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Modelling the Impact of Indian Ocean on Pakistan Summer Monsoon Rainfall

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Abstract

The challenging problem of long-range forecast of summer monsoon rainfall has grown into a major area of research in monsoon meteorology. This paper examines the impact of Indian Ocean on Pakistan summer monsoon rainfall. The correlation analysis shows that sea surface temperature of Indian Ocean has significant influence on Pakistan summer rainfall. We use Arabian Sea surface temperature index (AS1) and Central Indian Ocean temperature index (CIOI), geopotential height for 500 hPa at Tibetan Plateau and North Atlantic Oscillation to construct a multiple regression which explained 67% variability of summertime monsoon rainfall in Pakistan from 1961 to 2000.

Keywords and Phrases: Summer Monsoon Rainfall, SST, Linear Model.

AMS Classification: 62P12.

1 Introduction

In view of the critical influence of inter-annual variability in summer monsoon rainfall on agriculture, industrial production, etc., a forecast of the monsoon rainfall, at least a season in advance, assumes a profound importance for policy making and planning of efforts to mitigate the effects of natural hazards such as drought. In particular, given the exploding population scenario of today, the increasing threat to agriculture, the problem of potable water reserves, and energy generation abundantly speak for the importance of rainfall distribution models (Bounoua et. al, 1999). However, the question of reliable forecast of seasonal distribution of rainfall for any specific part of globe is now much harder to resolve. This challenging problem of long-range forecast of summer monsoon rainfall has grown into a major area of research in monsoon meteorology. The climatic changes during the last hundred years was rather peculiar in that one witnesses frequent as also abrupt attack of drought and flood (Christensen and Christensen, 2003; Hasan and Quamar, 2000) in places where it was hard to expect them.

As such, Chaudhary has constructed a summer rainfall model for Pakistan by considering the areal-weighted average of 38 climate stations (Chaudhary, 1994). This study, however, leaves out the hilly regions of the country, parallel to the large Himalayan mountain range, thus covering only about 88% of the total area of the country. Moreover, the important factor of impact of Arabian SST on the climate variability, in particular annual rainfall, of Pakistan is left unattended in Chaudhary. This contribution is, therefore, an attempt to fill the gap of a systematic study of summer rainfall forecast problem for the region. This contribution is an attempt to build a reason model for a description of behaviour of the dynamical system represented by the Pakistan summer monsoon rainfall. In particular, this paper explores the relationship between the Indian Ocean SST and Pakistan monsoon rainfall.

As for the dynamic of monsoon, several types of monsoon flow from the Bay of Bengal and the Arabian Sea into Pakistan (Haq, 1997). Most of the time the precipitation-inducing monsoon cloud systems are the outcome of the Bay of Bengal depressions, which move inland over India into the monsoon trough. Their direction of travel towards Pakistan depends on the blocking highs over India. Such blocking highs can be determined with TOVS (TIROS Operational Vertical Sounder) 850, 700, and 500 hPa dry / moist geo-potential height chart. The chance of rain-bearing monsoon systems reaching Pakistan also depends on their intensity and the extent of low pressure over Pakistan. The general paths of large, low-pressure, heavily moisture-laden monsoonal systems coming from the east to Pakistan are along either of the following directions:

(A) Bengal-Punjab-Kashmir-North-West Frontier Province,

(B) Orissa-Madhya Pradesh-Rajasthan to lower Punjab-upper Baluchistan- North-West Frontier Province in Pakistan, and

(C) Orissa-Madhya Pradesh-Gujarat-Kutch to Sindh and Baluchistan.

If the intertropical convergence zone (ITCZ) moves northward to high latitude (above 15°N), it seems to induce rain-bearing Arabian Sea depressions off the coast of Kathiawar peninsula in India. It is observed that if the surface pressure over Sindh is low, such depressions over Gujarat / Kathiwar almost always travel towards Sindh, causing heavy rainfall in eastern Sindh and some times even in Karachi. On the other side, under the influence of blocking highs, a deep depression over Gujrat / Kathiawar occasionally travels northward over western Rajasthan or bordering areas into Kashmir and brings heavy rain to the catchment areas of the Indus and other large rivers of Pakistan which drain her plains. These blocking highs, which channel the rain-bearing systems, can be observed with TOVS and APT (automatic picture transmission) visible / IT images. Such deep depressions may originate in the Arabian sea or travel from the Bay of Bengal through a monsoon trough located over Orissa, Madhya Pradesh, and into Gujarat / Kathiawar (Haq et al., 1997). Such blocking highs over northern India appear to be induced under the influence of westerly subtropical jet stream. Centered at 200 hPa level during the monsoon months, this jet is normally located north of Himalayan range over Tibet. Sometimes, it induces high pressure over northern India because of its wobbling. This high pressure acts as a blocking high to the normal monsoonal flow and channel rain-bearing systems towards Sindh and the lower Punjab in Pakistan.

