Influence of Natural Forcing Phenomena on Precipitation of Pakistan

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Abstract

According to IPCC TAR (2001), some natural climate variations such as ENSO (El-Nino Southern Oscillation), PDO (Pacific Decadal Oscillation), IOD (Indian Ocean Dipole) and NAO (Northern Atlantic Oscillation) / NAM (Northern Hemisphere Annular Mode), can significantly alter the behavior of extreme events, including floods, droughts, hurricanes and cold waves. This paper examines ENSO, NAO and IOD (DMI) in the context of their influence on the precipitation of Pakistan, by analyzing the historical data of rainfall for the period 1951-2012 supplemented by the re-analysis NCEP pressure data and the CRU precipitation data. These phenomena have been analyzed in relation to rainfall departures (monsoon rains in the case of ENSO, winter rains in the case of NAO and both monsoon & winter rains in the case of IOD) and the corresponding correlations are developed. Decadal correlations have also been worked out. The impact of IOD on El-Nino and La-Nina events in the monsoon dominated region and over the whole of Pakistan, particularly during the years of ENSO episodes, has also been studied. In most of the cases, the monsoon rainfall was found to drop drastically during the strong El-Nino years and positive IOD values, whereas it generally increased during the La-Nina years. During most of the strong El-Nino years, the monsoon depressions emerging from the Bay of Bengal and moving towards Pakistan dissipated over either Bangladesh or India, and did not reach Pakistan. The NAO forcing is seen positively correlated with the winter rains. Some NAO decadal correlations are found to be significantly high.

Introduction

The El-Nino Southern Oscillation (ENSO) phenomenon is associated with anomalous sea-level pressure, surface winds and Sea Surface Temperature (SST) near the equatorial Pacific (Barton et al 2004) and is caused by sea level pressure gradient between Darwin (Australia) and Tahiti (Wallace and Vogel, 1994). It has now been recognized that the single most important key to earth's year-to-year climate variability is the El-Nino Southern Oscillation phenomenon (Kriplani R.H. 1996). El-Nino episodes directly affect the climate of at least half the planet and in many instances result in heavy loss of life and resources. The Southern Oscillation Index (SOI) used in the study is air pressure anomaly between Tahiti and Darwin (Australia). The negative phase of SOI represents the below normal pressure at Tahiti and above normal pressure at Darwin and vice versa for the positive phase of the SOI. Prolonged periods of negative SOI values coincide with abnormally warm ocean waters across the eastern tropical pacific (El-Nino episodes) while the prolonged periods of positive SOI values coincide with abnormally cold ocean waters across the tropical Pacific (La-Nina episodes) (Philander, 1990).

The NAO describes a large-scale meridional oscillation in the atmospheric mass between the North Atlantic regions of the subtropical anticyclone near the Azores and the sub polar low pressure system near Iceland. It is a major source of seasonal to inter decadal variability in the worldwide atmospheric circulation (Hurrell, 1995) and represents the most important "teleconnection" of the North Atlantic-European area (Hurrell and van Loon, 1997; Kapala et al., 1998), where it is most pronounced in winter. The measure of the state of NAO, the North Atlantic Oscillation Index (NAOI) is widely used as a general indicator for the strength of the westerlies over the eastern North Atlantic and Western Europe and most importantly for winter climate in Europe (Hurrell and van Loon, 1997; Wanner et al., 1997; WMO, 1998). In fact, NAOI is highly correlated with a large variety of atmosphere-related environmental variables, mainly during the winter season (Dickson et al., 2000 and Souriau and Yiou, 2001)

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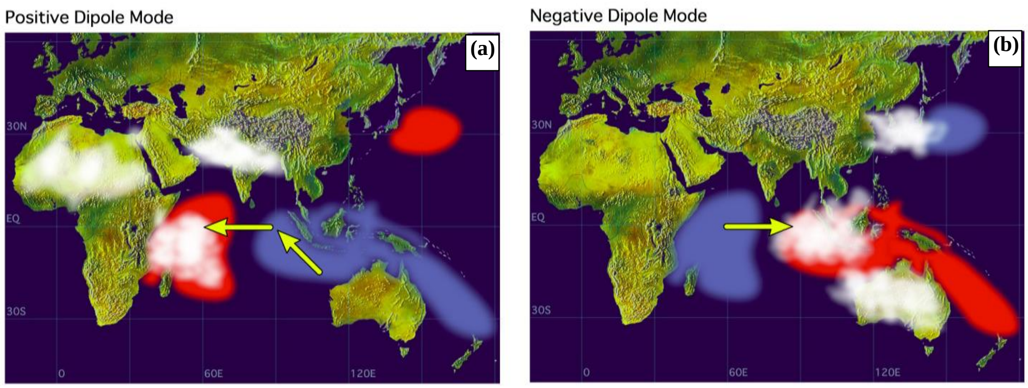
Indian Ocean Dipole (IOD) is a coupled ocean-atmosphere phenomenon in the Indian Ocean. It is normally characterized by anomalous cooling of SST in south eastern equatorial Indian Ocean and anomalous warming of SST in the western equatorial Indian Ocean (http://www.jamstec.go.jp/frsgc/). Associated with these changes, the normal convection situated over the eastern Indian Ocean warm pool shifts to the west and brings heavy rainfall over the east Africa and severe droughts/forest fires over the Indonesian region. The parts (a) and (b) of Figure 1 show respectively the positive and negative modes of IOD.



(Source: http://www.jamstec.go.jp/frcgc/research/d1/iod/IOD1.html)

Figure 1: Dipole Mode over the Indian Ocean.

An index to quantify the IOD has been proposed by Saji et al (1999). This is the difference in SST anomaly between the tropical western Indian Ocean (50° - 70°E, 10°S – 10°N) and the tropical Southeast Indian Ocean (90° - 110°E, 10°S – Equator) and is denoted as Dipole Mode Index (DMI). In this study, the GISST 2.3b data set is used to compute the DMI values.

