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Characteristics of certain surface meteorological parameters in relation to the interannual variability of Indian summer monsoon

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Abstract. With an objective to understand the influence of surface marine meteorological parameters in relation to the extreme monsoon activity over the Indian sub-continent leading to flood/drought, a detailed analysis of the sea level pressure over the Southern Hemisphere and various surface meteorological parameters over the Indian seas is carried out. The present study using the long term data sets (Southern Hemispheric Sea Level Pressure Analysis; Comprehensive Ocean Atmospheric Data Set over the Indian Seas; Surface Station Climatology Data) clearly indicates that the sea surface temperature changes over the south eastern Pacific (El Ninõ/La Niña) have only a moderate impact (not exceeding 50% reliability) on the Indian summer monsoon activity. On the other hand, the sea level pressure anomaly (SOI) over Australia and the south Pacific has a reasonably high degree of significance (more than 70%) with the monsoon activity over India. However, these two parameters (SLP and SST) do not show any significant variability over the Indian seas in relation to the summer monsoon activity.

Over the Indian seas, the parameters which are mainly associated with the convective activity such as cloud cover, relative humidity and the surface wind were found to have a strong association with the extreme monsoon activity (flood/drought) and thus the net oceanic heat loss over the Indian seas provides a strong positive feed-back for the monsoon activity over India.

Keywords. Interannual variability; Indian summer monsoon; southern oscillation; oceanic heat flux.

1. Introduction

The phenomenon of monsoon is global in character affecting India and a large area of Asia; parts of Africa and northern Australia. The Indian summer monsoon provides about 80% of the annual rain water over India and hence the high concentration of the rainfall received during the summer monsoon months (June–September) largely meets the country's water requirement. Summer monsoon is a regular phenomenon only in the sense that it comes every year. But its onset, its activity during the season and its withdrawal etc. are subject to variations that some times are large. Anomalies in the activity of monsoon during the season affect the agricultural production and large failures particularly, upset the country's economy. Thus, an early indication on the occurrence of large scale variability in the monsoon rainfall leading to drought/flood as far ahead as possible would bear a considerable importance.

Efforts to identify possible global surface meteorological parameters having teleconnections with the summer monsoon activity over India have been initiated by the various investigators since late 19th century (Blanford 1884; Lockyer and Lockyer 1904). Walker (1924) eventually discovered one of the most important oscillations of the planetary atmospheric pressure field widely known as the Southern Oscillation. It basically describes a see-saw effect in the sea level pressure oscillation between the equatorial Indian Ocean and the south eastern Pacific Ocean (Das 1968) which is generally considered as a shift in the distribution of air masses between the south east Pacific sub-tropical high and the Indian Ocean equatorial low. Bjerknes (1969) related these pressure changes to the strength of the equatorial zonal east-west circulation in the Pacific Ocean called the Walker Circulation. The Southern Oscillation has an irregular period varying between 2 to 6 years. Numerous studies have so far used different combinations of meteorological stations to compute the Southern Oscillation Index (SOI) (Walker 1924; Berlage 1957; Troup 1965; Trenberth 1976; Bhalme *et al* 1983). An extensive review of Southern Oscillation was provided by Julian and Chervin (1978) and all those studies have demonstrated the strong bearing of the Southern Oscillation on the total quantum of rainfall over India during the summer monsoon season.

A negative SOI (i.e. higher sea level pressure over equatorial Indian Ocean and lower sea level pressure over south eastern Pacific Ocean) is found during the years of deficient summer monsoon rainfall over India. Generally, it is believed that a nearly simultaneous teleconnection exists between the warm sea surface temperature (SST) over the eastern Pacific Ocean-El Niño and the monsoon rainfall through planetary scale divergent circulations. Rasmusson and Carpenter (1983) while exploring the relationship among El Niño events during negative SOI phases and the monsoon rainfall noted a strong tendency for the occurrence of below normal rainfall during the episodes of E1 Niño. Unfortunately, the southern hemispheric region which is considered to be the source region of several global teleconnections, is covered by a vast data sparse oceanic region. Due to this fact several studies have considered only limited station data or ship observations. In recent years, availability of a reliable long-term surface analysis of the Southern Hemisphere (SH) from the South African Weather Bureau and the Australian Bureau of Meteorology has provided an opportunity to undertake a comprehensive study to examine the influence of surface pressure of the SH on the summer monsoon rainfall.

Though, many studies have reflected the large scale linkage of the Pacific Ocean SST and southern hemispheric sea level pressure on the Indian summer monsoon rainfall, only a limited number of studies have examined the influence of the regional marine surface meteorological parameters on the monsoon rainfall. Most of such studies have investigated the relation between SST variations over the Indian seas and the monsoon activity over the Indian sub-continent (Shukla and Misra 1977; Weare 1979; Rao and Goswami 1988). However, an interesting observation about the variability of surface wind over the Indian seas is brought out by Cadet and Diehl (1984) having a reduction of wind speed in a drought monsoon season (1972) and a substantial increase in a flood monsoon season (1956). Recent studies by Mohanty and Mohan Kumar (1990) and Mohanty *et al* (1992) have demonstrated that air sea fluxes exhibit a strong link with the monsoon activity as the interaction between atmosphere and ocean takes place through the exchange of heat, moisture and momentum at the ocean surface. Infact, it is found that an active phase of the summer monsoon is characterised by a net oceanic heat loss which produces a positive feed-back for the maintenance of deep cumulus convection above the marine boundary layer. Hence, the study on the regional characteristics of the marine surface meteorological parameters which determine the surface fluxes over the Indian seas is carried out using the Comprehensive Ocean Atmospheric Data Set (COADS). Section 2 provides a brief description of the data and the computation procedure. Interpretation of the results is presented in section 3 and general comments and conclusions are given in section 4.