The above discussions clearly demonstrate about the role of Arabian Sea on Pakistan monsoon system. As far as the monsoon study of the Indian subcontinent is concerned, an empirical forecast of Indian monsoon rainfall has been performed using combinations of climatic parameters including atmospheric pressure, wind, snow cover, SST, and phases of ENSO El-Nino Southern Oscillation (Parthasarathy et al., 1988; Shukla and Mooley, 1987; Hastenrath, 1986; Hastenrath 1987; Harzallah and Sadourny, 1997; Sadhuram, 1997). Moreover, regression models based on these climatic parameters and other empirical variables result in prediction of 60-80% of total seasonal rainfall by May in India (Hastenrath, 1994). Also, it has been shown that the Indian ocean SST is significantly correlated with the Indian Rainfall several months preceding the onset of summer monsoon (see, for instance, Rao and Goswami, 1988; and Sadhuram, 1997).

This paper examines the impact of Indian Ocean on Pakistan summer monsoon rainfall. We also construct a model of Pakistan rainfall using sea surface temperature and sea level pressure of Indian Ocean / Arabian Sea, ENSO, 500 hPa Pressure at Tibet Plateau, North Atlantic Oscillation (NAO) and local temperature and pressure.

2 Data

We analyse monthly data of precipitation (including temperature and pressure data) in this paper for the following 44 climate stations of Pakistan (listed in Table 1, see Fig 1) for the time-interval 1961-2000, as compiled by Pakistan Meteorological Department, Karachi. Some data are missing for some climate stations. Tables 1 shows the number of monthly precipation observations missing for 44 different climate stations of Pakistan for the epoch 1961 to 2000. We employ simple spatial interpolation algorithm to determine the missing data.

Another dataset studied here is that of GISST (Global Sea-Ice and Sea-Surface Temperature data), version 2.2, compiled from ship records (Parker et al. 1995). They contain a global record of monthly ($1^\circ \times 1^\circ$)-grid cell of SST for 1903-2000. GISST and the (third) dataset of Global Mean Sea Level Pressure and Geo-Potential Height investigated here have been compiled by Meteorological Office of Hadley Centre

(UK). The source of Southern Oscillation Index employed here is this:

http://ingrid.ldgo.columbia.edu/SOURCES/.Indices/.standardized/soi/.
dataset_documentation.html.

The North Atlantic Oscillation Index data for 1961-2000 is from Phil Jones et al. (1997), Climatic Research Unit, University of East Anglia (Jones et al., 1997). The northern hemisphere landmass temperature data are taken from NCDC.

3 Computing Summer Monsoon Rainfall Series for Pakistan

In the arid / semi-arid region of Pakistan, comprising some planar area coupled with a sizeable percentage of mountainous areas, rainfall data of different climate stations taken together constitute a very patchy or noisy spatial structure due to large noise variance in the monthly or seasonal data. Thus producing a separate forecast at each station should not lead to a reasonable construction of rainfall model. In fact, in most operational seasonal forecasts some form of data averaging is employed, which is either large-scale area averages−such as those for India or the northeast Brazil or data reduction using techniques such as empirical orthogonal functions−as in the seasonal forecasts of National Centre for Environmental Prediction (USA).

Employing the rainfall dataset of the 44 stations of Pakistan for the period 1961 to 2000, we compute the standardised seasonal anomalies by subtracting the seasonal mean of June to September from the data and dividing the difference by the seasonal standard deviation. The resulting time series for each station has zero mean and approximately unit variance. We next compute for each year the mean of the standardised seasonal rainfall time series of 44 stations. Thus the all Pakistan summer monsoon rainfall index, I_ρ, for the year j may be defined as

$$I_{\rho j} = \frac{1}{N} \sum_{i=1} \left(\frac{R_{ij} - \bar{R}_i}{\sigma_i} \right) \tag{1}$$

$N \equiv$ [total number of climate stations],

$R_{ij} \equiv$ [amount of seasonal rain at the station i in the year j],

$\bar{R}_i \equiv$ [mean rainfall for all the years at station i], and

$\sigma_i \equiv$ [standard deviation of years for station i].