The main objective of this study is to analyze the natural forcing phenomena that include ENSO, NAO and IOD (DMI), specifically in terms of their effect on the precipitation of Pakistan. This is accomplished by studying above mentioned phenomena along with their indices particularly in relation to rainfall departures (monsoon rains in case of ENSO, winter rains in the case of NAOI and the relation of DMI with both summer and winter rains). The rainfall departures are worked out for summer season June to September (JJAS) for both monsoon dominated region and whole of Pakistan. These regions are referred as “Monsoon Region” and “Whole Pakistan” respectively. Rainfall departures are also worked out for winter season December to March (DJFM) for both Northern Half of Pakistan (above 31 °N to 37 °N) and the Whole Pakistan.

These phenomena have been analyzed and the corresponding correlations are developed with rainfall departures to assess the influence of these phenomena on the precipitation of Pakistan. Decadal correlations of rainfall departures with these phenomena have also been worked out to analyze the decadal variation of these phenomena. In most of the cases, the monsoon rainfall was found to drop drastically during the strong El-Nino years and positive IOD values, whereas it generally increased during the La-Nina years. The NAO forcing is generally seen positively correlated with the winter rains.

Data and Methodology used

Greater Himalayan region within 35°N to 37°N is mostly winter rain dominated whereas the region within 31.5°N to 35°N located along the southern slopes of western Himalayan mountains is monsoon rain dominated (30 years Normals of Pakistan, PMD, 1993). Monsoon (June to September) and winter (December to March) precipitation data for period (1951–2012) are used. The values of SOI differing from its mean value by more than $+1\sigma$ and -1σ have respectively been treated as El-Nino and La-Nina events. Different researchers, however, have different ideas and there is no single method used to identify the El-Nino and La-Nina events. However, a common method in use is based on Nino 3.4 Index, which is the departure in monthly sea surface temperature from its long term mean averaged over the Nino 3.4 region.

In this method, an event is identified as El-Nino if 5 month running average of the Nino3.4 Index exceeds +0.4°C for at least 6 consecutive months and is La-Nina if the same falls below -0.4°C for at least 6 consecutive months. In this study, El-Nino and La-Nina events which are common to those based on the Tahiti minus Darwin pressure, on Nino 3.4 index and on the SOI values above and below 1 standard deviation have been considered. The SOI values have been related to the rainfall departures from the mean of monsoon rains over the Monsoon Region and Whole Pakistan for the period 1951-2012 and to the mean precipitation of the mountainous regions above and below 31°N. Correlation coefficients are then worked out. During the El-Nino years, the pressure conditions over the South Asia region using the NCEP reanalysis data have also been examined to see as to what could be the position of pressure patterns over the region during the ENSO periods. ENSO precipitation patterns are also developed using the CRU precipitation gridded data collected from the Climate Research Unit (CRU), USA.

Analysis are also carried out for identifying the correlation of NAOI values differing from its mean value by more than one standard deviation, with the precipitation in the regions above 31 °N. Decadal correlations between rainfall departures and NAOI are also developed in extreme NAOI years for the region 31°N – 37°N and the Whole Pakistan. Dipole Mode Index (DMI) correlations have been worked out with SOI and with rainfall departures in both El-Nino and La-Nina years.

The analysis also uses the Climate Research Unit, CRU precipitation data set (Mitchell et al; 2003), which includes monthly air temperatures and precipitation for the period 1901-2000 on a regular 0.5° grid size. ENSO composite of geo-potential heights over South Asia region and precipitation patterns during El-Nino and La-Nina years also make part of the study. This data is provided by the NOAA-CIRES Climate Diagnostic Centre, Boulder Colorado, USA through their website at http://www.cdc.noaa.gov. Extreme rainfall events above and below 1 standard deviation are also studied against the ENSO episodes.

ENSO (El-Nino & La-Nina) Tele-connections

Rainfall departures of Monsoon Region of Pakistan and Whole Pakistan from the corresponding long term mean (1951-2012) during the El-Nino and La-Nina years are shown in Table 1 (a) & (b).

Table 1: Rainfall Departures from 1951-2012 mean values for El-Nino and La-Nina years

(a) El-Nino Years				
Years	**Rainfall Departure (mm) (Monsoon Region)**	**Rainfall Departure (mm) (Whole Pakistan)**	**SOI (JJAS)**	**DMI (JJAS)**
1965	-67.77	-25.71	-1.68	-0.04
1972	-36.97	-19.23	-1.53	0.88
1977	51.15	11.51	-1.54	0.10
1982	-39.35	-16.93	-2.29	0.61
1987	-57.27	-25.56	-1.83	0.55
1993	-28.84	-8.31	-1.44	0.12
1994	37.08	30.39	-1.72	0.87
1997	58.84	13.66	-1.95	0.79
2002	-24.50	-14.04	-1.00	0.21
2004	-21.08	-11.62	-0.96	0.07
2009	-62.74	-17.19	-0.13	0.23

(b)

(b) La-Nina Years				
Years	**Rainfall Departure (mm) (Monsoon Region)**	**Rainfall Departure (mm) (Whole Pakistan)**	**SOI (JJAS)**	**DMI (JJAS)**
1955	53.52	17.23	1.55	-0.19
1956	51.05	34.90	0.89	-0.55
1964	22.52	4.94	0.99	-0.40
1971	31.91	-3.35	0.83	-0.16
1973	60.79	17.19	1.08	-0.21
1974	-20.24	-14.37	0.77	-0.05
1975	42.25	16.27	2.00	0.01
1988	74.65	18.63	1.06	0.03
1996	12.38	-1.39	0.82	-0.30
1998	-26.62	-7.51	1.10	-0.01
2010	26.02	40.06	1.60	0.19