2. Description of data and computation procedure

The present study to examine the characteristics of the southern hemispheric sea level pressure (SLP) patterns on the summer monsoon rainfall over India is carried out with the help of a long-term sea level pressure analysis of the two operational weather centers of the Southern Hemisphere–South African Weather Bureau Analysis for 8 years: 1951–58 and Australian Bureau of Meteorology Analysis for 12 years: 1972–83. For this study, the classification of excessive and deficient rains over India as a whole is made on the basis of the standard deviation of the monsoon rainfall above or below 0.9 and obtained the respective years from the studies of Rasmusson and Carpenter (1983); Bhalme *et al* (1983). Thus, the years of excessive/deficient rains (above/below $0{\cdot}9\sigma$) over India as a whole for which the SLP analysis are available over the Southern Hemisphere are given below:

Flood	Drought
1955	1951
1956	1952
1973	1972
1975	1974
	1979

The available SLP analysis thus contains four years of large excessive and five years of large deficient rainfall over India. The method of computation deals with the grouping of seasonal (February–April [FMA] and June–September [JJAS]) SLP and surface geostrophic wind over the Southern Hemisphere according to the years of excessive and deficient rainfall over India as a whole. From such a composite of SLP analysis the nature of distribution of these surface meteorological parameters during the large excess and large deficient years of monsoon rainfall over India are examined. Though the length of the data record considered here was not large enough to study the significance of the difference fields between the large excess and large deficient rainfall years, student t-test was applied on the difference fields in order to analyse the statistical significance of the differences between the two extreme categories of the monsoon over India. In order to study the regional characteristics of the marine surface meteorological parameters over the Indian seas in relation to the summer monsoon rainfall over India, the COADS data archives are utilised. This data set is the first of its kind where the most efficient and modern methods were used to compile the surface meteorological parameters available over the world oceans. COADS consists of monthly means of surface marine meteorological parameters, compiled and checked for quality, collected by ships and analysed on 2° latitude/longitude resolution from 1854 to 1979. The data set used for the study comprises of 30 monsoon seasons (1950–79) and is a reanalysed data set of original COADS on 1° latitude/longitude resolution [Levitus 1982] at the Geophysical Fluid Dynamics

Laboratory [GFDL], USA. A large number of studies have been carried out with this data set to study the influence of oceans on the climatic variability (Oort *et al* 1987; Rao *et al* 1989 and others) have established the reliability and the quality of the COADS.

The variability of marine surface meteorological fields over the Indian seas is studied during the summer monsoon seasons (June–September) of the large excessive and large deficient rainfall over India as a whole. The domain of the study extends from 39·5°S to 39·5°N and 0·5°E to 179·5°W which represents all major oceanic regions surrounding the summer monsoon regime. Following Rasmussón and Carpenter (1983) and Bhalme *et al* (1983), the categorisation of the 30 monsoon seasons (1950–79) is carried out based on the seasonal rainfall over India as a whole as shown below:

Flood	Drought
1955	1951
1956	1952
1959	1965
1961	1966
1970	1968
1973	1972
1975	1974
	1979

Out of the 30 monsoon seasons considered, seven were flood cases and eight were drought cases. Here also, the differences of the various surface meteorological parameters between flood and drought groups over the Indian seas are analysed and their statistical significance in relation to the monsoon variability is also studied.

3. Interpretation of the results

The summer monsoon (June–September) rainfall over India as a whole expressed in terms of its departure from the long-term mean (1890–1980) is utilised in this study. Based on the individual summer monsoon rainfall departures from its long-term mean value, the identification of the extreme monsoon seasons over India characterised by flood/drought is carried out. Accordingly, a large excess rainfall season (flood) is identified when standard deviation exceeds 0·9 and a large deficient rainfall season (drought) is identified when standard deviation is lower than $-0{\cdot}9$ of the long-term mean of rainfall over India as a whole. Table 1 denotes the years of excessive and deficient rains as per the above mentioned analysis.

Among the 91 summer monsoon seasons considered (1890–1980), a total of 23 drought years and 21 El Niño years (warm event over south east Pacific) are identified (Van Loon and Shea 1985). Interestingly, out of 23 drought cases identified, it is found that only 11 of them are associated with a warm event over the Pacific (48% of cases are associated with El Niño and the remaining 52% of observed droughts over India are not associated with El Niño) indicating that 52% of the warm events over the Pacific had led to drought situation over India and the

Table 1. Years of large excessive (flood) and large deficient (drought) rain fall over India as a whole.

Large excess		Large deficient	
Rainfall years	Standard deviation	Rainfall years	Standard deviation
1890	0·9	*1891	−1·0
†1892	1·5	*1899	−2·6
1893	1·4	1901	−1·3
1894	1·7	*1902	−0·9
†1916	1·2	*1904	−1·2
1917	1·0	1905	−1·6
1933	1·5	1907	−0·9
†1942	1·3	*1911	−1·4
†1949	1·0	*1913	−1·1
1955	0·9	1915	−1·0
1956	1·0	*1918	−2·4
1959	1·4	†1920	−1·7
1961	2·2	1928	−0·9
†1970	0·9	*1939	−1·0
†1973	0·9	1941	−1·4
†1975	1·5	*1951	−2.0
		1952	−0·9
		*1965	−1·5
		†1966	−1·1
		1968	−1·1
		*1972	−2·3
		1974	−0·9
		1979	−1·9

*Warm Events (El Niño)
†Cold Events (La Niña)

remaining 48% cases, occurrence of El Niño did not lead to a drought situation. Thus, it may be inferred that only about 50% of the drought periods over India observed during the summer monsoon season are associated with the occurrence of a warm event over the south east Pacific.

