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MONSOON

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PREFACE

All living beings need water for survival. One of the basic conditions for life on earth is that the water be available in liquid form. Water serves in many other ways to maintain life, health, vigour and social stability. The agricultural production in the country depends on monsoon. Over our country's land surface of about 329 million hectare, the precipitation generates about 400 million ha m of water in a year. Annual normal precipitation of the country is 116.6 cm with coefficient of variation equal to 30%. During monsoon months (June-Sept.), 770 million ha m of moisture is transported over India from the Arabian Sea and 340 million ha m from the bay of Bengal. During hot weather season (March-May), the Western Himalayas receive good amount of precipitation in association with western disturbances, for example Jammu & Kashmir 24 cm, Himachal Pradesh 19 cm and U.P. hills 13 cm. A Significant fraction of it falls as rain over snow bound areas. Monsoon rainfall (June-September) usually reaches up to foot hills. But occasionally when a depression is passing across, heavy rains are experienced even at high reaches of snow and glacier areas. The rain accompanied with accelerated melt water may cause severe floods.

This document has been prepared by Dr. D.S. Upadhyay, Director, Hydrometeorology, India Meteorological Department, New Delhi. In this publication an attempt has been made to present features of summer monsoon system, seasonal and annual rainfall, normals and coefficient of variability, onset and withdrawals of monsoon, monsoon experiment and monsoon variability. Also Himalayan snow and South West monsoon over India and predictability of monsoon have been highlighted.

S M SETH

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MONSOON

1.0 INTRODUCTION

Economy of tropical countries depends on agriculture, hence, is more sensitive to weather. In temperate countries economy largely depends on production of goods and services which are less affected by variabilities in weather. The information regarding weather and climate of tropics, gains even more importance as the humid tropics, being the surplus water region, may be the source of fresh water supply in future.

Dependence of India's food grain production on the performance of south-west monsoon has been illustrated from the following time series (1960-92) showing annual crop yield quantity Q (lakh ton) and percentage departure of monsoon (June-Sept) rainfall (R) over the country as a whole. The series Q has been detrended by using 4-year cêntralised moving average as trend values. After detrending, the grain production yields a high correlation of 0.9 with rainfall departure. The data are provided below :

year (x-y)	Food Grain Production (10^5 ton)	4-yr centralised moving av. (10^5 ton)	Q series (Col2-Col3)	Departure of monsoon rainfall from normal in year x(%) (R)
1960-61	823	-	-	0
61-62	824	-	-	22
62-63	803	823	- 20	- 3
63-64	807	820	- 13	- 2
64-65	894	799	95	10
65-66	723	809	- 86	- 18
66-67	742	833	- 91	- 13
67-68	951	873	78	0
68-69	940	950	- 10	-10
69-70	995	1006	- 11	0
70-71	1084	1022	62	-12
71-72	1052	1027	25	-4
72-73	970	1028	- 58	-24
73-74	1047	1037	10	8
74-75	998	1074	- 74	-12
75-76	1210	1118	92	15

Contd...2

year (x-y)	Food Grain Production (10^5 ton)	4-yr centralised moving average (10^5 ton)	Q series (Col2-Col3)	Departure of monsoon rainfall from normal in year x(%) (R)
76-77	1112	1186	- 74	2
77-78	1264	1211	53	4
78-79	1319	1219	100	9
79-80	1090	1246	-156	-19
80-81	1296	1256	40	4
81-82	1333	1307	26	-3
82-83	1295	1381	- 86	-13
83-84	1524	1422	102	13
84-85	1455	1460	- 5	- 4
85-86	1504	1460	44	- 7
86-87	1434	1470	- 36	-13
87-88	1384	1526	-142	-21
88-89	1699	1595	104	18
89-90	1710	1685	25	01
90-91	1762	-	-	+06
1991-92	1770	-	-	-7