In both the cases (Monsoon Region and Whole Pakistan), eight (08) out of eleven (11) El-Nino events that occurred in the period 1951-2012 are found associated with deficient rainfall. Rainfall departures were positive during the years 1977, 1994 and 1997. In case of La-Nina years, nine (09) events showed excess rainfall whereas only two (02) (1974 and 1998) showed deficit rainfall. DMI was found to have a positive phase during all the El-Nino years except in 1965 when it was negative and made the rainfall relatively more deficient. Both positive phase of DMI and negative phase of SOI are associated with deficient rains over Pakistan (for both Monsoon Region and Whole Pakistan). Rainfall departures in the years1977, 1994 and 1997 are an exception as they are found to be positive both in case of negative SOI (El-Nino) and Positive DMI. Similar rainfall patterns are seen in case of both El-Nino years and positive DMI values. La-Nina years and negative DMI values both yielded excess rainfall except in the year 1998. Prasanth and Mohankumar, 2010 also identified that in some years, positive IOD with the simultaneous occurrence of the positive phase of ENSO (El Nino) has facilitated normal or excess rainfall over the Indian region. On the other hand, during some other years, the prevailing negative IOD and El Nino have mutually caused an anomalously deficit rainfall during the monsoon season. The composite analysis of rainfall anomalies demonstrates that the IOD significantly reduces the impact of ENSO on the Indian summer rainfall whenever these events with the same phase co-occur (Ashok et al., 2004). The results of this study are also in line with these studies as can be seen in table-1 that rainfall departures were positive during some positive IOD and El-Nino years 1977, 1994 and 1997.

Figures 2 & 3 show the correlations of SOI with Rainfall Departures during JJAS for Monsoon Region and Whole Pakistan respectively for the period 1951-2012. During the monsoon period (JJAS), the positive correlation over Monsoon Region and Whole Pakistan is significant at 95% level which indicates that more rainfall occurs in La-Nina years compared to the El-Nino years.

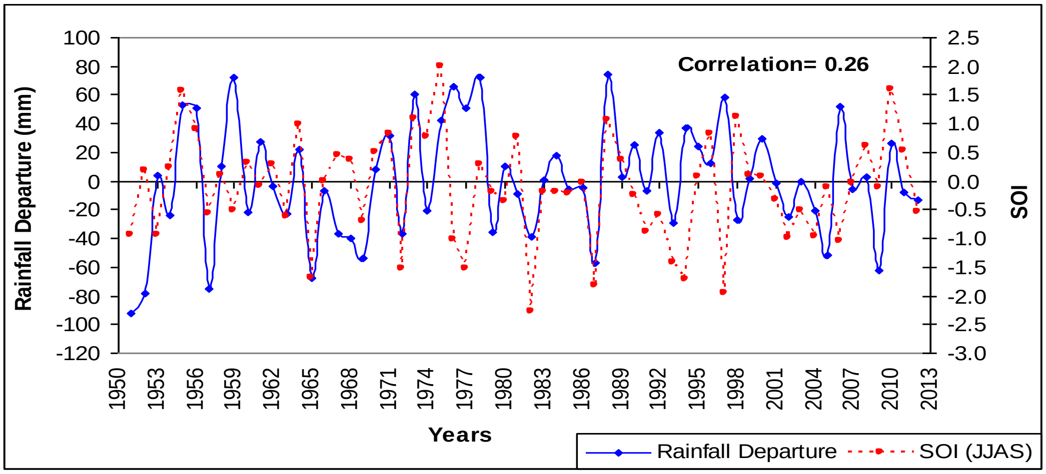


Figure 2: Variation of SOI with Rainfall Departure during JJAS (Monsoon Region)

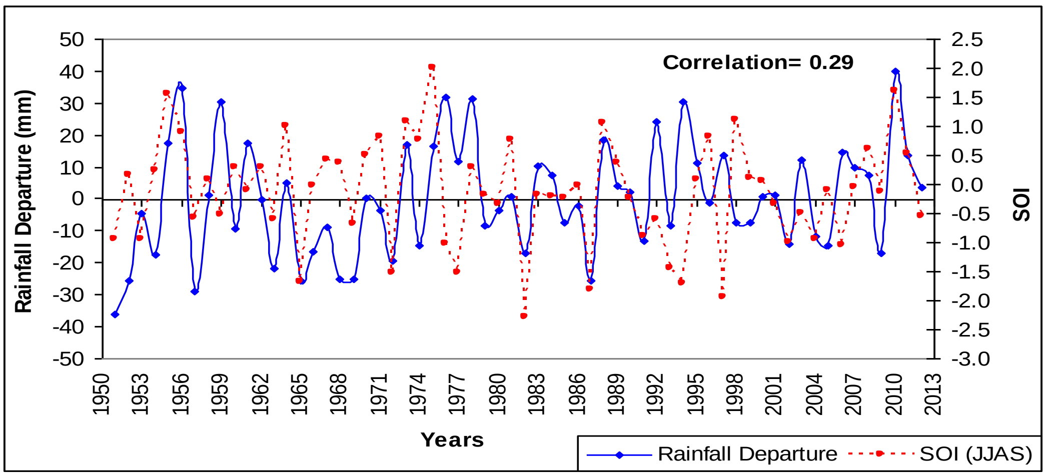


Figure 3: Variation of SOI with Rainfall Departure during JJAS (Whole of Pakistan)

Figures 4 & 5 show the annual patterns of DMI (JJAS) with Rainfall Departures of Monsoon Region and Whole Pakistan respectively. DMI (JJAS) has a slight negative correlation with the rainfall departures.