On the other hand, a total of 16 flood monsoon seasons and 20 cold events (La Niña) over the south east Pacific are identified from the long period considered in this study. Generally, identification of a La Niña event is difficult as no clear method of its identification exists. Also, La Niña in many cases either precedes a year of El Niño or follows it subsequently. Among the 16 flood monsoon seasons identified about 44% of them are associated with a cold event over the Pacific (La Niña) and the remaining 56% of flood cases are not associated with La Niña at all. Further, it is found that among the 20 La Niña events observed, 35% of them are only associated with a flood monsoon season over India and about 10% of them (1920 and 1966) are even associated with a drought over India too. The remaining 55% of cold events are found to have no association with the occurrence of extreme monsoon activity over India. Hence, the association of cold event over the south east Pacific with the extreme monsoon activity over India is considered to be weak.

Analysis of the sea level pressure over the few selected stations which are traditionally used for computing the SOI (table 2) shows that there exists a strong association of the surface pressure oscillation (with above 70% of deviation from its normal value) over the eastern Indian Ocean (Darwin) and eastern Pacific Ocean (Rapa). Such an oscillation is found to be more pronounced during the years of extreme monsoon activity (flood/drought). Hence, this aspect is further investigated in this study by analysing the southern hemispheric surface pressure analysis during the years of extreme monsoon activity over India. Schematic representation of the various linkages among the El Niño La Niña, SOI and the summer monsoon rainfall over India as a whole as seen in the present study is presented in figure 1.

Table 2. Characteristics of sea level pressure at key stations on the Southern Hemisphere in years of excessive or deficient rains (above or below 0·9 σ) over India as a whole: the number of years in each extreme; the sign of the mean deviation of SLP; and the number of times when the SLP in a rainfall extreme had the same sign as the mean deviation.

		Mean deviation	Percentage of events which are of the same sign as the mean deviation						
			May	Jun	Jly	Aug	Sep	Oct	Nov
Darwin (12°S, 131°E)	Flood (16)	MSLP < Normal	81	75	56	75	93	93	87
	Drought (23)	MSLP > Normal	74	76	74	82	82	74	78
Adelaide (35°S, 138°E)	Flood (16)	MSLP < Normal	63	63	53	71	50	71	62
	Drought (23)	MSLP > Normal	65	62	61	54	50	65	67
Samoa (14°S, 172°W)	Flood (16)	MSLP < Normal	64	64	56	63	56	50	53
	Drought (23)	MSLP > Normal	61	73	78	61	61	52	52
Rapa (28°S, 144°W)	Flood (7)	MSLP < Normal	50	71	80	80	71	57	71
	Drought (7)	MSLP > Normal	50	57	67	83	83	83	83
Malindi (3°S, 41°E)	Flood (6)	MSLP < Normal	60	33	50	75	100	67	60
	Drought (8)	MSLP > Normal	50	50	71	50	83	50	57
Beira (20°S, 35°E)	Flood (12)	MSLP < Normal	67	58	73	55	67	60	73
	Drought (15)	MSLP > Normal	50	60	47	40	47	47	60
Marion (47°S, 38°E)	Flood (8)	MSLP < Normal	50	38	50	75	57	50	38
	Drought (8)	MSLP > Normal	62	43	62	62	83	50	71