Product moment correlation coefficient between Q and R works out to be

$r_{QR} = 0.86$

2.0 PRINCIPAL SEASONS

Indian subcontinent is an excellent example of monsoon type climate region. Over this region sea level pressure and hence the surface wind undergo complete reversal from January to July. In a year two types of monsoon currents flow. During winter high pressure develops over land low over seas. Dry and cold air of land origin of northerly latitudes flows in NEly direction over sea regions. This is called winter or north-east monsoon. By the end of summer low pressure is set up over landmass of north India and high shifts to the seas. Now the flow of warm and moist air of ocean occurs from sea to land on the path of winter monsoon, but in opposite direction. This is called Summer or South-west monsoon. There are 4 principal seasons :

(i) winter or NE monsoon (Dec-Feb)
(ii) Hot weather season (Mar-May)

(iii) Summer or SW monsoon (Jun-Sept)
(iv) Transition period or post monsoon season (Oct-Nov)

Although SW monsoon period for the whole country is taken to be 4 months, but its actual period at a specific place will be the span between the dates on onset and withdrawal of monsoon at that place. It varies from less than 75 days in west Rajasthan and extreme NW India to above 150 days over parts of peninsular India.

2.1 Pressure and Wind

(i) In winter season low temperature prevails over entire land mass of Asia and subtropical (ST) high pressure centered around 45°N, 105°E extends from Arab to central Asia and then to NE China. India lies on its periphery. Pressure gradient is very strong towards north of Himalayas but weak over Indian region. Equatorial low shifts southwestward and occupies a position between 0 to 10°S in Indian ocean. A weak ridge runs from west Rajasthan to central Bihar. Trough is well marked from Kerala to Gujarat and from Tenasarim coast to north Myanmar. Over Assam region NEly wind prevails over sea and land below 25°N. Over land winds are light and over sea of the order of 10 knots and even stronger over SW Arabian sea. North of 25°N except over Assam and Rajasthan, light Wly or NWly winds are common.

(ii) As the sun crosses equator, moving northward in March pressure gradient sharply decreases over Indian subcontinent and weak low extends from southern peninsula to north eastern regions. A line of discontinuity rises from southern parts of peninsula, drawn on an average northward upto 20°N, 77°E and then to NE ward upto 25°N, 92°E. Towards east of this line, Sly or SWly flow upto 1 km level prevails which advects enough moisture from Bay over peninsula. This causes thunderstorm and shower around the line of discontinuity during the month of March. Similar events of NE India develop in the form of Norwesters.

During April heat low builds up over peninsula and shifts northward slowly as the season advances. At the same time ST high of central Asia breaks into the cells of low due to intense heating. By May whole landmass of Asia becomes a low pressure zone whose centre is around 30°N, 75°E. Peninsular low merges with it and a well marked trough extends upto Orissa. Wind pattern over various regions are :

	Region	April	May
1.	West of Peninsular trough axis	Wly or NWly	NWly
2.	East of Peninsular trough axis	Sly or SWly	NWly
3.	NE Region	Sly or SWly	NWly
4.	Sea Region	NEly flow of winter backs slowly and by June reversal is completed with setting of SWly currents. During transition period flow is weak, usually less than 10 knots.	

(iii) During May SWly currents of bay start flowing over Myanmar, Assam, Bangladesh and Bengal. By end of May seasonal heat low over NW India sets in. It drives SEly trade winds of south hemisphere to cross equator and join Arabian sea and bay of Bengal branches of monsoon from south west. Onset of monsoon occurs over Andaman islands and Tenasarim coast by 20th May, central Myanmar coast by 25th May and Bangladesh by 1st June. As this flow is reflected eastward by Assam and Myanmar hill ranges, natural trough develops over plains of north India. By this time the trade winds of Arabian sea also starts flowing in Wly or SWly direction driven by low pressure area of NW India. This causes onset over Kerala coast at the start of June. Arabian sea branch of monsoon slowly moves northward and strengthens the monsoon trough.