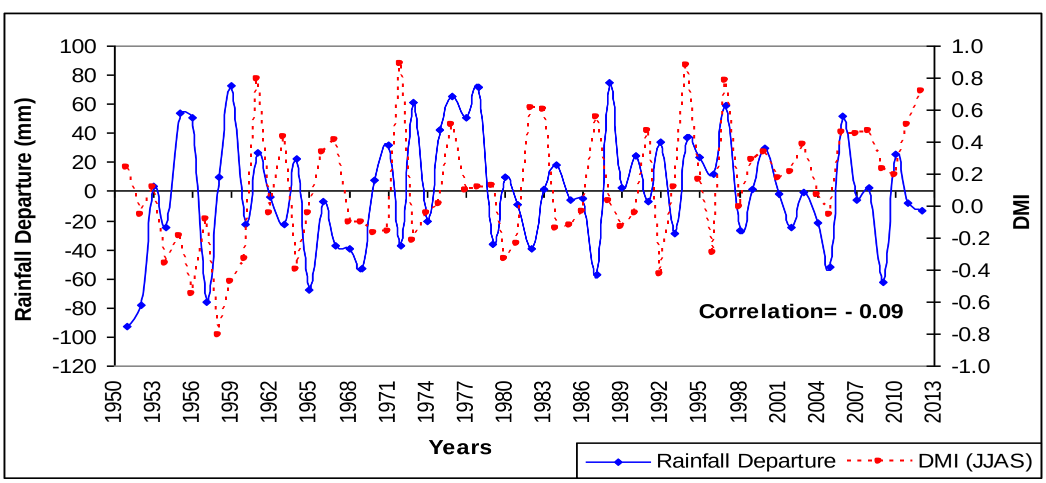


Figure 4: Variation of DMI with Rainfall Departure during JJAS (Monsoon Region)

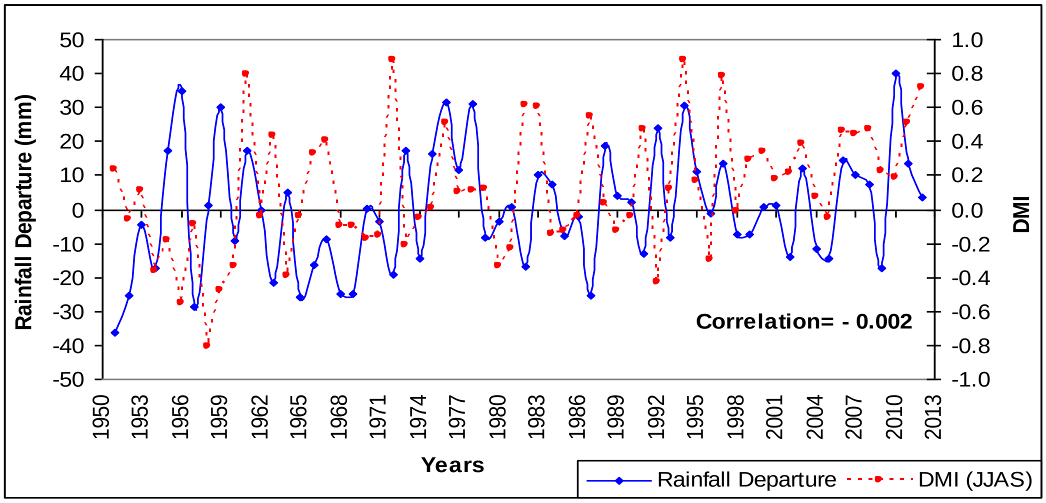


Figure 5: Variation of DMI with Rainfall Departure during JJAS (Whole of Pakistan)

Correlation of SOI and DMI with Rainfall Departures in Different Decades

Decadal correlation coefficients of SOI & DMI with rainfall departures in Monsoon Region and Whole Pakistan are shown in Table 2. In case of SOI, both in the Monsoon Region and in Whole Pakistan, positive correlations are seen during the decades 1951-1960, 1961-1970, 1971-1980, 1981-1990, 2001-2012 and a negative correlation during 1991-2000 (Table 2). In case of DMI, both in the Monsoon Region and in Whole Pakistan, positive correlations are seen during the decades 1951-1960, 1971-1980, 1981-1990 and negative correlation during 1961-1970, 1991-2000, 2001-2012 (Table 2).

Table 2: Correlations of SOI & DMI values with rainfall departures for different decades

	SOI		DMI	
Decades	**Monsoon Region**	**Whole of Pakistan**	**Monsoon Region**	**Whole of Pakistan**
1951-1960	0.46	0.49	-0.60	-0.61
1961-1970	0.67	0.57	0.15	0.22
1971-1980	0.19	0.13	-0.25	-0.07
1981-1990	0.78	0.84	-0.50	-0.44
1991-2000	-0.39	-0.43	0.35	0.19
2001-2012	0.13	0.63	0.39	0.01

Monsoon Depressions Reaching Pakistan during El-Nino Years

From available records of monsoon depressions (Annual Flood reports of Pakistan Meteorological Department for the period 1971-2000), approaching Pakistan from Bay of Bengal and Arabian Sea during the El-Nino years, it is seen that no depression could reach Pakistan except in 1997. In 1997, only two depressions could manage to enter Pakistan. No monsoonal system of the level of a depression could develop in the Arabian Sea in any of El-Nino years (Table 3).

Table 3: Monsoon Depression reaching Pakistan from Bay of Bengal and Arabian Sea during the El-Nino years

Year	Depressions from Bay of Bengal	Depressions from Arabian Sea	Depressions reaching Pakistan
1972	5	-	Nil
1982	7	-	Nil
1987	1	-	Nil
1993	1	-	Nil
1994	Record not available	-	-
1997	6	-	2

Source of Data: Pakistan Meteorological Department

ENSO Composite of Geo-Potential Heights over South Asia Region and Precipitation Patterns during El-Nino and La-Nina Years

During the El-Nino years, most of the depressions dissipated over Bangladesh or over India. The geo-potential height pattern during the El-Nino years compared to La-Nina years developed using the NCEP pressure (850 hPa) reanalysis data showed that the situation was not conducive for the uninterrupted flow of depressions from the Bay of Bengal because of increased geo-potential heights at 850 hPa over India compared to Bay of Bengal and could not allow the flow of depressions to Pakistan across India (Figure 6).