The time series of All Pakistan Summer Monsoon Rainfall Indices is graphed in Fig. 2.

4 SST-Pakistan Rainfall Relationships

Most of the studies aimed at resolving the challenging problem of modelling and long-range forecast (LRF) of summer monsoon are based on statistical and empirical techniques. However, diagnostic studies of historical data models over the years have brought to light several parameters for monsoon rainfall forecasting pertaining to different regions of the globe. Such parameters represent different components of atmosphere-ocean-land system and their effects appear to be wide-ranging and often severe. Thus it is important to understand the role of parameters in any modelling and forecasting problem which are basic in the above sense. Albeit techniques for identifying parameters range from simple correlation analysis to advanced procedures such as canonical correlation and neural network (Hsieh, 2000; Koslo, 1992), we go here-below for the standard correlation analysis because it is the simplest.

4.1 Sea Surface Temperature

As regards South Asia, an important question to ask is what the relationship of Indian Ocean to summer monsoon in the region is. Specifically, how this will contribute to a prediction of Pakistan rainfall at lead times significantly longer than the May preceding the onset of South Asian summer monsoon. Several studies report empirical links between this monsoon and the Indian Ocean SST (Nicholls, 1983; Shukla and Mooley, 1987; Joseph and Pillai, 1984; Rao and Goswami, 1988; Allan et al., 1995; Kumar, Soman and Kumar, 1995). In particular, the present study explores the relationship between the Indian Ocean SST and Pakistan monsoon rainfall.

Albeit the butterfly effect (chaos theory) asserts that phenomena in distant regions can have a profound influence on a local event, nevertheless it is manifest that physically what is directly relevant to Pakistan is a region spanning the waters from Arabian Sea to Bay of Bengal and the contiguous portion of central tropical Indian Ocean. So we restrict our analysis to the region of tropical Indian Ocean within latitudes 24°S to 24°N and longitudes 40°E to 120°E and employ a moderate-sized ($4° \times 4°$) trial grid of monthly SST data model for 1961-1990 (Parker et al., 1995). To assess the relationship of I_ρ to the monthly SST preceding the monsoon, we work out the correlation between these two parameters at each grid point within the range within (24°S-24°N, 40°E-120°E). Performing computations at all grid points leads to only two independent variables, with significantly large correlation, on which I_ρ appears to depend. As for exact results of our computation, they are summarised in Table 2. The discussion and the emerging findings are as follows. The correlation of I_ρ with average December temperature of the area of a ($4° \times 4°$)-grid cell centred at the position (17°N, 63°E) in Arabian Sea−Arabian Sea SST Index (ASI)−turns out to be 0.553 (cf. Table 2). Further, time series plots of ASI and I_ρ reveal that for 10 out of 16 years in which ASI was above the mean, Pakistan summer rainfall was also above normal. On the other hand, 10 out of 14 years in which ASI was below the mean also had below-average rainfall in Pakistan. Therefore, it is not unwarranted if we take the

ASI to be a basic parameter which influences monsoon strength, $I\rho$.

Our computations also reveal that there exists another useful SST parameter related to the time series I_ρ. It is the average of April temperature of the area of ($4^\circ \times 4^\circ$)-grid cell centred at the location (23°S, 83°E) in the Central Indian Ocean−Central Indian Ocean April SST Index (CIOI)−in that there exists a high correlation of 0.6 (as summarised in Table 2) between CIOI and our rainfall index I_ρ. The time series plots of I_ρ and CIOI show that 12 out of 17 years in which the CIOI is above-average have above-average Pakistan rainfall, and 11 out of 13 years in which the CIOI is below-average has below-average rainfall. Hence it is not unreasonable to consider CIOI as another independent variable affecting Pakistan monsoon. It is interesting to observe that our findings are compatible with previous studies which used different SST data models (Harzallah and Sadourny, 1997; Sadhuram, 1997).

