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SEASONAL VARIATIONS OF THE RELATIONSHIP BETWEEN SOME ENSO PARAMETERS AND INDIAN RAINFALL

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Canonical correlation analysis is used to examine the seasonal relationship between ENSO and Indian rainfall by analysing their 12 monthly values for an 80-year period. Three ENSO indices are considered. These ENSO indices are the Darwin surface pressure, the sea-surface temperature of the central and eastern equatorial Pacific, and rainfall of central equatorial Pacific islands (hereafter denoted as DSP, SST, and RAIN respectively). The ENSO indices are also analysed for relationships between themselves.

The analysis reveals that the seasonal variations of these ENSO indices are highly intercoupled with no lag. These indices show the minimum association during April and the maximum after the monsoon season. Further, the seasonal variation of the Indian rainfall is found to be better associated with the seasonal variations of SST as compared with that of DSP or RAIN. This association is at its strongest during the period August–October. An apparent reversal in the relationship between ENSO and Indian rainfall is also observed from summer to winter. The warm ENSO years are associated with weak summer monsoon rainfall and at the same time high winter monsoon rainfall.

KEY WORDS; ENSO; Indian rainfall; canonical correlation analysis.

INTRODUCTION

The sea-surface temperature exerts a significant control over the atmospheric circulation, the remarkable example of which is the El Niño – Southern Oscillation (ENSO) phenomenon. The ENSO is a complex phenomenon involving the ocean–atmospheric interaction on a short-term climatic scale. The most well-known atmospheric component of the phenomenon is the Southern Oscillation, representing the sea-saw of the pressure variation between the Indonesian–Australian and the equatorial South Pacific regions. When the pressure is high over the south-east Pacific it is low over the Indonesian region. The trade winds in this case are stronger and an upwelling is observed off the west coast of South America. In an opposite situation, a warming of the sea-surface temperature over the central through eastern equatorial Pacific is noted. This anomalous warming is known as the El Niño and the combined atmospheric-oceanic phenomenon is known as ENSO.

Although the relationship between the Southern Oscillation and Indian rainfall was noted during the early part of the present century, a considerable revival of the interest in the relationship is found during recent years. The occurrence of deficient monsoon rainfall during the years of increased Line Islands (central Pacific) rainfall was noted by Sikka (1980). Pant and Parthasarathy (1981) and Bhalme *et al.* (1983) found significant correlation between the Indian monsoon rainfall and the Southern Oscillation index. Rasmusson and Carpenter (1983) and Ropelewski and Halpert (1987) found less rainfall over the Indian region during the extreme negative phase of the Southern Oscillation, i.e. El Niño years. Later, Ropelewski and Halpert (1989) noted an increase in the Indian rainfall during the years of extreme positive phase of the Southern Oscillation. Angell (1981) found a relationship between the Indian monsoon rainfall and the following December–January equatorial sea-surface temperature from the date line to the South American coast. Barnett (1983, 1984a,b) has shown that the warm episodes in the equatorial Pacific are accompanied by wind and pressure fluctuations over the tropical Indian Ocean as well.

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Shukla and Paolino (1983) found a change of sign in the relationship between the Darwin surface pressure and the Indian rainfall from January to April. Hence, he suggested the Darwin surface pressure tendency from January to April as a better predictor of the Indian monsoon rainfall than the magnitude of the pressure in an individual month. Subsequently, Shukla and Mooley (1987), Hastenrath (1988) and Prasad and Singh (1992) used this tendency as one of the predictors in their prediction schemes for the Indian monsoon rainfall.

The above studies have, generally, related the seasonal (June to September) Indian monsoon rainfall with the monthly or seasonal ENSO indices. The temporal (annual) evolution of the relationship between the monthly Indian rainfall and the ENSO indices seems to have received little attention. In the present paper, we study the temporal evolution of relationship between the three different ENSO indices and of these ENSO indices with the Indian rainfall by analysing their monthly variables. Although such an analysis may also be carried out by the use of simple correlation technique, we use here an advanced multivariate technique, namely canonical correlation, which effectively and optimally summarizes the relationship contained in a large sample of the correlations and lag correlation coefficients. The technique has been used previously and discussed by Glahn (1968), Barnett (1981, 1983), Nicholls (1987) and Bretherton *et al.* (1992) among others. We provide a brief discussion of the technique in section 2. The data utilized as well as the design of the present study is also described in that section. The results are discussed in section 3 and the important conclusions are presented in section 4.