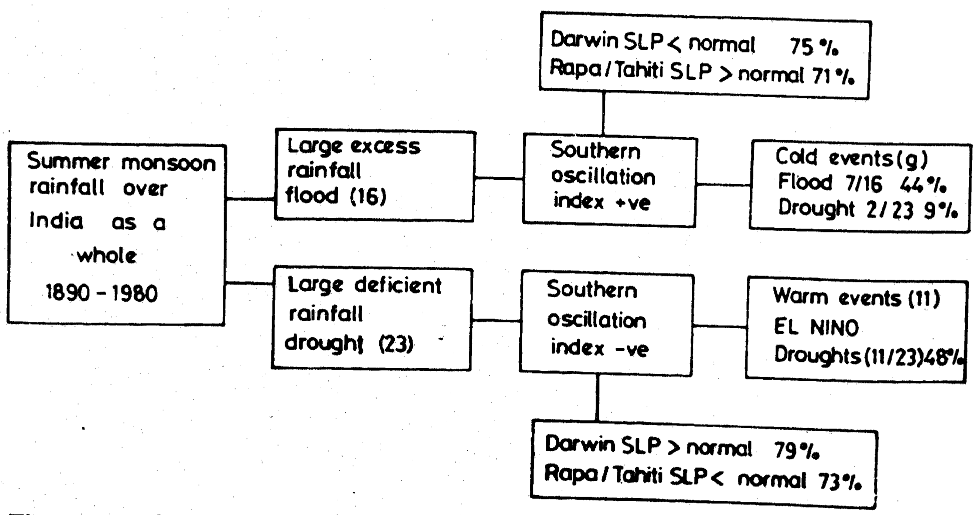


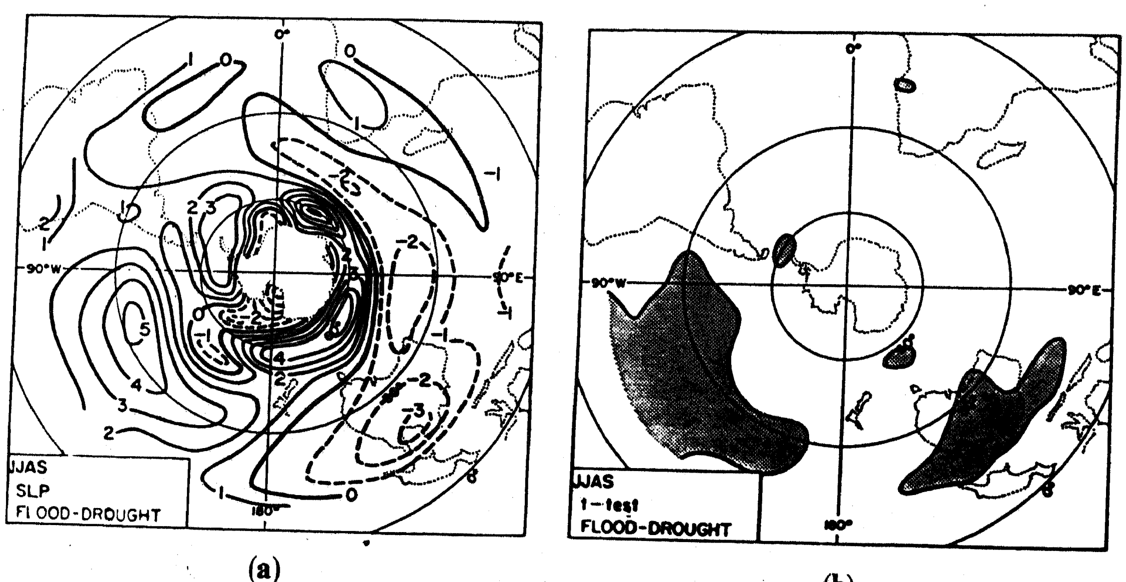
Figure 1. Schematic representation of the various linkages among El Niño/La Niña, SOI and the summer monsoon rainfall over India as a whole.

3.1 *Characteristics of the southern hemispheric sea level pressure analysis*

Although, we are dealing with limited southern hemispheric sea level pressure analysis having only four years of flood and five years of drought in this study, it is worthwhile examining to what extent each category contributes to the differences. It is therefore, the difference between the flood and drought seasons compiled together with a student t-test that is used for evaluating its statistical significance.

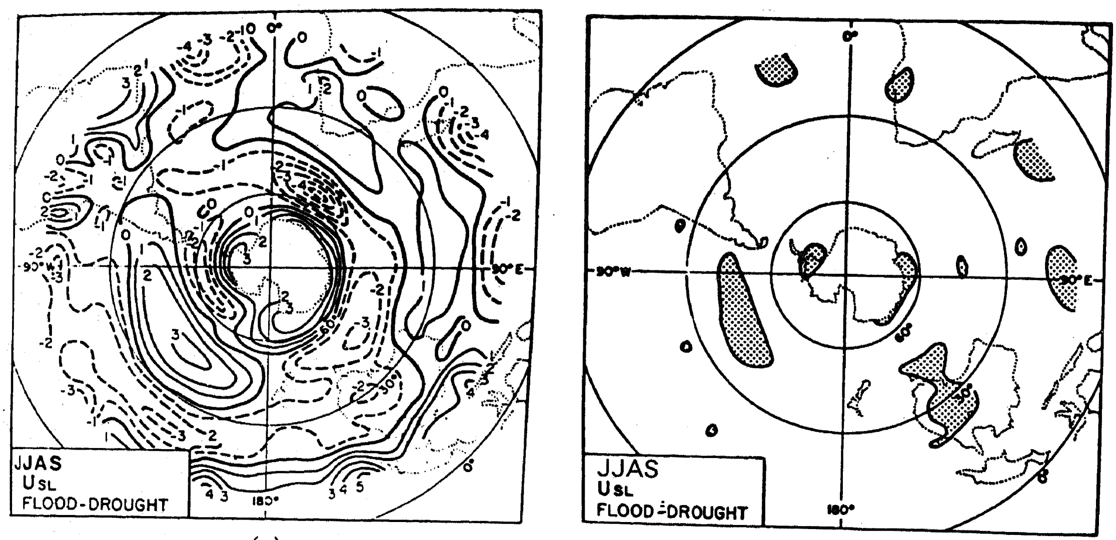
The difference between flood and drought for the period June–September (JJAS) is shown in figure 2a and its corresponding t-distribution is shown in figure 2b where shaded areas denote regions of statistical significance with a confidence level above 95%. This and the following maps of the difference between flood and drought are found to have the same sign as that of flood year anomalies. It is seen that the sea level pressure is significantly higher in the flood years than in drought years over the tropical and sub-tropical Pacific Ocean and conversely over Australia and the neighbouring oceanic region. It is found that over both the regions differences attain widespread statistical significance. The pattern observed between 90°E and the west coast of South America is that of the Southern Oscillation. Also, the differences are found to be statistically significant over a small region situated to the south of Australia, South America and south west coast of Africa.