4.2 Sea Surface Pressure

Over the large ocean basins, seasonal changes in the tropical circulation are limited to minor latitudinal shifts and small variations in intensity of main climate parameters but the general pattern remains virtually the same throughout the year. However, over the tropical continents and adjacent seas, the picture is different. Here important seasonal temperature and pressure changes appear to take place. Specifically, seasonal contrasts in landmass temperatures produce atmospheric pressure changes which in turn produce seasonal reversals of pressure gradient force, the basic driving force of winds.

To check for the influence of Arabian Sea-level pressure (SLP) on I_ρ, we confine our analysis to the portion of tropical Indian Ocean with latitudinal range 25°S to 25°N and longitudinal range 40°E to 125°E. For computations, we use a ($5^\circ \times 5^\circ$) grid of monthly SLP data model covering the period 1961-1990. To determine the monthly SLP-I_ρ relationship preceding the monsoon, we compute the correlation between the two parameters at each grid point within the range (25°S-25°N, 40°E-125°E). As regards computational results and emerging findings, they are as follows. The correlation of an individual month SLP occurring in the Arabian Sea in May at (25°N, 60°E) with I_ρ comes out to be 0.57 (Table 2). This establishes the May SLP as yet another physical variable having impact on the monsoon for Pakistan.

4.3 El-Nino Southern Oscillations

In addition to the conventional parameters of temperature, pressure, etc. governing fluid dynamics, hydrodynamics of the open thermodynamical system of terrestrial atmosphere- ocean-landmass appears to be governed by important nonstandard parameters dubbed ‘anomalies’ (Sharp, 1992). A significant progress has been made over the last decade in understanding the mechanism and global manifestation of the weather and climate anomalies referred to as Southern Oscillations (ENSO). The ENSO phenomenon is related to the warming of specific portions of Earth’s upper ocean, with a relatively intense warming during a certain period, punctuated by a moderate warming during another. In particular, it is responsible for longer-term changes arising from the upper ocean heat loss in the Pacific Ocean and constitutes the largest single source of inter-annual climatic variability on a global scale.

It is expected that global warming will result large changes in climate of Asia, including changes in the monsoon intensity and duration over South Asia, Southeast Asia, and East Asia, and in the relationship between ENSO and monsoon (Kitoh et al, 2005; IPCC, 2001). As for the role of ENSO phenomena in the variability of annual rainfall / drought over south Asia, computations of areal mean rainfall during 1867-85 based on a varying network of about 500 rain gauges show that the mean annual rainfall of the Indo-Pakistan subcontinent ranges from 900 mm in 1868 to 1240 mm in 1878 (Blanford, 1886). Another estimate of the countrywide mean summer (June to September) monsoon of the subcontinent provides a negative correlation of monsoon data with the SOI (Walker, 1910).

As regards Pakistan, our computations show that we receive less than average summer rainfall in most part of the country during 60% of el-Nino years. For instance, Lahore receives less than average summer rainfall in 15 el-Nino years out of 25 el-Nino years during the epoch 1882-2000. Therefore, for our selected epoch 1961-1990, it makes sense to consider the possibility of a relationship of I_ρ to the monthly values of SOI during the preceding as well as succeeding period of monsoon. The correlation analysis shows that the correlation coefficient (CC) between I_ρ and SOI of previous June is 0.54 (cf. Table 2), with the p-level given by 0.002. Similarly, the CC between I_ρ and SOI of February minus May turns out to be 0.41 (Table 2) with the p-level as 0.026. Hence it is not unreasonable to consider SOI as a further independent variable which affects I_ρ.

4.4 Geopotential Height

As most of solar radiation reaching the Earth is received in the Tropics, the tropical belt plays a very important role in the general circulation of atmosphere. In fact, the Tropics are major source of heat, moisture, and angular momentum governing climate. As regards the pressure structure of the important region of Tropics, the mean sea level pressure pattern shows a section of high pressure cells between the latitude 20° to 40° north and south, with a longitudinal extent of about 10° to 20°. Between these belts of high-pressure cells, often referred to as 'subtropical high' or 'anticyclones' , there is an area of low pressure, called the 'equatorial trough'. And this zone of low pressure, enclosed between the subtropical high-pressure belts of the two terrestrial hemispheres, extends around the globe. The strong and steady winds blowing in the lower troposphere between the subtropical high-pressure belts and the equatorial trough are known as trade winds. The trade winds from both hemispheres meet in the equatorial trough zone, giving rise to the ascending atmospheric motion. In other words, the equatorial trough constitutes the ascending portion of the so-called Hadley cells between the two hemispheres (Pant and Kumar, 1997). Again, there is the tropical maritime air on the equator side of inter-tropical climate zone (ITCZ), while on the polar side there is subsiding air descending limb of the Hadley cell which is relatively warm and dry. Thus the air is cooler on the equator side of ITCZ. Consequently, ITCZ slopes towards the side of cooler air with height i.e. equator. As regards the wind discontinuity, ITCZ is deepest over South Asian region during July, extending up to 400 hPa. On the other hand, it is rarely seen above 700 hPa elsewhere (Pant and Kumar, 1997).