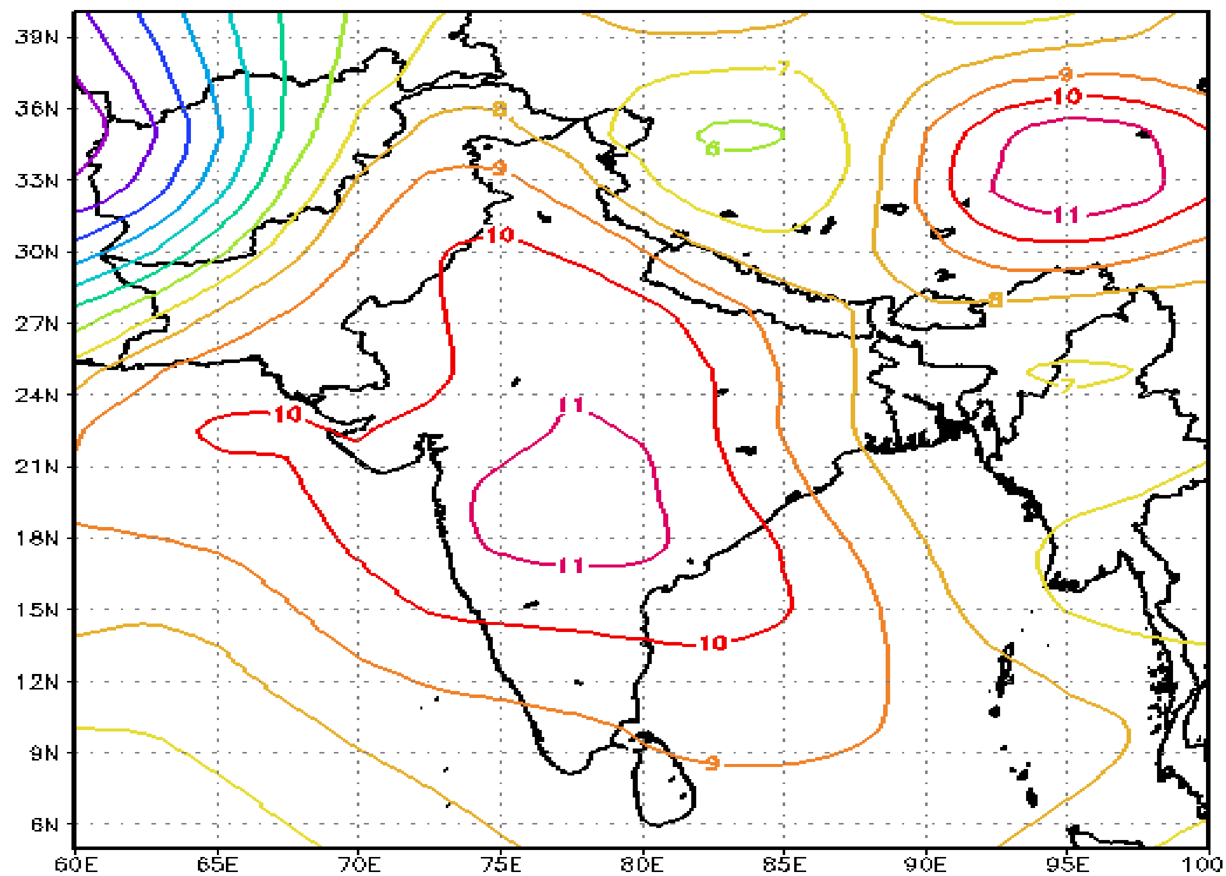


Figure 6: ENSO composite of geo-potential heights at 850hpa over South Asia.

Using the CRU precipitation data set validated for Pakistan, a composite picture was developed over South Asia for the El-Nino and La-Nina years (Figure 7). Rainfall is seen drastically dropped over upper parts of Pakistan.