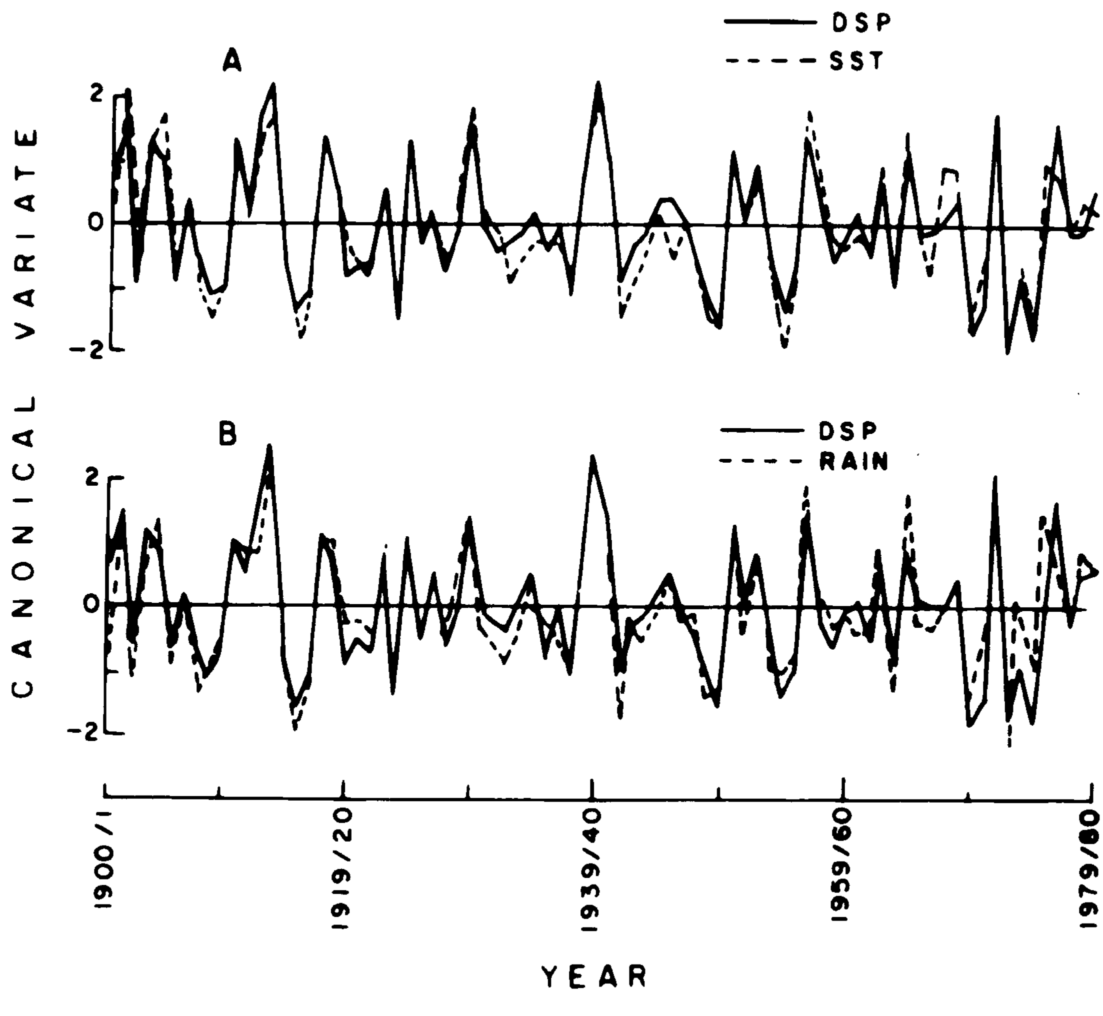

Figure 1. Time series of the first canonical variates for the pair of parameters analysed: (A) DSP–SST and (B) DSP–RAIN.