What precedes suggests that the subtropical high plays an important role in the monsoon circulation. This asks for a more exact determination of the relationship between the geopotential height and our I_ρ time series. For this, we use the geopotential height data model for 500 hPa for the epoch 1961-1990. Our computations show that there is a reasonable correlation between I_ρ and the geopotential height for 500 hPa at the coordinates (40°N, 110°E), which is the Tibetan Plateau. In particular, as Table 2 shows, the April geopotential height data at Tibet Plateau correlates to I_ρ at CC = 0.4. We, thus, arrive at a mathematical demonstration of a rather significant influence of the geopotential height on I_ρ model of Pakistan rainfall time series constructed above in Section 3.

4.5 North Atlantic Oscillations

Yet another major mode of variability over northern hemispheric atmosphere−which includes the region under study viz. Pakistan−is the North Atlantic Oscillations (NAO). The NAO is traditionally defined as the normalised pressure difference between a station on Azores and one on Iceland. It is particularly important in winter, when it exerts a strong control on the climate of Northern Hemisphere (Jones et al., 1997). It is also the season which exhibits the strongest interdecadal variability. These considerations suggest that NAO influences the temperature of Indian ocean. To assess the possibility of such a relationship more exactly, we consider the data model of NAO for the epoch 1961-1990. Our computations show that the correlation between NAO for the month of January and I_ρ is 0.4 (Table 2). Thus NAO turns out to be another independent variable influencing the rainfall index I_ρ.

4.6 Northern Hemisphere Surface Temperature

Similar considerations and computations yield the result that the CC between Northern Hemisphere landmass temperature (NHST) for winter and I_ρ during the selected epoch 1961-1990 is 0.45 (see Table 5.2). Therefore, we can identify the winter NHST as another independent variable which influences Pakistan summer monsoon rainfall.

4.7 Regional Conditions

It is generally known that development of southwest summer monsoon over Pakistan is closely linked to the hottest region over the southern parts of Pakistan and the adjoining northwest part of India (Chaudhary, 1994). In particular, the evolution of a heat low over Baluchistan is an important annual cycle precursor of summer monsoon. This helps build up a strong meridional pressure gradient from south Indian ocean right to South Asia and hence a strong lower troposphere cross-section equatorial flow. This, in turn, transports large amounts of water vapour into the Northern hemisphere. Therefore, we can assume that the years with high temperatures during pre-monsoon period over these regions may get good monsoon rainfall over Pakistan and vice-versa.

For a quantitative relationship between I_ρ and regional conditions, we compute CCs between the temperature of Hyderabad and I_ρ using each monthly temperature series of Hyderabad for the epoch 1961 to 1990. What we find is that CC for May temperature of Hyderabad is 0.47 (cf. Table 2). As another instance of the influence of regional conditions on I_ρ, our computations show that CC for May pressure of Hyderabad is 0.51 (Table 2). Therefore, May temperature and pressure of Hyderabad can be taken as two other independent variables affecting Pakistan rainfall index I_ρ.

5 Constructing a Model of Summer Monsoon Rainfall

We finally consider the modelling and forecasting problem for summer rainfall pattern for Pakistan. For the purpose, we apply stepwise linear multiple regression analysis to our 1961-1985 data of independent variables (listed with their correlation coefficient with I_ρ in Table 2) and of responses I_ρ to build a rainfall model:

$$I_\rho = 15.79 + 0.8483x_1 + 0.3041x_2 - 0.008039x_3 + 0.09078x_4, \tag{2}$$

with

$I_\rho =$ (All Pakistan Summer Monsoon Rainfall Index),

$x_1 \equiv$ (Arabian Sea Temperature Index),

$x_2 \equiv$ (Central Indian Ocean Temperature Index),

$x_3 \equiv$ (geopotential height for 500 hPa at Tibetan Plateau),

$x_4 \equiv$ (January North Atlantic Oscillation),

for Pakistan using these predictors. The immediate question we now face is to determine how accurate the proposed model (2) is. A straight-forward as well as effective way to do this is to compute the multiple correlation coefficient (R) or, alternatively, coefficient of determination (R^2) between our predictors x_i and response variable I_ρ figuring in Eq. (1). A quick calculation shows that R^2 comes out to be 80.8% , corresponding to the respective computed t-statistics and chosen p-value of confidence level. All these computations are summarised in Table 3. Table 4 summarises the analysis of variance of the stepwise multiple regression model for Pakistan summer rainfall model,

I_ρ. The root mean square error is 0.2579. What is the net result emanating from these computations? As the coefficient of determination turns out to possess quite a high value, it provides a sufficiently strong confirmation of a minimal presence of errors in the model (2). Moreover, the model is validated using the data for the period 1986 to 2000. Finally, Fig 3 gives a comparison between the observed and the predicted values of I_ρ. Fig 3 shows that our predicted values finely coincide with the observed ones for the period 1986 to 2000 with 67% accuracy.

6 Conclusion

The Asian region weather system prediction, including climate variability over a smaller area like that of Pakistan, is a poorly understood problem. Notice the added difficulty that recent complications like global warming play up the standard problem of rainfall / drought predictability. The climatic change during the last hundred years was rather peculiar in that one witnesses frequent as also abrupt attack of drought and flood in places where it was hard to expect them. In particular, the question of reliable forecast of seasonal distribution of rainfall for any specific part of globe is now much harder to resolve. Our calculations showed that Pakistan summer monsoon rainfall is strongly correlated with Indian Ocean sea surface temperature variability. We employed Arabian Sea surface temperature index (AS1) and Central Indian Ocean temperature index (CIOI), geopotential height for 500 hPa at Tibetan Plateau and North Atlantic Oscillation to construct a linear regression model which explained 67% variability of summertime monsoon rainfall in Pakistan from 1961 to 2000. The validation of the model shows that the model is reasonable for the prediction of Pakistan summer monsoon rainfall in view of this that rainfall prediction is quite difficult task. However, one should try to construct physical / numerical model (GCM / RCM) for the prediction of Pakistan summer monsoon rainfall as an alternative method.

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Table 1. Pakistan climate stations, with number of missing data in the monthly precipitation time series for the epoch 1961 to 2000

#	*Stations/ Months*	JA	FB	MR	AP	MY	JN	JL	AG	SP	OC	NV	DC
1	Bahawalnagar	5	5	6	6	6	8	7	7	6	7	5	5
2	Bahawalpur	3	3	3	2	2	2	2	2	3	2	2	3
3	Faisalabad	0	0	0	0	1	2	0	0	1	0	1	1
4	Islamabad	0	0	0	0	0	0	0	0	0	0	0	0
5	Jhelum	0	0	0	0	0	0	0	0	0	0	0	0
6	Khanpur	0	0	0	1	0	0	1	1	1	1	0	0
7	Lahore	0	0	0	0	0	0	0	0	0	0	0	0
8	Multan	0	0	0	0	0	0	0	0	0	0	0	0
9	Murree	3	3	3	3	2	1	0	0	0	0	0	0
10	Sialkot	0	0	0	0	0	0	0	0	0	0	0	0
11	Badin	0	0	0	1	0	0	0	0	0	0	0	0
12	Chhor	1	0	0	0	0	0	0	0	0	0	0	1
13	Hyderabad	0	0	0	0	0	0	0	0	0	0	0	0
14	Jacobabad	0	0	0	0	0	0	0	0	0	0	0	0
15	Karachi	0	0	0	0	0	0	0	0	0	0	0	0
16	Nawab Shah	1	2	1	1	1	2	1	1	1	1	1	1
17	Padidan	0	0	0	0	0	0	0	0	0	0	0	0
18	Sukkar	0	0	0	0	0	0	0	0	0	0	0	0
19	Barkhan	7	7	6	6	7	6	7	6	7	6	7	6
20	Dalbadin	1	0	0	0	0	0	0	0	0	0	0	0
21	Jiwani	0	0	0	0	0	0	0	0	1	1	0	0
22	Khuzdar	5	5	5	5	5	5	6	5	5	5	5	5
23	Nokkundi	1	0	0	0	0	0	0	0	0	1	0	1
24	Panjgur	0	0	1	0	0	0	0	0	0	0	0	0
25	Pasni	4	5	3	2	2	1	3	4	5	4	4	2
26	Quetta	0	0	0	0	0	0	0	0	0	0	0	0
27	Sibbi	1	1	1	1	1	1	1	1	1	1	1	1
28	Zhob	0	0	0	0	0	0	0	0	0	0	0	2
29	Balakot	5	5	4	4	5	5	4	5	5	5	5	5
30	Chitral	4	4	4	4	4	4	3	3	3	3	3	3
31	D I Khan	0	1	1	1	1	1	1	1	1	1	1	1
32	Dir	6	6	6	6	6	6	6	6	6	6	6	6
33	Drosh	0	0	0	0	0	0	0	0	0	0	0	0
34	Gilgit	0	0	0	0	0	0	0	0	0	0	0	1
35	Gupis	2	1	0	0	2	1	0	1	0	0	2	1
36	Kotli	0	0	0	0	0	0	0	0	0	0	0	0
37	Muzaffarabad	1	1	1	0	0	0	0	0	0	1	0	1
38	Peshawar	0	0	0	0	0	0	0	0	0	0	0	0
39	Astor	1	1	1	1	1	1	1	1	1	1	1	1
40	Bunji	0	0	0	0	0	0	0	0	0	0	1	0
41	Chilas	0	0	0	0	0	0	0	0	0	0	1	1
42	Garhidupatta	0	0	0	0	0	0	0	0	0	0	1	0
43	Kalat	4	4	4	3	3	3	4	4	4	4	4	3
44	Skardu	0	0	0	0	0	0	0	0	0	1	0	0