It is found that the signal of the SO is strong over the Australia and Pacific Ocean during the summer monsoon season (JJAS). The differences are further analysed through the computation of surface zonal geostrophic wind (U_{SL}) from the gradients of sea level pressures. Distributions of zonal geostrophic wind between flood and drought years together with its t-distribution are shown in figure 3. Positive values of U_{SL} mean that the westerlies are stronger/easterlies weaker in flood years and negative values signify that easterlies are stronger/westerlies weaker in flood years i.e. the mid-latitude westerlies are stronger in the Pacific and weaker in the other oceans during the flood years of monsoon. It is interesting to observe that the easterlies



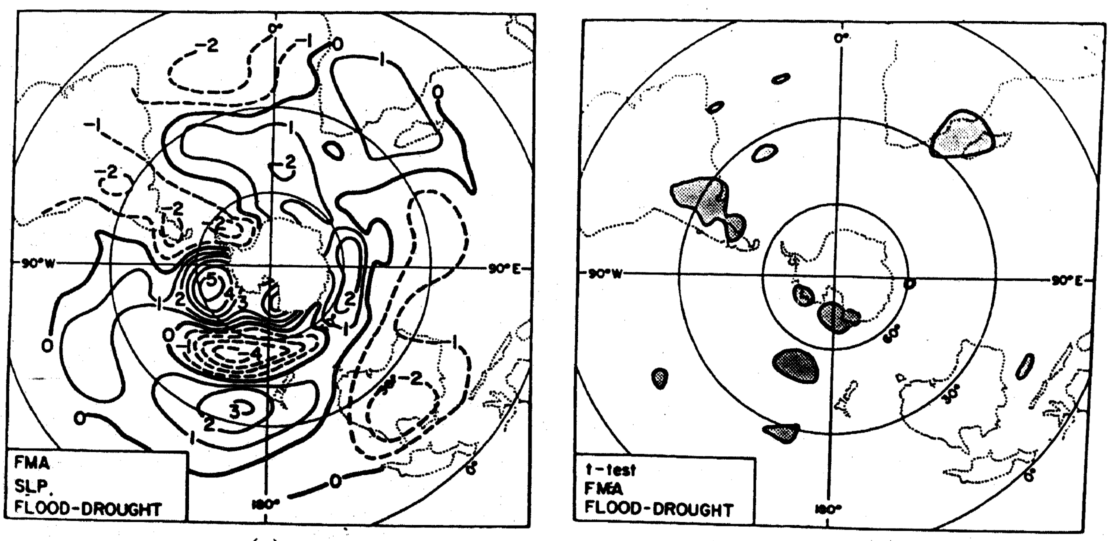
(a) (b)

Figure 2. Distribution of the sea level pressure over the southern hemisphere (**a**) anomaly between the two extreme categories of the summer monsoon (flood-drought) [Contour interval : 1mb]; (**b**) its corresponding t-distribution [shaded areas denote statistical significance above 95%] for the period June-September (JJAS).



(a) (b)

Figure 3. Same as figure 2 but for surface zonal geostrophic wind [Contour interval : 1 ms^{-1}].



(a) (b)

Figure 4. Same as figure 2 but for the period February–April (FMA) [Contour interval : 1mb].

in the central and western tropical parts of the Indian Ocean are stronger in flood years than in drought years.

The SO signal prior to the monsoon season is analysed with the help of the mean difference of SLP between flood and drought cases for the period February–April (figure 4). Already by this time of the year the pressure difference from the coast of west Antarctica to the region of north east New Zealand is similar to the signal of the Southern Oscillation (figure 4a). From this analysis it may be said that there exists a modest amount of skill to an early prediction of the outcome of a subsequent monsoon season by knowing the signal in the sea level pressure patterns on the Southern Hemisphere.

The observation of the type of pressure pattern seen in figure 2 is complemented with the evidence at few selected stations (figure 5) with the mean monthly sea level

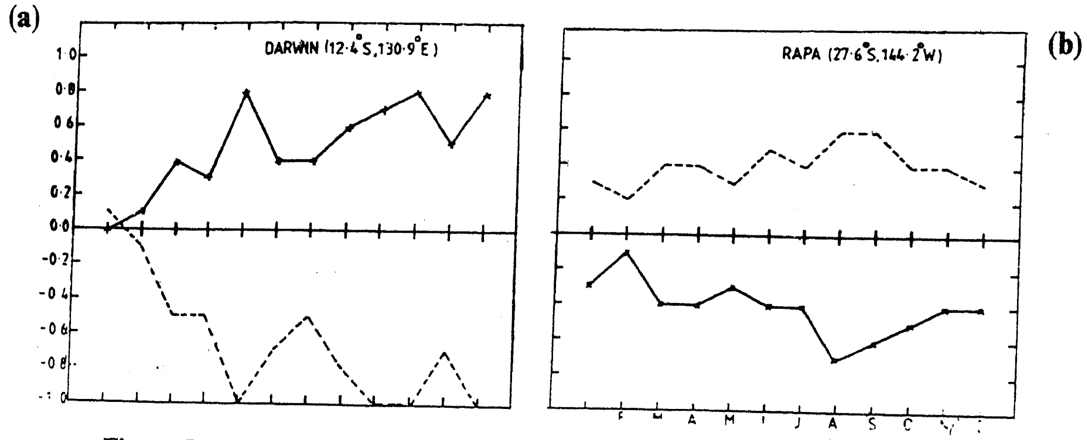


Figure 5. Mean monthly sea level pressure anomalies, normalised, at (a) Darwin and (b) Rapa on the southern hemisphere in years of excessive and deficient summer rains over India as a whole.

pressure anomalies normalized at these stations on the Southern Hemisphere in years of excessive and deficient summer monsoon rains over India as a whole. Common to all of the mean anomalies in figure 5 is that they are of opposite sign in years of drought and years of flood. It is found that at Somoa and Rapa the anomalies are higher and at Darwin and Adelaide they are lower in the years of excessive rains. Thus, this part of the pattern seen in figure 2 appears to be a stable one. Table 2 states how frequently the anomaly of single events had the same sign as the mean anomaly at the stations having comparatively long records of observations. It is to be noted that percentages would have been higher if the difference between flood and drought had been used instead of single months.