DATA AND METHODOLOGY

2.1. Data

The monthly rainfalls of 306 stations uniformly distributed over the contiguous area of India for the period 1900–1980 (Parthasarathy *et al.*, 1987) form the basic rainfall data used in this study. The area-weighted average for the whole of contiguous India (IRN) has been formed by weighting each rainfall station by the area of the administrative district in which the rainfall station lies. Some of the ENSO indices considered in the study are Darwin sea-level pressure (DSP), sea-surface temperature (SST) of the central and eastern equatorial Pacific, and rainfall (RAIN) of the central equatorial Pacific islands. Although the difference of the surface pressure between Tahiti and Darwin is a commonly used index in the study of the interannual variability and the teleconnection of the ENSO, we use here the pressure at Darwin as an index of the changes in the atmospheric circulation related with the ENSO. This is because we have a consistent accurate record of the surface pressure at Darwin for a sufficiently long period. The pressure at Darwin shows a stronger relationship with the Indian monsoon rainfall compared with the pressure at Tahiti. The significant relationship between the pressure at Darwin and the Indian monsoon rainfall has been demonstrated by Shukla and Paolino (1983) and Shukla and Mooley (1987). Hence, we feel that the consideration of the Darwin surface pressure instead of the pressure difference between Tahiti and Darwin will not affect the results of the present study. The data of DSP are obtained from the Climatic Analysis Centre, USA and that of SST and RAIN are obtained from Wright (1989). Wright's SST index is defined as the

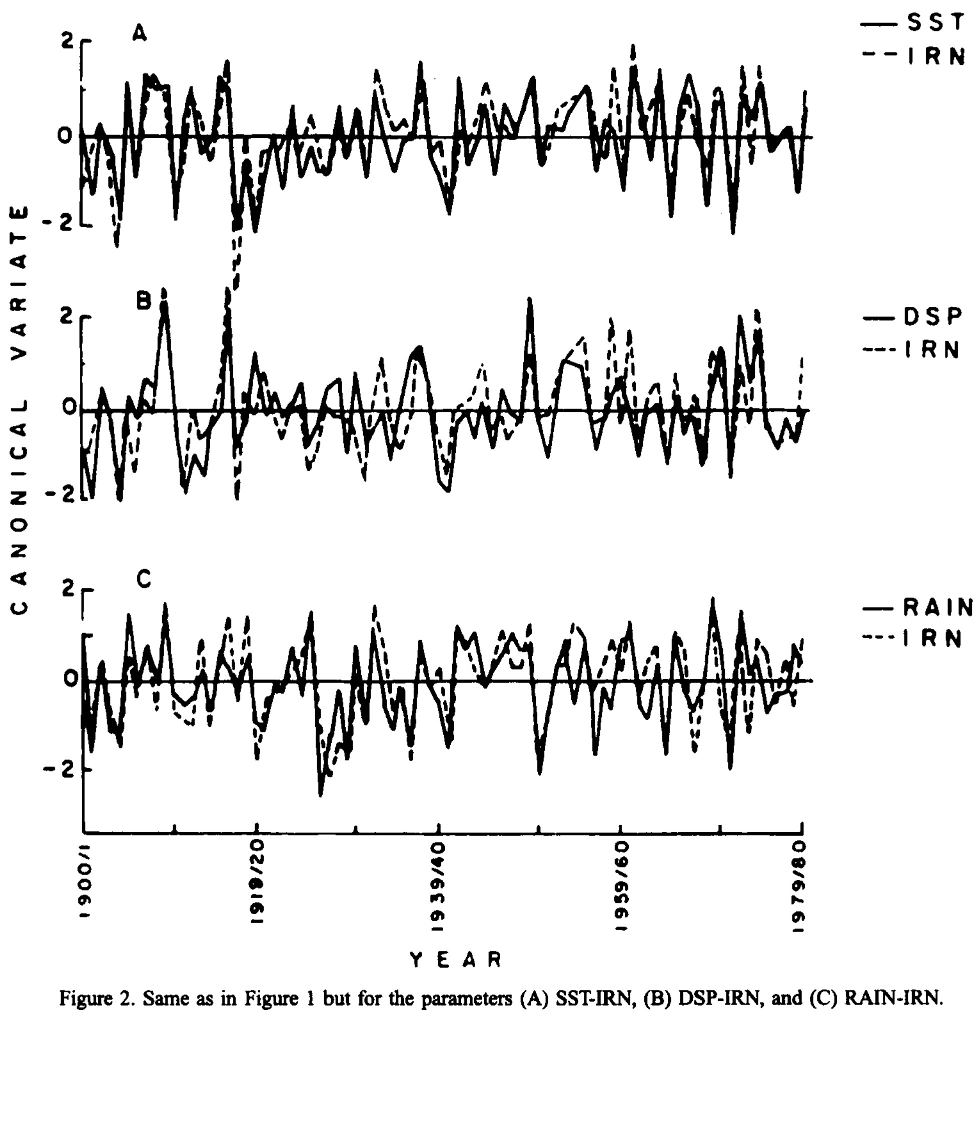

Figure 2. Same as in Figure 1 but for the parameters (A) SST-IRN, (B) DSP-IRN, and (C) RAIN-IRN.