(iv) In second half of September monsoon starts withdrawing from Northwest, where dry and colder air sets in. Bay branch withdraws from the plains of north India and Arabian sea branch from Rajasthan, Gujarat and then from Peninsular states. Seasonal low vanishes by October. Pressure rises faster over NW India than over peninsula. Reduction in pressure occurs in Central and Southern bay. Hence pressure gradient becomes very weak over the whole country. The entire pressure system is in diffused state during post monsoon months. Oct-Nov is the period of transition from SW to NE monsoon. Change in pressure and flow pattern takes place very slowly. Weak flow usually prevails, NWly in north India, Wly in southern parts of peninsula and Ely or NEly in northern peninsula. During November ST high strengthens over central Asia and NW India comes under its influence initiating reversal of pressure and wind. The reversal is completed by early December.

2.2 Rainfall

Annual normal rainfall of India is about 117 cm which is more than global average of 100 cm. But its temporal and spatial variation is erratic. About three fourth of rain is concentrated in one-third of the year (June-Sept.). Spatially it ranges from 10 cm in extreme western parts of Rajasthan and north India to above 1000 cm in part of Meghalaya. Monthly distribution of normal rainfall over plains of India (except J&K and H.P.) is

Month:	J	F	M	A	M	J	J	A	S	O	N	D
Rain : (mm)	13.3	15.3	15.0	27.7	51.4	167.7	312.8	262.1	176.4	77.4	35.6	11.7

Subdivision wise seasonal normal rainfall are given in Table 1.

Table 1: Seasonal and Annual Rainfall Normals and Co-efficient of variability (Based on 1950 normals)

Sl. No.	Sub-Division	Total area in Sq.Km.	Jan-Feb	Mar-May	June-Sept	Oct-Dec	Annual (mm)	CV (%)
1.	Arunachal Pradesh	83,578	106.1	621.2	2084.6	182.6	2,996.5	11
2.	Assam & Meghalaya	1,01,012	56.4	638.1	1623.8	178.9	2,497.2	11
3.	Nagaland, Manipur, Mizoram & Tripura	70,447	51.6	545.2	1507.9	209.2	2,313.9	11
4.	Bay Islands	8,295	135.1	504.4	1587.8	708.4	2,935.7	11
5.	Sub-Himalayan West Bengal & Sikkim	28,924	28.2	411.6	2172.4	166.6	2,778.5	15
6.	Gangetic West Bengal	66,228	38.9	175.5	1078.5	186.0	1,428.9	15
7.	Orissa	1,55,782	39.3	125.5	1142.9	176.4	1,484.1	14
8.	Bihar Plateau	79,638	52.4	89.8	1124.6	103.7	1,370.5	13
9.	Bihar Plains	94,238	34.1	74.1	1023.5	71.8	1,203.5	16
10.	Uttar Pradesh East	1,46,509	34.6	30.7	893.3	55.6	1,014.2	20
11.	Plains West Uttar Pradesh	96,782	41.7	30.7	726.0	37.2	835.6	16
12.	Hills West Uttar Pradesh	51,122	130.9	127.8	1408.9	82.3	1,749.6	27
13.	Punjab	50,362	60.4	51.2	467.3	31.6	610.5	34
14.	Haryana, Delhi & Chandigarh	45,821	38.4	31.3	462.6	23.2	555.5	
15.	Himachal Pradesh	55,673	182.8	202.0	9993.1	139.9	1,517.8	21
16.	Jammu & Kashmir	2,22,236	193.7	246.8	458.1	97.9	996.5	22
17.	Rajasthan East	1,47,128	14.7	16.8	646.6	22.0	700.1	23
18.	Rajasthan West	1,95,086	11.2	15.2	275.3	8.2	309.9	40
19.	Madhya Pradesh West	2,29,550	22.6	21.4	945.1	53.5	1042.6	20
20.	Madhya Pradesh East	2,13,291	43.8	49.1	1,227.3	77.8	1,398.0	15
21.	Gujarat Region	86,597	4.3	10.5	920.0	32.4	967.2	29
22.	Saurashtra & Kutch	1,89,990	3.6	9.2	479.4	23.1	515.3	37
23.	Konkan & Goa	34,095	3.3	36.7	2,705.2	135.8	2,881.0	18
24.	Madhya Maharashtra	1,15,306	6.5	38.9	788.2	106.7	940.4	23
25.	Marathwada	64,525	11.0	36.1	660.1	86.4	793.6	25
26.	Vidarbha	97,537	30.0	35.2	960.3	86.6	1,102.1	19
27.	Coastal Andhra Pradesh	93,045	23.1	87.5	572.6	324.6	1,007.8	18
28.	Talangana	1,14,726	18.9	57.6	759.1	94.9	930.5	21
29.	Rayalseema	69,043	15.0	76.4	367.0	217.3	675.7	20
30.	Tamil Nadu & Pondicherry	30,549	53.1	147.1	30.7	475.8	1,006.7	14
31.	Coastal Karnataka	18,717	4.3	148.7	2,886.3	252.6	3,29.9	15
32.	North Interior Karnataka	79,895	5.8	87.7	447.1	144.1	684.1	19
33.	South Interior Karnataka	93,161	9.9	162.7	868.2	230.2	1,2710	20
34.	Kerala	38,864	38.6	413.6	1,977.9	547.6	2,977.7	14
35.	Lakshadweep	32	32.8	155.4	1001.2	357.1	1546.5	14