Table 2. Computed correlation coefficients between I_ρ and early monsoon predictors for the period from 1961 to 2000

#	*Predictors*	*Months*	*CC*	*p-value*
1	Arabian Sea Temperature Index (ASI)	Previous Dec	0.55	0.002
2	Central Indian Ocean Temperature Index (CIOI)	Apr	0.60	0.000
3	Arabian Sea Level Pressure	May	−0.57	0.001
4	Southern Oscillation Index (SOI)	Previous Jun	−0.54	0.002
5	SOI	Feb minus May	−0.41	0.026
6	Geopotential Height at Tibet Plateau for 500 mb	Apr	−0.39	0.034
7	North Atlantic Oscillation (NAO)	Jan	0.41	0.023
8	Northern Hemisphere Surface Temperature (NHST)	Jan	0.45	0.012
9	Hyderabad Pressure	May	−0.51	0.004
10	Hyderabad Temperature	May	0.47	0.009

Table 3. Parameter estimation in multiple regression analysis for Pakistan summer rainfall model, I_ρ

Parameters	*Coefficients*	*t-value*	*p-value*
Const.	15.79	1.09	0.292
x_1	0.8483	4.991	0.000
x_2	0.3041	2.511	0.021
x_3	−0.008039	−3.27	0.004
x_4	0.09078	3.71	0.001

Table 4. Analysis of variance of the multiple regression model for Pakistan summer rainfall model, I_ρ

Source	DF	*SS*	*MS*	*F-value*	$p-$value
Regression.	4	5.5988	1.3997	21.04	0.000
Residual Error	20	1.3303	0.0665		
Total	24	6.9291			