Table I. The first (a) and second (b) canonical correlations and the first canonical vectors for different pair of parameters analysed· Canonical correlation significant at (*) 1 per cent and (**) 0·1 per cent levels determined using the Bartlett (1946) test· The 5 per cent levels of significance, for Monte Carlo procedure, are 0·71 and 0·68 for the first and second canonical correlations (respectively)·

No	The parameters considered	Canonical correlations		Canonical Vectors for Months;											
				April	May	June	July	August	September	October	November	December	January	February	March
1	DSP	a	0·92**	0·02	0·18	− 0·10	0·06	− 0·0	0·19	0·06	0·26	0·13	0·16	0·23	0·23
	SST	b	0·72*	− 0·01	− 0·01	0·09	0·30	− 0·13	− 0·15	− 0·18	0·61	− 0·03	0·35	0·06	0·16
2	DSP	a	0·91**	− 0·03	0·23	− 0·07	− 0·06	0·20	0·13	0·14	0·15	0·23	0·19	0·06	0·22
	RAIN	b	0·67	0·08	0·07	0·02	0·29	− 0·12	− 0·02	0·32	0·15	0·10	0·33	− 0·06	0·13
3	SST	a	0·82**	0·22	− 0·82	0·58	0·72	− 0·87	− 1·12	− 0·12	0·87	− 0·33	0·31	− 0·48	0·27
	IRN	b	0·66	− 0·12	0·01	0·53	0·47	0·39	0·24	− 0·06	− 0·27	0·13	− 0·47	− 0·28	0·14
4	DSP	a	0·73*	− 0·53	0·09	− 0·10	0·10	− 0·39	− 0·10	0·46	− 0·23	− 0·28	− 0·33	− 0·16	0·17
	IRN	b	0·65	− 0·19	− 0·32	0·59	0·12	0·05	0·25	0·29	− 0·17	− 0·22	− 0·04	− 0·48	0·23
5	RAIN	a	0·71*	0·36	− 0·01	− 0·21	− 0·33	0·59	− 1·06	0·67	− 0·09	0·19	− 0·47	− 0·53	0·47
	IRN	b	0·65	− 0·23	0·11	0·24	0·10	0·74	0·40	− 0·32	0·04	0·0	− 0·02	− 0·22	0·43

Table II. Individual and average variances explained (in per cent) by the first canonical mode for each pair of the parameters analysed.

Number	Individual variance	Months												Average variance
		April	May	June	July	August	September	October	November	December	January	February	March	
1	SST	7	40	28	37	59	67	38	45	52	46	42	22	44
	IRN	0	0	15	19	24	27	19	7	0	8	5	1	10
2	DSP	49	15	26	29	55	24	21	40	34	28	26	3	29
	IRN	4	0	21	2	7	23	34	4	7	0	21	3	10
3	RAIN	0	1	8	28	4	48	17	28	30	41	24	2	19
	IRN	5	3	6	2	52	27	4	0	0	2	4	10	9

mean sea-surface temperature over the region 6–2°N and 170–90°W, 2–6°S and 180°–90°W, and 6–10°S and 150–110°W; and RAIN is defined as the mean rainfall of six stations close to the Equator in the longitudinal range, 160°W–150°W (for more details, see Wright, 1989). These data are normalized by subtracting the monthly long-term mean and dividing by the monthly standard deviation to remove the annual cycle. The 12 monthly standardized values for a period of 80 years (1900–1980) are considered in the canonical correlation analysis.

2.2 Principle and method of canonical correlation analysis

Nicholls (1987) has provided the basic details of the principle and method of computations involved in the canonical correlation analysis relevant to the present study. Recently, Yaglom (1990) and Bretherton *et al.* (1992) have given a more extensive review of the technique. We provide here only the limited details, sufficient for understanding the analysis procedure and the terminology used in the following.