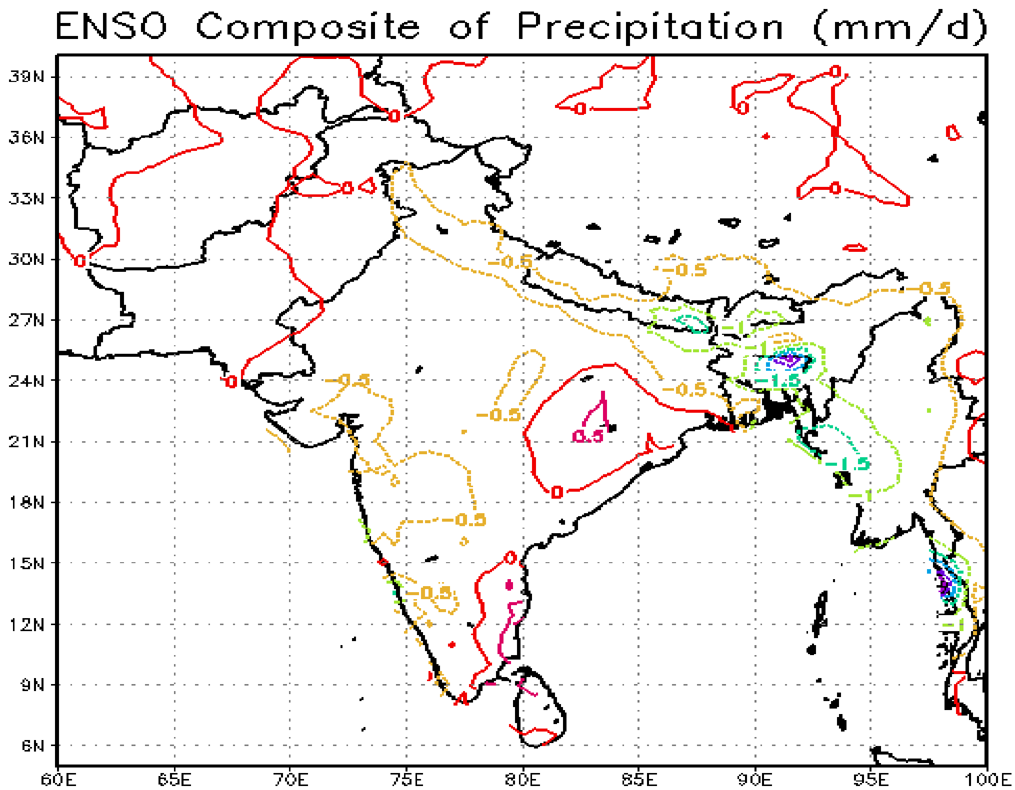


Figure 7: ENSO composite of precipitation (mm/d) over South Asia.

CRU based precipitation patterns during the monsoon season and winter season in Pakistan are respectively shown in Figures 8 (a), (b) for comparison. Both monsoon and winter rains are concentrated in the sub-mountaine regions between around 32°N to 35°N

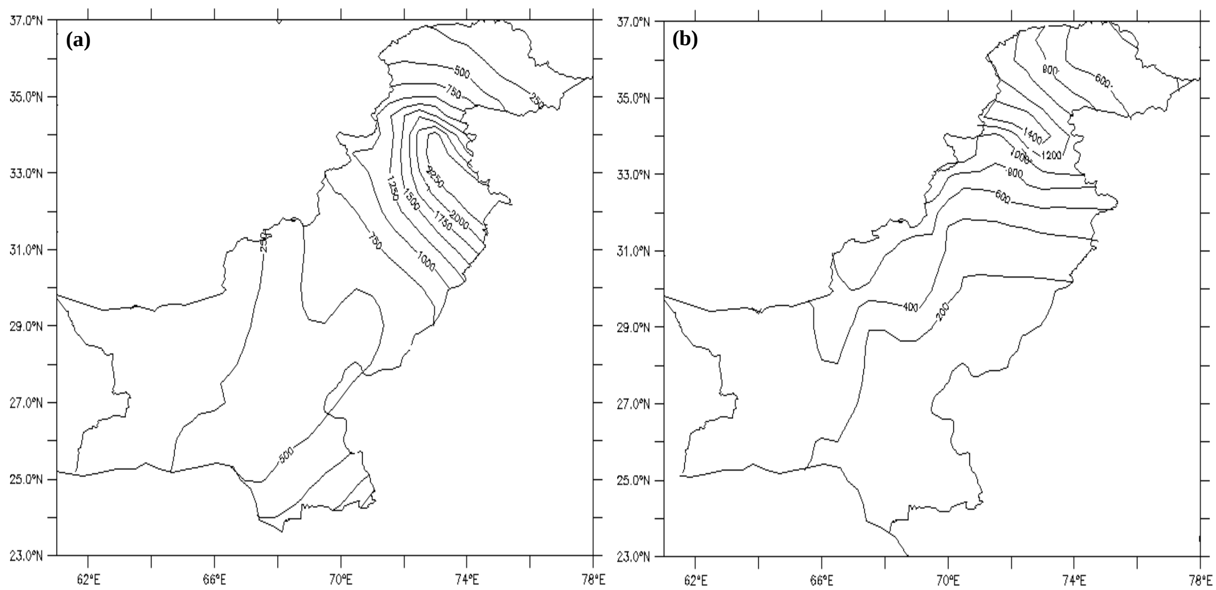


Figure 8: CRU Precipitation in mm/d during JJAS and DJFM over Pakistan.

Rainfall Extremes versus ENSO Episodes

Rainfall events in the Monsoon Region that remained above 1 Standard Deviation (σ) from the 1951-2012 mean value during different years are examined in the context of ENSO episodes mentioned against each. (Table 4)

Table 4: Rainfall Extremes above 1 σ versus ENSO episodes

Year	Precipitation events above	El Nino/La Nina/Neutral	% Departure from mean country rainfall	% Departure from mean monsoon rainfall
1955	1σ	C-	---	41.1
1959	2σ	N	---	49.7
1973	1σ	C-	58.5	32.9
1976	1σ	N	77.1	38.9
1978	1σ	N	78.3	32.6
1992	1σ	W-	16.5	26.6
1994	1σ	W	114.8	20.2
1997	1σ	W+	8.9	27.6

(C-), weak La-Nina; (W-), weak El-Nino; (W), moderate El-Nino; (W+), strong El-Nino; (N), neutral

Source: NOAA/National Weather Service, USA

Extreme rainfall events occurred during either the weak El-Nino or La-Nina years or during the neutral years except during 1994 & 1997 which had have respectively the moderate and strong El-Ninos. In most of the cases, heavy rains in the upper catchments of the rivers caused flooding downstream. The years 1955, 1959, 1973, 1976, 1992 & 1997 witnessed catastrophic floods in Pakistan. (Annual Flood Reports, PMD)

The position in case of precipitation events below 1σ remained as in Table 5.

Table 5: Rainfall Extremes below 1 σ versus ENSO episodes

Years	Below	Classification
1952	1 σ	N
1957	1 σ	W
1965	1 σ	W
1969	1 σ	W-
1982	1 σ	W to W+
1987	1 σ	W+

Most of the cases have deficient rains during both the moderate and strong El-Nino years.