3.0 FEATURES OF SUMMER MONSOON SYSTEM

3.1 Seasonal heat low

It is a part of low pressure belt extending from Sahara to Central Asia across Arabia, Iran, Pakistan and North West India. Its progressive development and location over Indian sub-continent is an important factor for driving monsoon. A seasonal low is shallow extending upto 850 hPa having weak ascending motion upto 850 hPa and downward motion aloft. Over India Pressure reduces from south to north. Higher pressure gradient is more favourable for active monsoon.

3.2 Mascarene high

This high pressure zone develops in Indian Ocean from 30°S 50°E to SE of Madagascar and plays an important role in generating cross equatorial flow and occasional monsoon surges.

3.3 Tibetan high

This east-west oriented anticyclone over Tibet develops in middle and upper troposphere during summer months to the east of 70°E. The centre at 200 hPa is around 30°N 88°E. If the high shifts westward, the monsoon also extends westward into Pakistan and Afghanistan.

Tibetan plateau becomes a heat source in mid troposphere which is important input for driving monsoon circulation. Latent heat of condensation released due to rainfall over Indo-Gangetic plain also warms up atmospheric column and provides energy for convection. Tibetan plateau also plays a key role in reversing the direction of thermal gradient between equator and Himalayas during summer months and development of tropical easterly jet.

3.4 Onset and withdrawal of monsoon

From agricultural point of view it is more logical to associate onset with arrival of rains rather than with changes in moisture and wind. Monsoon first arrives on southern tip of the main land of India. On bay island the onset occurs about a week earlier. Over Kerala the normal date of onset is June 1. However the past available records show that the date of onset over Kerala has fluctuated between May 11 and June 15. In deciding onset in other parts of the country, alongwith rainfall the other features like increase in moisture and change in wind direction are also considered. Normal dates are given at fig. 1. These dates have a standard deviation of about one week.

Dates of monsoon withdrawal from different parts of the country are shown at fig. 2. From these two diagrams it is clear that actual period of southwest monsoon varies from 75 days over Rajasthan and extreme NW India to more than 150 days over southern parts of peninsula.

Main synoptic features related to onset over Kerala coast are (i) Trough in SE Arabian sea (ii) increase in depth and speed of SWly flow over Srilanka and extreme southern parts of peninsula; simultaneously strengthening of easterlies in upper troposphere upto 40 Kts or more at 14-16 km level (iii) Northward displacement of westerly jet to outside Indian latitudes (iv) development of anticyclone over Tibet.