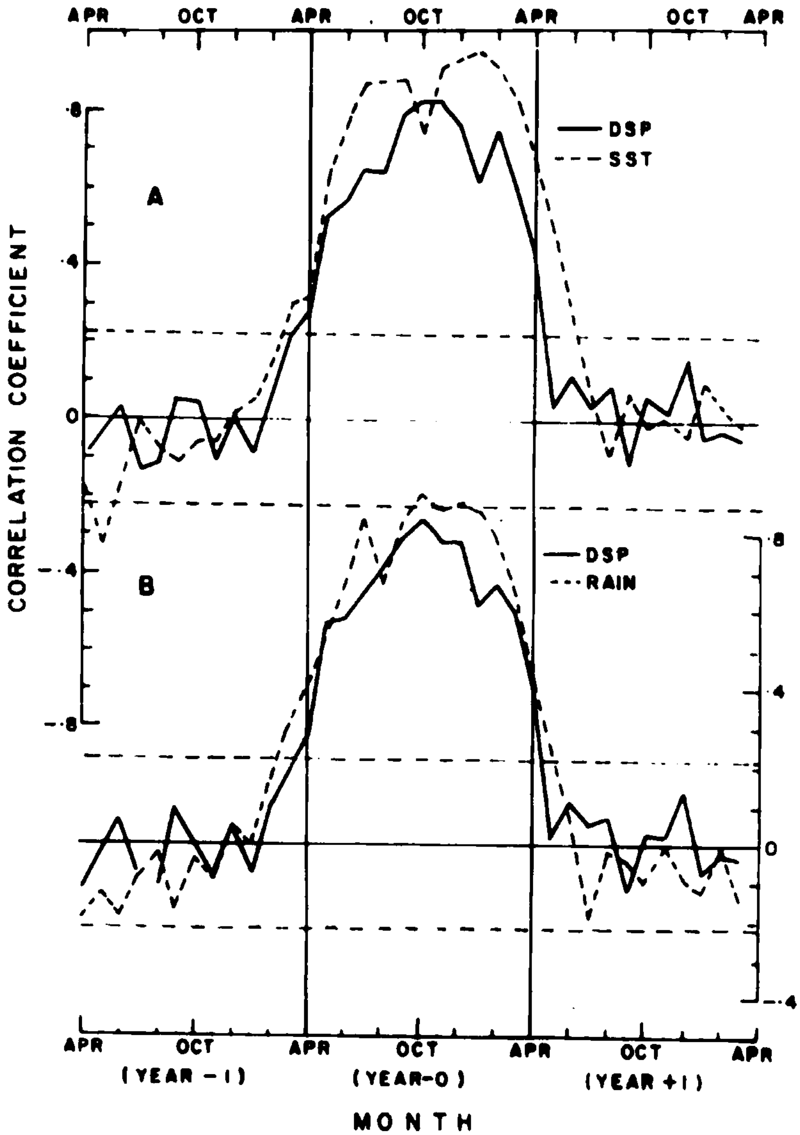

Figure 3. Correlation coefficients between the first canonical variates and their corresponding original monthly variates for year -1, year 0, and year + 1 for the pair of parameters analysed: (A) DSP–SST and (B) DSP–RAIN. Horizontal dashed lines show correlation coefficient significant at the 5 per cent level.

Consider two vector variables x and y of dimension p and q, with $q \leq p$. The canonical correlation analysis derives the new variables as a linear combination of the original vector variables, such that the correlation between them (the new variables) is maximized. These new variables are known as the canonical variates. Let U and W be the first canonical variates, such that