3.2 *Characteristics of certain surface meteorological parameters over the Indian seas*

In this section, the variability of certain meteorological parameters during the contrasting years of summer monsoon activity over the Indian sub-continent is studied with the help of the differences between the category of large excess rainfall years (flood years) and the category of large deficient rainfall years (drought years). The statistical significance of the differences between the two extreme categories of monsoon is carried out using the student t-test.

The variability of SST over the tropics has been extensively studied by a number of investigators (Weare 1979; Shukla 1987; Rao and Goswami 1988 etc) and it is found that the variability of SST over the Arabian Sea and the Bay of Bengal is very small on an interannual scale. The difference of sea surface temperature field between two extreme categories of the summer monsoon (flood–drought) together with its corresponding t-distribution is shown in figure 6. It suggests that no significant differences in SST exists over the north Indian Ocean. However, the SST differences attain statistical significance over small regions of south Indian Ocean and south Pacific (over a small area between Africa and Madagascar; south eastern Indian Ocean to the north west of Australia and south western Pacific Ocean). Thus, over the Indian seas, it can be said that SST variations do not exhibit significant differences between the extreme categories of the Indian summer monsoon.

The distribution of sea level pressure difference between the flood and drought

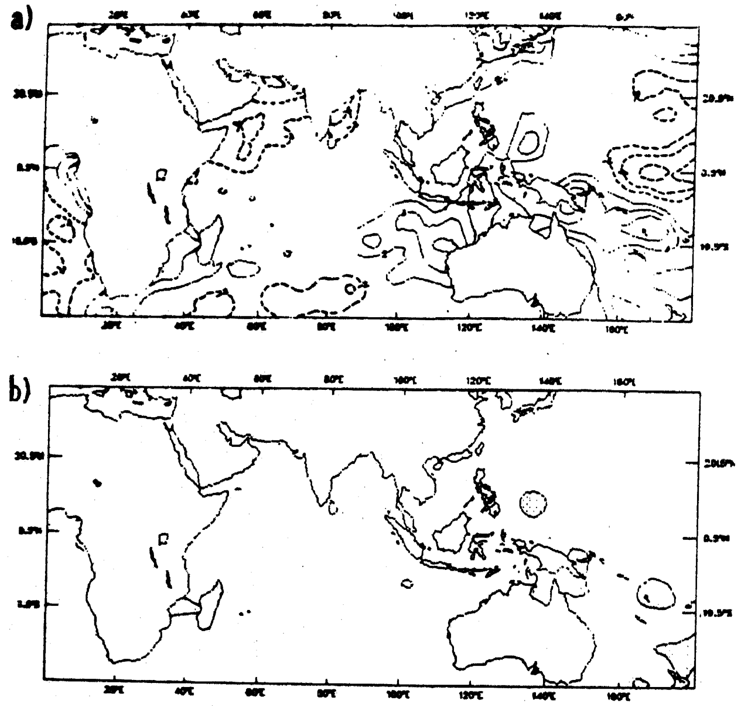


Figure 6. Same as figure 2 but for the sea surface temperature over the tropical eastern hemisphere [Contour interval : 0·2°C].

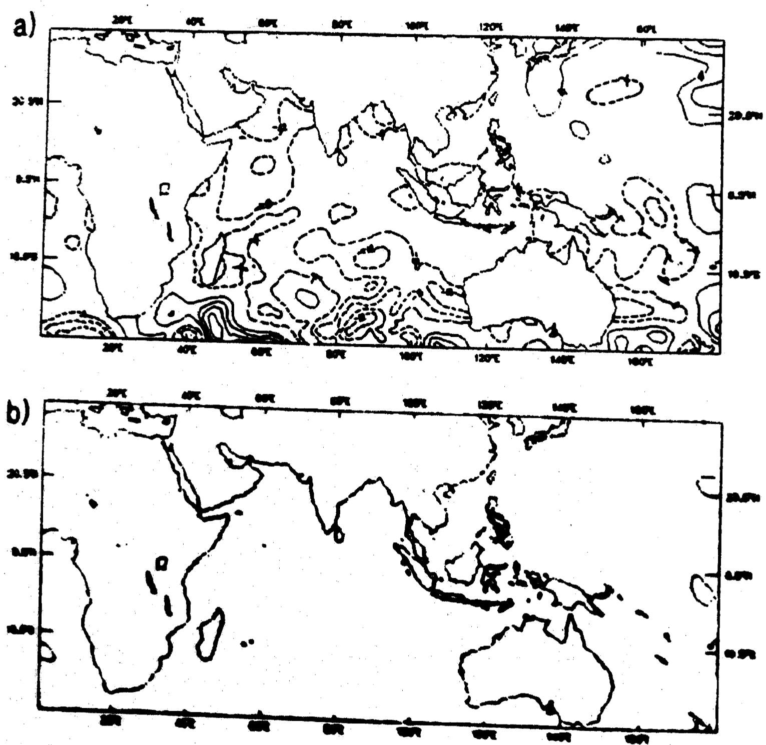


Figure 7. Same as figure 6 but for the sea level pressure [Contour interval : 0·4 mb].

monsoon seasons (figure 7) follows more or less similar to the SST pattern over the north Indian Ocean. Though, certain zones of SLP differences found over the Pacific Ocean, south Indian Ocean and south eastern Atlantic etc., some of them only attain statistical significance (north and central Pacific and eastern Atlantic).