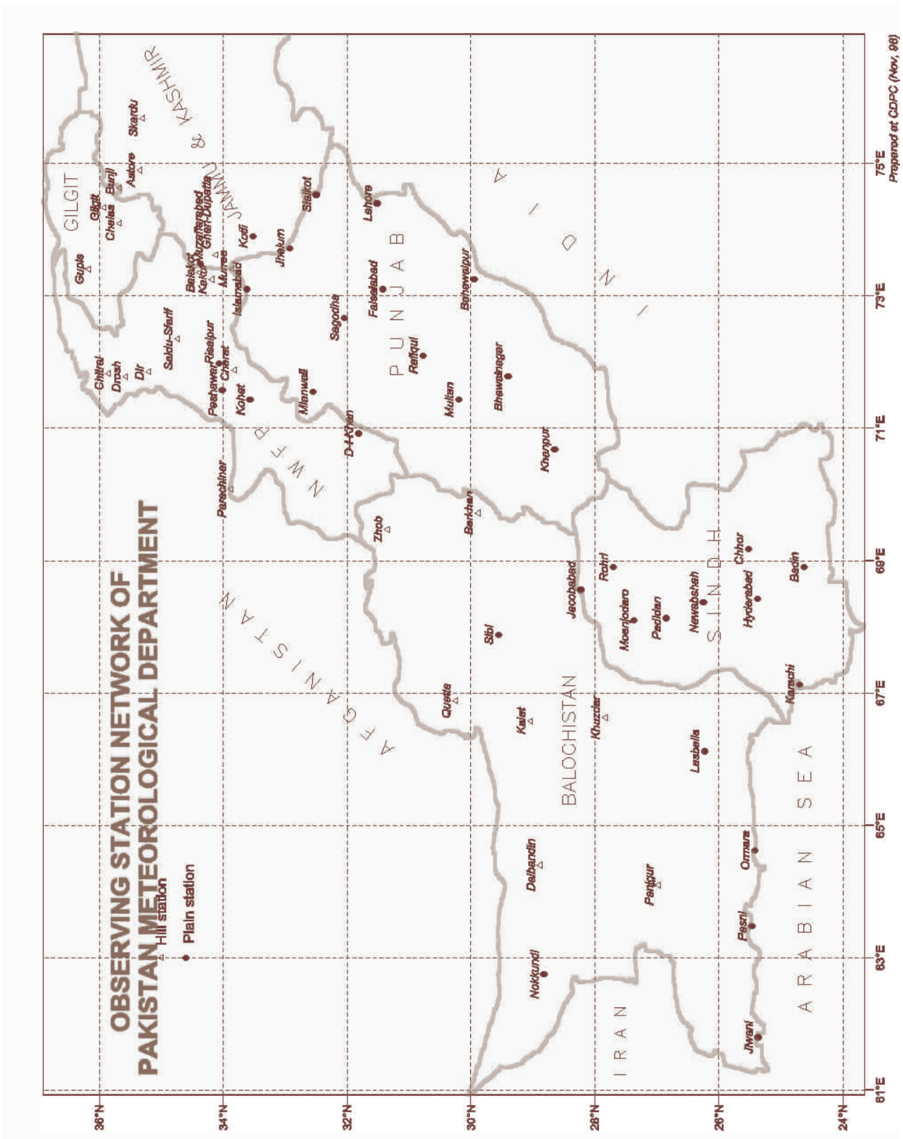

Figure 1: Observing stations of Pakistan Meteorological Department

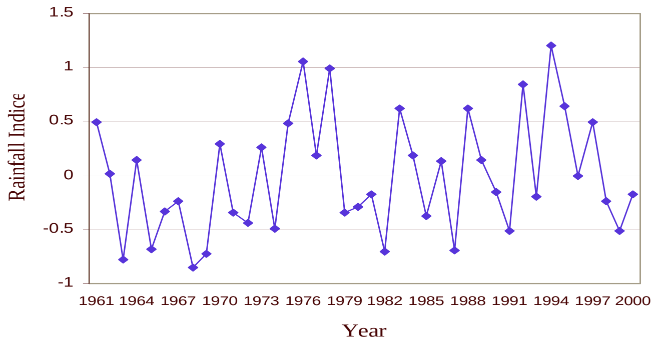

Figure 2: Time-series of Pakistan summer monsoon rainfall index (I_ρ)

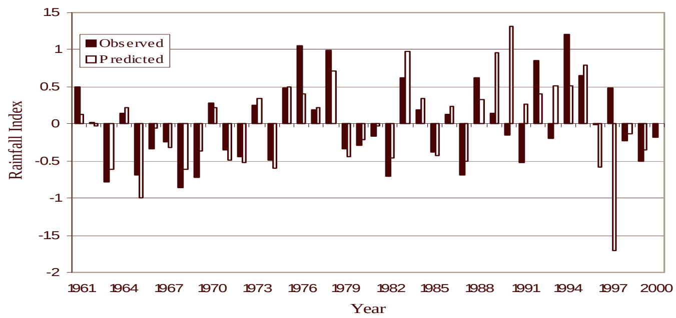

Figure 3: Comparison between observed values (black bar) and predicted values (white bar) for Pakistan summer monsoon rainfall (I_ρ)