$$U = a_1'X \quad \text{and} \quad W = b_1'Y \tag{1}$$

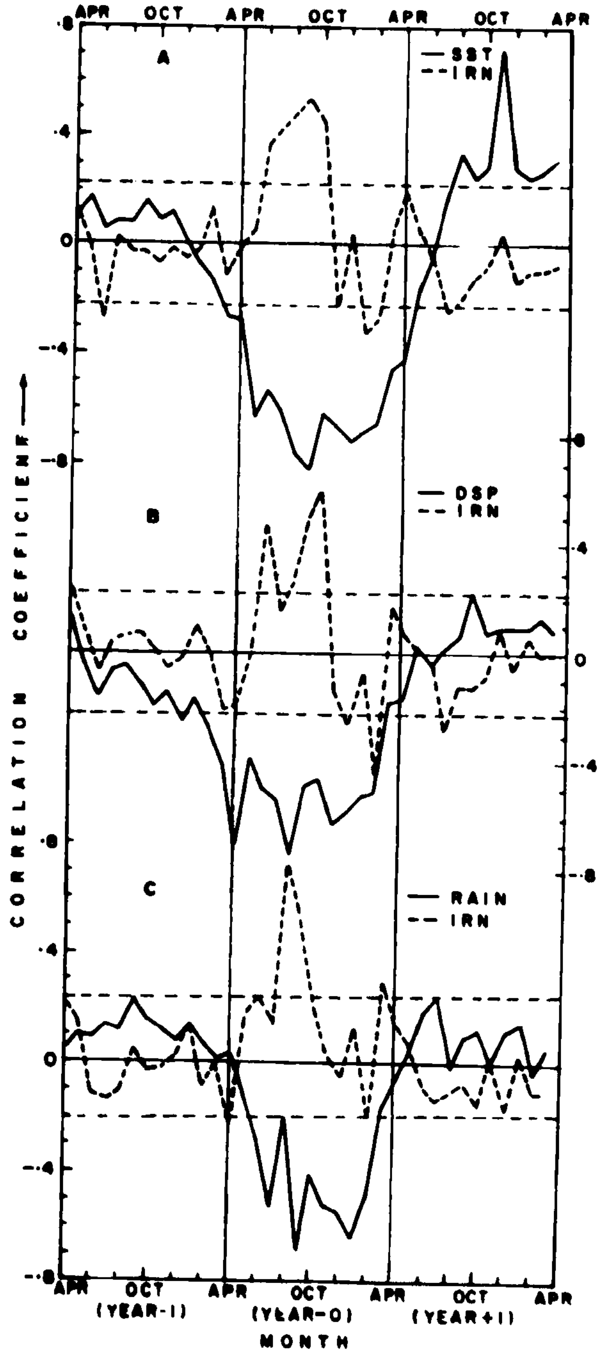

Figure 4. Same as in Figure 3 but for the parameters (A) SST–IRN, (B) DSP–IRN, and (C) RAIN–IRN.

where

$$M_x = 0, S_x^2 = 1 \quad \text{and} \quad M_y = 0, S_y^2 = 1 \tag{2}$$

The objective is to determine the vectors $\boldsymbol{a}_1$ and $\boldsymbol{b}_1$ such that the correlation between U and W given by

$$\varrho_1 = \frac{1}{N}\sum_{I+1}^{n} U_i W_i \tag{3}$$

is maximized Where N is the number of observations. This leads to eigenvalue solutions of a complicated characteristic equation given by;

$$(\mathbf{R}_{22}^{-1}\mathbf{R}_{21}\mathbf{R}_{11}^{-1}\mathbf{R}_{12} - \lambda_j I)b_j = 0 \tag{4}$$

with the normalization constraint of

$$\boldsymbol{b}_j'\boldsymbol{R}_{22}\boldsymbol{b}_j = 1 \tag{5}$$

where λ_j are the eigenvalues, $\mathbf{R}_{12}$ is the cross-correlation matrix between X and Y, and $\mathbf{R}_{21}$ is its transpose. $\mathbf{R}_{11}$ and $\mathbf{R}_{22}$ are the correlation matrices of X and Y respectively. The first canonical correlation is obtained as the square root of the maximum eigenvalue of the characteristic equation (4) and the associated eigenvector ($\mathbf{b}_1$) is the first canonical vector of Y. The corresponding canonical vector of X is obtained from the relation (Anderson, 1958):

$$\mathbf{a}_1 = (\mathbf{R}_{11}^{-1}\mathbf{R}_{12}\mathbf{b}_1)/\sqrt{\lambda_1} \tag{6}$$

The other canonical correlations and canonical vectors corresponding to the other eigenvalues and eigenvectors of equation (4) are similarly determined. The j canonical variates U_j and W_j are obtained by substituting the canonical vectors $\mathbf{a}_j$ and $\mathbf{b}_j$ in equation (1). The significance of the canonical correlations is tested by applying Bartlett's (1946) classical confirmatory test. The traditional significance test sometimes can give rise to misleading results of the canonical correlations. Hence, the significance is further confirmed using the Monte Carlo procedure described in section 3.1. The canonical structure patterns (Nicholls, 1987) are determined by correlating the canonical variates with their corresponding original variables. These patterns provide the insight into the temporal evolutions of the relationships between the variables analysed.

2.3. *Design of analysis procedure*

As mentioned above, in the canonical correlation analysis a set of p variables x is optimally related with a set of another q variables y. The analysis design followed here, for investigating the evolution of the temporal relationship amongst two sets of variables, is similar to that the Nicholls (1987) who considered 11 bimonthly periods as 11 variables. The 12 monthly values of the ENSO indices or the Indian rainfalls here make the 12 variables and therefore, the number of variables p and q, mentioned above, are each equal to 12. These 12 variables correspond to the period April through to March, rather than the period January through to December, allowing the month of the strongest autocorrelation in ENSO indices to fall in the middle of the period.