The south west monsoon season (JJAS) is marked by the presence of consistent south-westerly flow over the Indian seas. Earlier studies of Cadet and Diehl (1984) suggest a reduction of wind speed over the Indian seas in a drought monsoon season (1972) and a substantial increase in a flood monsoon season (1956). Wind fields exhibit significant differences between two extreme categories of monsoon (figure 8) over the Arabian Sea and the Indian Ocean. Over the Bay of Bengal variability of the surface wind fields having a desired level of statistical significance is found over a small region

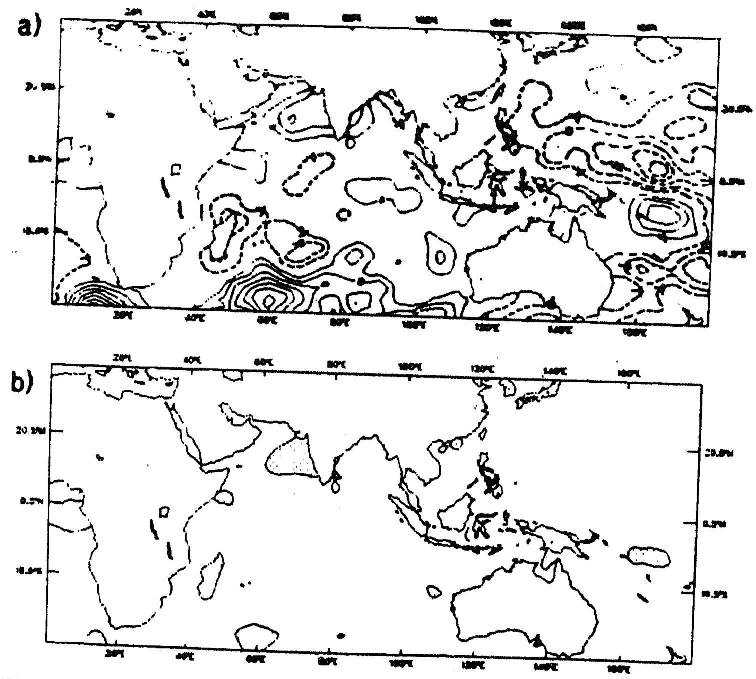


Figure 8a-b. Same as figure 6 but for zonal wind [Contour interval : 0·4ms^{-1}].

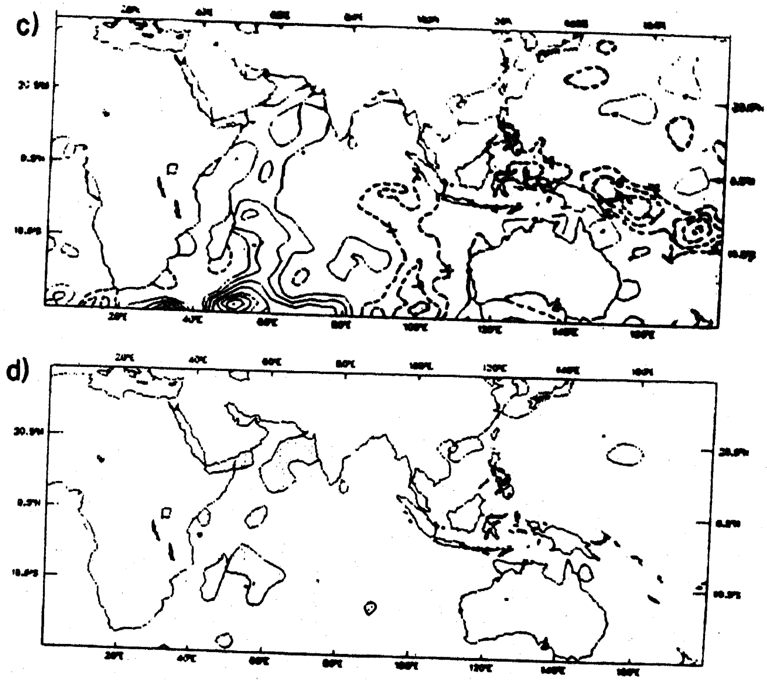


Figure 8c-d. Same as figure 6 but for meridional wind [Contour interval : 0·4ms^{-1}].

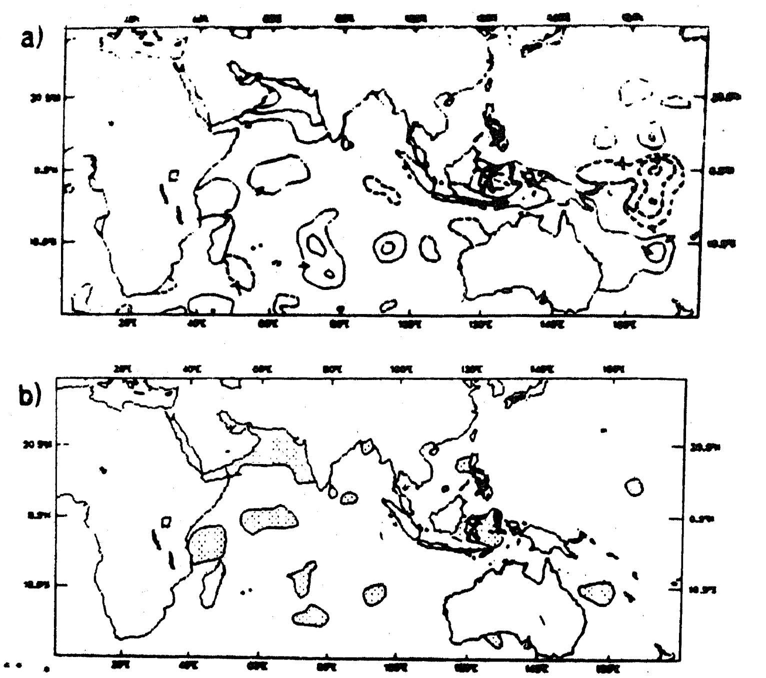


Figure 9. Same as figure 6 but for cloud cover [Contour interval : 0·4 octa].

along the south east coast of India. Surface zonal wind shows maximum variability over the large area covering central and eastern Arabian Sea and a small region off the coast of Somalia (figure 8b). On the other hand, surface meridional wind displays strong variability over the Arabian Sea and the Indian Ocean off Madagascar (figure 8d) indicating that cross-equatorial flow is stronger during the flood monsoon seasons as compared to the drought seasons.

