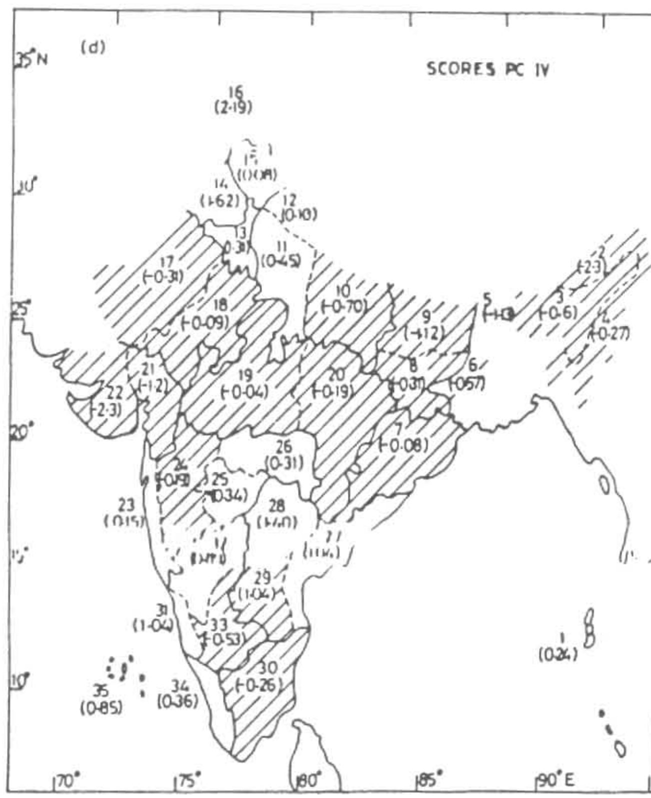

Fig.1(d). PC IV scores plotted in parenthesis in each subdivision. Names of meteorological subdivisions are indicated in Fig.1(a). Areas having negative scores are shaded

The off-shore troughs (west coast) were also present on many occasions.

The ten weeks with very low loadings (less than -0.35) associated with PC IV had a large number of westward moving systems affecting southern parts of the country. The monsoon trough was close to the foothills of the Himalayas on many occasions and only the eastern half of the trough was active.

The scores of PC IV (Fig.1d) have high values over northern parts, central parts of the peninsula and west coast of the country and low values over the northeastern and the western parts of the country. Westerly systems in the north, short-lived weak low pressure systems with high southward tilt with height and off-shore (west coast) troughs are associated with such distribution of PC IV scores.

The PCs obtained in Part I have been quite different from the PCs in this analysis. While the PC I in spatial domain resembles the overall mean pattern, the PC I of temporal domain has been associated with the most active phase of the SW monsoon. The weeks related to PC I had on an average one intense low pressure system of the intensity of D or DD or CS and one and half LOPAR and about 3 CCs per week. The intense low pressure systems mostly originated from the north Bay of Bengal and had long west-northwesterly course of movements across the country. The western and the northwestern parts of the country were affected by a large number of systems in westerlies, CCs and LOPARs which mostly developed *in situ*. The off-shore (west coast) troughs were also present. The PC II of S-mode has been similar to PC I of this analysis.

The PC II of this PCA is associated with another type of active phase of the SW monsoon. There had been on an average half D/DD and one LOPAR with northwesterly movements per week associated with weeks having moderately high loadings, with PC II. A large number of systems in westerlies also affected northwestern parts of the country during these weeks.

The PC III has been related to yet another kind of active phase of monsoon. The weeks associated with PC III were characterised by almost stationary low pressure systems forming over land areas of UP and MP along with off-shore troughs (west coast). While weeks associated with PC IV had low pressure systems originating from the Bay of Bengal having short life spans with a large southward tilt with height and systems in westerlies affecting northern parts. The PC IV of this analysis resembles the PC IV of S-mode.

The synoptic features associated with the weak monsoon situations corresponding to each PC could not be effectively differentiated. However, the salient features of each PC included:

(*i*) A monsoon trough close to the foothills and/or,

(*ii*) A monsoon trough with only eastern end seen at the lower levels,

(*iii*) Many systems in the mid-latitude westerlies over north/northwestern parts of the country, and

(*iv*) Low pressure systems moving in the lower/middle tropospheric levels over the peninsula along 10-15° N latitude.

5. Conclusions

The T-mode PCA has been applied to study the PCs in temporal domain. The PCs have been interpreted with the help of actual conditions available in the synoptic charts after identifying strong/weak phases of SW monsoon by an objective manner. The study suggests a method of interpretation of PCs by utilising synoptic charts.

The salient features of the study are found to be useful for synoptic diagnostic studies and can be of use in developing synoptic models. These are briefly as follows:

(*i*) The PC I has correspondence to the most active phase of the SW monsoon when intense low pressure systems (including depressions/deep-depressions/cyclonic storms) originating from the Bay of Bengal had westerly/west-northwesterly course of movements affecting the low rainfall western most part of the country. In addition, *in-situ* formation of low pressure systems in the western/northwestern parts of the country and movement of systems in midlatitude westerlies affecting the western/northwestern parts of the country, and troughs in lower levels off the west coast are associated with the PC.

(*ii*) The PC II has been related to another type of active phase of the SW monsoon. When the depressions and low pressure systems originating from the Bay of Bengal had northwesterly movements and a large number of systems in westerlies affected north-west India.

(*iii*) The PC III has been related to yet another kind of active phase of the monsoon. It has been characterised by *in-situ* formation of low pressure systems over the land areas of UP and MP. The off-shore troughs (west coast) is also found to be significant component of this type.

(*iv*) The PC IV has association with short-lived low pressure systems originating from the Bay of Bengal with a large southward tilt with height and systems in the mid-latitude westerlies affecting northern parts.

The weak monsoon situation corresponding to these four PCs is not so clearly distinguishable. However, in association with each PC the following features are noticed:

(*i*) The monsoon trough lies close to the foothills of the Himalayas.

(*ii*) Westward moving low pressure systems form and move in the southern parts of the country.

(*iii*) Low pressure systems and circulation having general eastward movements affected the northern parts of the country.

The PCs of S-mode and T-mode have been found to be different. The PC I and PC IV of T-mode have resembled with PC II and PC IV of S-mode, respectively.

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