North Atlantic Oscillation (NAO) Forcing

Extreme NAOI values falling above and below 1 standard deviation were identified. Values of NAOI (Dec - Mar) were correlated with the rainfall departures from the 1951-2012 mean values for winter (Dec - Mar) in the northern half of Pakistan (within the region 31°N to 37°N). Correlations of NAOI with winter (DJFM) rainfall departures are positive in both regions. DMI values have a negative but insignificant correlation with winter rains in both regions, as winter rains are usually caused by the moving western disturbances across the regions and do not seem to have a direct link with the IOD phenomena in the Indian Ocean. Figures 9 & 10 show the correlations of NAOI with Rainfall Departures during DJFM for Northern half of Pakistan and Whole Pakistan respectively for the period 1951-2012. During the winter period (DJFM), correlations of NAOI with rainfall departure are positive for both northern half of Pakistan and Whole Pakistan.

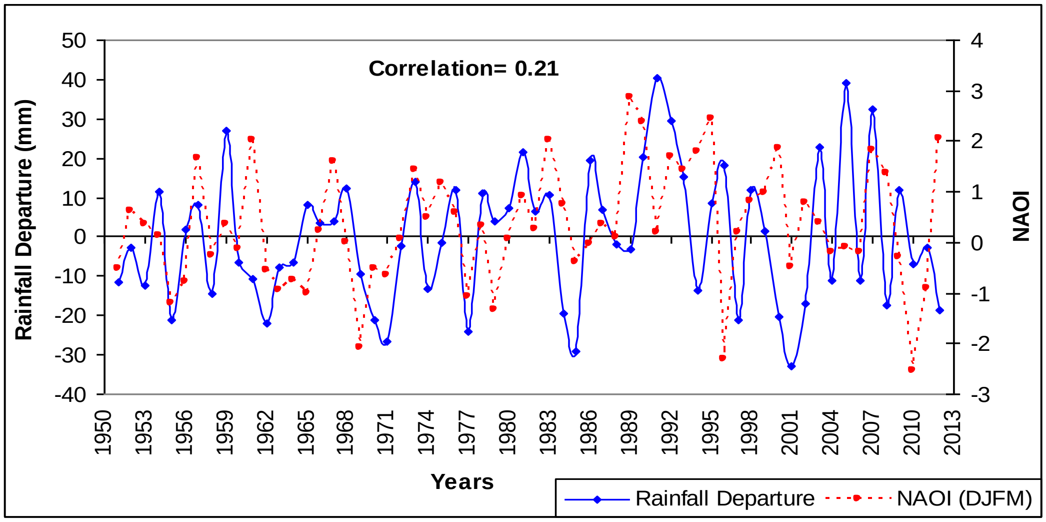


Figure 9: Variation of NAOI with Rainfall Departure during DJFM (Northern half of Pakistan)

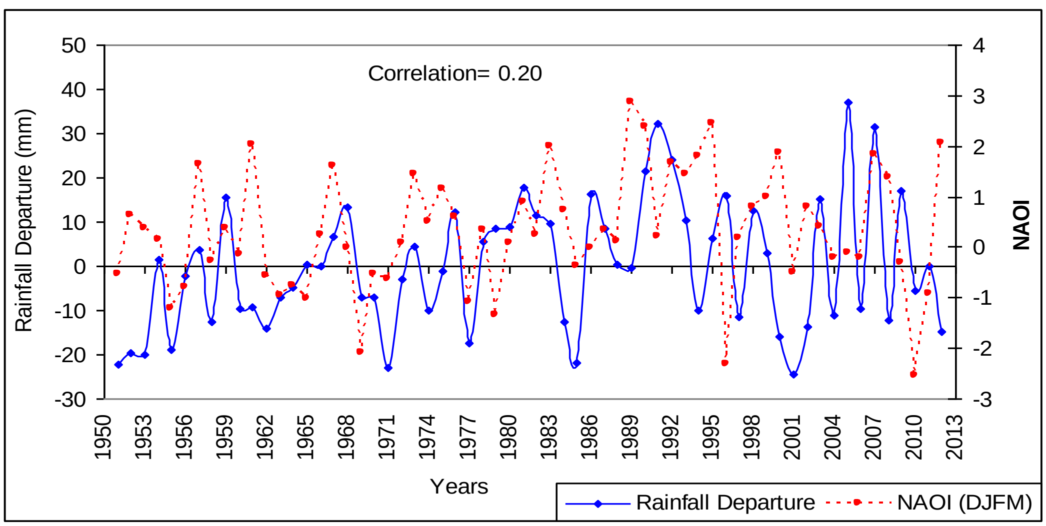


Figure 10: Variation of NAOI with Rainfall Departure during DJFM (Whole Pakistan).

Figures 11 & 12 show the correlations of DMI with Rainfall Departures during DJFM for Northern half of Pakistan and Whole Pakistan respectively for the period 1951-2012. During the winter period (DJFM), correlations of DMI with rainfall departure are negative for both northern half of Pakistan and Whole Pakistan.