During the summer monsoon season (JJAS), a very significant spatial variations of the cloudiness are observed over the Indian seas. The difference of total cloud amount between the years of large excess rainfall (flood years) and the years of large deficient rainfall (drought years) is found to be significant over the entire Arabian Sea to the north of 10°N latitude, head Bay of Bengal, equatorial Indian Ocean (5°N–5°S) and tropical south Indian Ocean (around 72°E and 92°E) (figure 9). It may be inferred that the zones of significant cloud amount differences between the two extreme categories of the summer monsoon over India are characterised by the increased convective activity during the flood monsoon seasons as compared to a drought season.

Distribution of the relative humidity difference between the flood and drought categories of monsoon (figure 10) shows that air above the sea surface contain more moisture over the Arabian Sea and over few sectors of south Indian Ocean (at 65°E; 90°E and 100°E longitudes) during the years of large excess rainfall over India as compared to the category of large deficient rainfall seasons.

It is observed in the present analysis that ocean surface meteorological parameters have distinct characteristics in the years of large excess rainfall (flood) and large deficient rainfall (drought) over India. The surface parameters such as SST and SLP which have displayed significant variations over the Southern Hemisphere during the two extreme categories of the monsoon did not however show any significant variability over the Indian seas. On the other hand, the surface parameters like wind

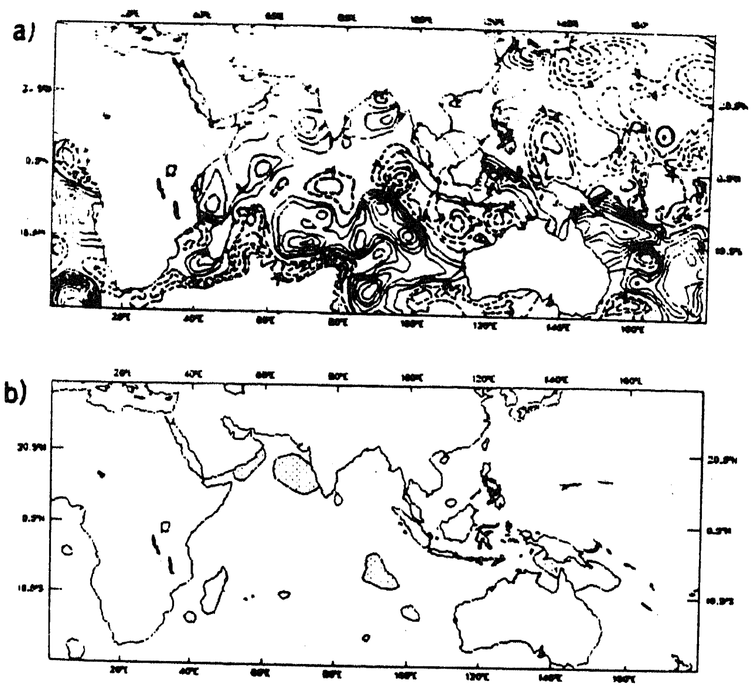


Figure 10. Same as figure 6 but for the relative humidity [Contour interval : 0·4].

speed, cloud amount and relative humidity which basically determine the flux transfer of heat, moisture and momentum at the air-sea interface show remarkable variability in their distribution over the Indian seas.

4. Conclusions

On the basis of the results discussed above on the characteristics of marine surface meteorological parameters in relation with the interannual variability of Indian summer monsoon, the following general conclusions may be drawn

- The teleconnection link which exists between the El Niño and the Indian monsoon is found to be not strong enough (as only 50% of the observed droughts over India during the summer monsoon season are associated with the occurrence of El Niño event over the south eastern Pacific). It is interesting to note at the same time that not a single occurrence of a flood monsoon situation over India is found in association with an El Niño event. On the other hand, however, drought situations prevailed (only on two occasions) over India during the summer monsoon season in association with a La Niña event over the Pacific Ocean.
- A very strong association is observed between the southern hemispheric sea level pressure pattern (SOI) and the summer monsoon activity over India (with a probability of more than 70%).
- The marine surface meteorological parameters such as sea surface temperature, sea level pressure which have shown significant variability over the Southern Hemisphere in association with the extreme monsoon activity over India leading to flood/drought do not display any significant variability over the Indian seas. It is however, found that the other marine surface meteorological parameters such

as wind speed, cloud amount and relative humidity which determine the flux transfer of heat, moisture and momentum at the air–sea interface exhibit distinct characteristics over the Indian seas in the years of large excess/large deficient rainfall over India.

- Hence, net oceanic heat loss from the ocean surface in the form of evaporation associated with low level convergence is responsible for the intense convective activity over the central Arabian Sea and the west coast of India during the summer monsoon season. In particular, the enhanced net oceanic heat loss observed during the month of May preceding a large excess rainfall season over India provides a positive information about the extreme nature of activity during the subsequent monsoon season (Mohanty *et al* 1992).
- The regional characteristics of the surface meteorological parameters over the Indian seas observed during the summer monsoon season are in good agreement with the tropospheric circulation characteristics found in the heat and moisture budget analysis over the same region (Mohanty *et al* 1983)

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