The canonical correlations and canonical vectors corresponding to the eigenvalues and eigenvectors of equation (4) are computed. The canonical variates (U_j, W_j) are obtained by the linear transformation of the original vector of observations on the canonical vectors (see equation 1). The canonical correlations, representing the strength of the relationship between the corresponding canonical variates, are tested for their significance as mentioned in section 2.2. The canonical structure patterns are derived by correlating the canonical variates with their corresponding original monthly variables.

RESULTS

3.1. *Canonical correlations*

In order to quantify the overall strength of the relationships between the monthly varying indices of the ENSO and the Indian rainfall, canonical correlation analyses are performed with these parameters using their 12 monthly values. The different sets of canonical correlations computed are: two sets for the relationships between the ENSO indices (namely, (i) DSP–SST and (ii) DSP–RAIN) and three sets for the relationships of each of these ENSO indices with the Indian rainfall. The significance of the canonical correlations is tested by the classical confirmatory test and also by a Monte Carlo procedure. In the latter method, the canonical correlation analyses are performed repeatedly (over 100 times) each time using the resampled data. The level of significance of the canonical correlation for each canonical mode is determined based on these trials and is compared with the canonical correlation of the actual data. The significant values at the 5 per cent level in the present case are found to be 0·71 and 0·68 for the first and second canonical correlations respectively.

The seasonal variations of these ENSO indices seem to be highly intercoupled, because the first canonical correlation in each case is found to be highly significant (Table I). Between the ENSO indices the highest intercoupling is found between DSP and SST as compared with DSP and RAIN. The second canonical mode is also found to be significant in case of DSP–SST. This shows that generally two canonical modes may be sufficient to describe the seasonally evolving relationship between the ENSO indices examined. The second canonical mode, however, could not be found significant in the case of DSP–RAIN. This shows that RAIN is contaminated with more random noise and can be considered a less reliable indicator of an ENSO phenomenon.

The overall seasonal variations of these ENSO indices also appear to be intercoupled with that of the Indian rainfall (as the first canonical mode is found significant in each of these cases, Table I). It also appears from the table that the best association of the Indian rainfall is with SST. We will see later on that the average and the individual (monthly) variances explained are also found to be high in this case.

Table I also lists the first canonical vectors (i.e. $\mathbf{a}_1$ and $\mathbf{b}_1$ of equation 1, section 2.2). The variables analysed were for the months April through to March, as such these canonical vectors also correspond to these months. The canonical vectors indicate (Bretherton *et al.*, 1992) which values (here months) are dominant in forming the first canonical variates (which have the maximum correlation coefficient but explain a smaller fraction of the covariance between the two sets of variables as compared with the other similar method).

3.2. Canonical variates

The canonical variates, which are the linear combinations of their original vector variables, are maximally correlated with the each other. The first set of canonical variates have the highest correlation among all the other pairs of canonical variates. Each value of the canonical variates corresponds to the observation time (here the years) of the original variables. Accordingly, the canonical variates can be plotted as the time series corresponding to the observational time of the original data. These canonical variates, portraying the relationship amongst the different ENSO indices and among the ENSO–Indian rainfall analysed, are presented in Figures 1 and 2, respectively. The agreement in the interannual variations among these ENSO indices and among the ENSO–Indian rainfall can be seen from these figures. The better intercoupling between the Indian rainfall and SST, as indicated in the magnitude of their canonical correlation (Table I), is also seen from these figures.

The correlations of the original variables with their corresponding first canonical variates are also determined. The squared correlations indicate how much of the variance in the variables can be accounted for by a particular canonical variate. Summing the squared correlations for a particular canonical variate and dividing by the number of variables provides the average variance in the variable set accounted for by a particular canonical variate. The individual and average variances explained by each of the canonical variates for the three cases of the ENSO–Indian rainfall analyses are presented in Table II. The individual variances explained are generally large during August and September in each case. The first canonical variate of SST–Indian rainfall explains a larger average or individual variance compared with the other two cases. The average variance explained by the first canonical variates of the Indian rainfall in all these cases is found to be of the order of 10 per cent.