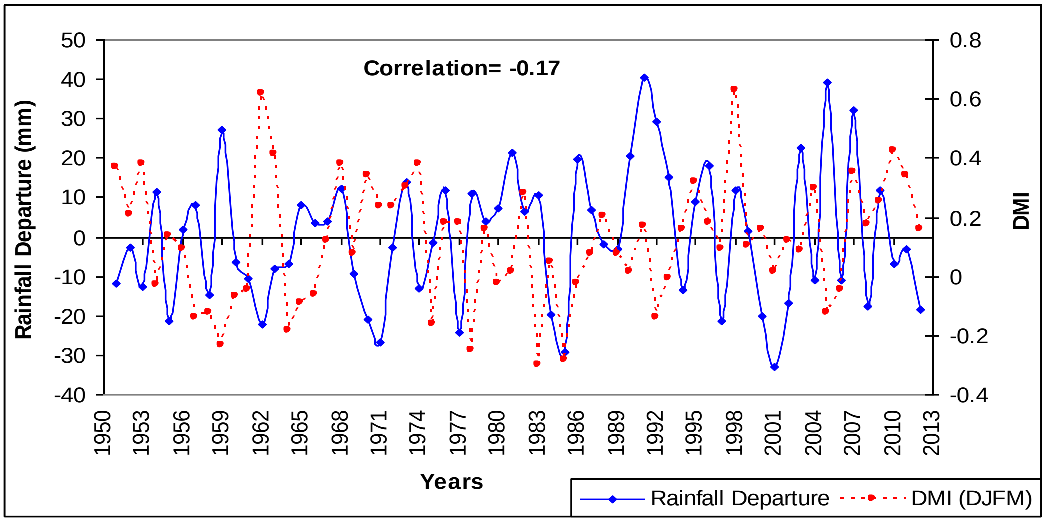


Figure 11: Variation of DMI with Rainfall Departure during DJFM (Northern half of Pakistan).

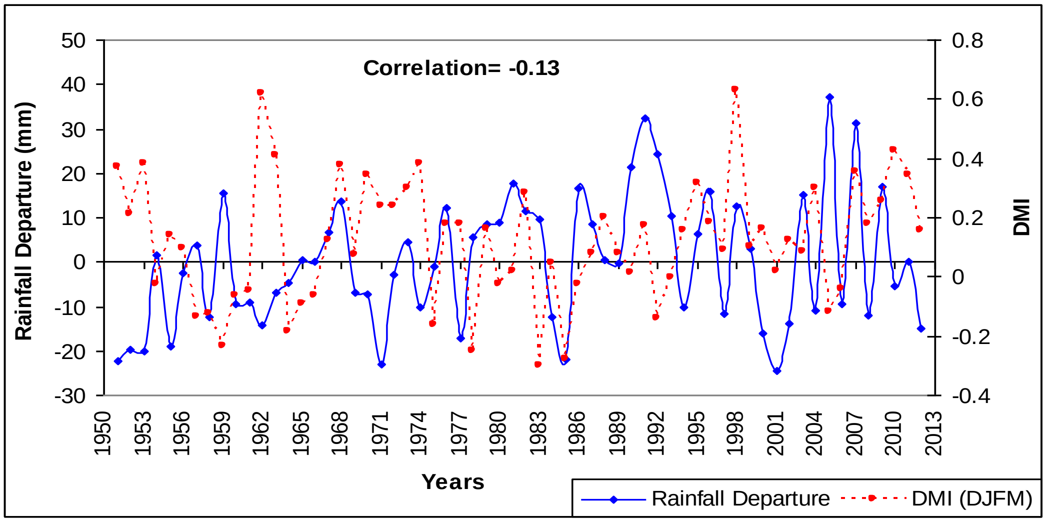


Figure 12: Variation of DMI with Rainfall Departure during DJFM (Whole Pakistan).

Extreme NAOI values falling above and below 1 standard deviation were identified and correlated with rainfall departures from 1951-2012 mean values for winter (Dec-Mar) for both Northern half of Pakistan and Whole Pakistan. Positive correlations were found with NAOI values and negative correlations with the corresponding values of DMI (Table 6)

Table 6: Correlation of Extremes NAOI values and Corresponding DMI values with the rainfall departures

Extreme NAO Years		
	NAOI (DJFM)	DMI (DJFM)
Rainfall Departure (Northern Half of Pakistan)	0.21	-0.20
Rainfall Departure (Whole Pakistan)	0.23	-0.17

Decadal correlations of NAOI with winter rainfall departures from the 1951-2012 mean values for the period (Dec-Mar) for both regions were also computed and are shown in Table 7. In case of NAOI, both in Northern half of Pakistan and in Whole Pakistan, positive correlations are seen during the decades 1951-1960, 1961-1970, 1971-1980, 1981-1990, 2001-2012 and a negative correlation during 1991-2000 (Table 7). In case of DMI, both in Northern half of Pakistan and in Whole Pakistan, negative correlations are seen during the decades 1951-1960, 1971-1980, 1991-2000, 2001-2012 and positive correlation during 1981-1990 (Table 7).

Table 7: Correlation of NAOI and DMI values with rainfall departures for different decades.

	NAOI		**DMI**	
Decades	**Northern half of Pakistan**	**Whole of Pakistan**	**Northern half of Pakistan**	**Whole of Pakistan**
1951-1960	0.51	0.38	-0.60	-0.81
1961-1970	0.18	0.25	-0.40	-0.15
1971-1980	0.52	0.35	-0.35	-0.36
1981-1990	0.29	0.31	0.20	0.27
1991-2000	-0.24	-0.30	-0.07	-0.04
2001-2012	0.09	0.09	-0.03	-0.20

Conclusions

1. El-Nino years and positive DMI values are associated with deficient rainfall over both Monsoon Region and Whole Pakistan. Rains are in excess in the last decade (1991-2000).
2. La-Nina years are generally positively correlated with rainfall departures, except during the last decade of 1990s.
3. NAOI values were seen to have a positive correlation with winter rains for the region 31°N-37°N and for Whole Pakistan.
4. DMI values showed only slight negative correlation with the winter rains for both region 31°N-37°N and the Whole Pakistan but those were found insignificant.
5. The composite pattern of Geo-potential heights over India, the passage for the flow of monsoon depressions from Bay of Bengal to Pakistan, indicated higher pressure over most of India compared to the pressure over Bay of Bengal blocking the uninterrupted flow of monsoonal systems to Pakistan.
6. The ENSO composite of precipitation pattern over South Asia showed drastic drop in rainfall over the upper parts of Pakistan.

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