Apparently, the three ENSO indices examined share common information. It may be desirable to investigate whether they contain significant uncommon information, particularly with respect to Indian rainfall. It is noted from Table I that the relationship of IRN is highest with SST. We have investigated whether DSP contains any additional information with respect to IRN. For this, first we find the residual Indian rainfall series by subtracting the rainfall series, reconstructed from the first canonical mode of SST–IRN, from the original IRN. This removes the influence of SST from IRN. Next, we conduct canonical correlation analysis between this residual rainfall series and DSP. The magnitude of the first canonical correlation from this analysis is found to be 0·63, which is lower than the value of significance (= 0·68) at the 5 per cent significance level. Therefore, we conclude that DSP does not provide any additional information, over and above SST, regarding IRN.

3.3 Canonical structure patterns

The canonical structure patterns are analysed in this section in order to understand the phase relationships between different ENSO indices and between ENSO and Indian rainfall. The canonical structure patterns are obtained following Nicholls (1987) by correlating the first canonical variates with their corresponding original monthly variates for the preceding (year -1), concurrent (year 0), and the subsequent (year + 1) years. This way we obtain 36 correlations for each pair of the variables examined and thus provide an effective and simple summary of the interrelationship between the sets of variables, otherwise portrayed by a 36 × 36 matrix of simple correlations.

The plots of the correlation coefficients (Figure 3) for different pairs of the ENSO indices (i.e. DSP–SST and DSP–RAIN) indicate a well-marked annual cycle of the relationship between these ENSO indices, as found by the other investigators. The relationship between these variables starts building up from April of year 0, attaining a peak value during October–December. The relationship falls thereafter but it remains significant until April of year + 1. The plots also reveal that the seasonal variations between these ENSO indices are in phase and that there is no evidence of any lag relationship between them, consistent with the findings of Rasmusson and Carpenter (1982) and Nicholls (1987).

The similar plots of the canonical correlation structures for different ENSO indices and Indian rainfall (Figure 4) indicate that Indian rainfall is generally significantly correlated with each of these ENSO indices during year 0 and that the annual patterns of the relationships remains more or less similar in all three cases. The relationship increases from April of the year 0 through October and changes its phase during winter (November to February). Examination of Figure 4 further reveals that the warm ENSO years are related with weak Indian summer monsoon rainfall and winter Indian rainfall is increased during warm ENSO years. The relationship between the ENSO and the Indian rainfall is found to be strongest during August to October.

For examining the reversal of the relationship in winter, we further prepared scatter plots between ENSO indices and IRN. These scatter plots (not presented) support the relationship noted above. It may be noted that Rasmussen and Carpenter (1983) reported a similar relationship but for Sri Lanka rainfall. They reported that rainfall over Sri Lanka during the post-monsoon period increases during a warm ENSO episode. The wind (north-east monsoon) system which affects Sri Lanka during this period also affects the south-east peninsula of India. Therefore, we have also prepared scatter plots between rainfall over the south-east peninsula and ENSO for the winter period. These scatter plots show a marginal improvement of the relationship over those of the all India rainfall. However, all these results support an opposite sense of the relationship between ENSO and IRN during the winter.

CONCLUSIONS

We used canonical correlation analysis for examining the seasonal variations of the relationship between ENSO and Indian rainfall. Three ENSO indices, namely, DSP, SST and RAIN are analysed, each separately, with the Indian rainfall using their 12 monthly data for an 80-year period. The ENSO indices are also examined by a similar method for relationships between themselves. Monte Carlo procedure as well as the classical confirmatory tests are applied to test the significance of the canonical correlations. The seasonal variations of the relationships are examined by correlating the significant canonical variates with their corresponding original monthly variates for three consecutive (year -1, year 0, and year + 1) years. From this analysis the following important conclusions are drawn.

The seasonal variation of these ENSO indices is found to be in phase and there seems to be no lag relationship between them. The maximum coupling between them occurs after the monsoon season (October–December) and the minimum during April.

The seasonal variations of the Indian rainfall are found to be better linked with the seasonal variations of SST, as compared with DSP or RAIN. Hence, it appears that the variations of the Indian rainfall can be best inferred from the variation of SST if the latter is forecast well in advance by any suitable technique.

There seems to be a change in the relationship between the ENSO and the Indian rainfall during the course of the year. The relationship between the ENSO indices examined and Indian rainfall is negative during summer, whereas during winter it appears to be positive. Hence, summer monsoon rainfall is likely to be deficient and winter monsoon rainfall is likely to be increased during warm ENSO years. The relationship between ENSO and the Indian rainfall, however, reaches a peak value only after the monsoon season, that is during August to October.

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