3.5 The axis of monsoon trough

It is a separating line between bay of Bengal branch and Arabian sea branch of monsoon currents. Its normal position on surface weather chart passes through Ganganagar, Kanpur, Gaya and Calcutta. The axis is well marked on upper air charts also upto 6 Km above sea level, but slopes southward with increasing height. When a break condition in SW monsoon sets in, the axis shifts northward and lies along the foot hills of Himalayas. In this situation rainfall over southern slopes of Himalayas and adjoining plains increases, while rest of the country except Tamil Nadu goes practically dry. As a result of heavy rains in mountainous catchments several rivers of UP, Bihar and Bengal experience delayed floods in plains.

Dhar et al (1984) analysed rainfall on 75 days in 14 breaks from 1957 to 69 in the month of July and August and concluded that increase in rainfall has been maximum and most frequent in 79 - 89°E belt of southern Himalayas particularly in Teesta, Kosi, Bagmati, Gandak, Rapti and Karnali (Ghaghra) catchments. The entire Himalayan ranges do not experience increase in rainfall.

Break period is usually for about a week. Prolonged breaks are also observed, more frequently in second half of monsoon season.

During active phase, the axis shifts slightly southward dipping into head bay of Bengal. This position of trough is also favourable for the formation of lows and depressions in north bay.

3.6 Mid Tropospheric Cyclonic Vorticity

Over north east Arabian sea and adjoining India, westerlies prevail at the surface and easterlies in upper troposphere. In the middle troposphere (700-500 hPa) cyclonic vorticity (upper and low) develop. These low remain quasi stationary for several days. Heavy rains are possible in association with strong vorticities.

3.7 Off shore vorticities

These are small scale vorticities produced near west coast when a part of southwesterly monsoon flow is deflected back by Ghat's ranges. These vorticities may cause good amount of rainfall on windward side of Ghats.

3.8 Indian Monsoon and Jet Streams

Except for the period of SW monsoon. The subtropical (ST) westerly jet stream flows at 9-12 Km level over India, north of 20°N. Height of maximum intensity core decreases and depth of current increases as we move northward. 60 Knot jet speed at 20°N is observed at 12 Km level, while at 23°N at 9 to 12 Km level. Jet intensity is maximum in February which reduces to 60 Kt in April. During May westerly jet shifts north of 30°N and its core speed further reduces to 50 Kt. By the time monsoon sets in over Kerala coast, Wly jet completely moves out of Indian region. In October it again returns to 30°N at 12 Km level as a week jet of 50-60 Kt, which goes on intensifying as the season advances. Whenever there is prolonged break in monsoon or it is very weak, westerly jet again arrives over Indian latitudes.

During monsoon months easterly jet stream flows at 14-16 Km level, south of 25°N. This stream extends upto eastern coasts of Africa. On an average the axis of Ely jet is over 15°N at 16 Km level with a speed of 80 Kt. During active and weak phases of monsoon, Ely jet shifts towards north and south respectively. During SW monsoon upper air temperature is usually maximum at 30°N for each layer and decreases southward. This temperature gradient is clear upto 100 hPa level. It results into Ely thermal winds and hence Wly flow decreases with height, Ely grows and develops into Ely jet. In June the jet is confined to the southern parts of peninsla but later the axis of maximum wind shifts northward and its height also slightly increases.

3.9 ENSO (El Nino and Southern Oscillations)

The air sea interactions cause large scale energy transfer over Arabian sea in north and over the region between Madagascar and Australia in South Indian Ocean. Abnormal interactions may cause climate anomalies like droughts & floods and can be inferred by events like ENSO. El Nino (EN) refers to wide spread warming of tropical ocean surface around Peru coast and weakening of trade winds. This is sea component of interaction. Southern oscillations (SO), the atmospheric component of interaction is related to sea surface temperature. The oscillations in pressure and temperature over north atalantic, pacific and Indian ocean are well known. Southern oscillation describes the fluctuation over pacific with Indian ocean. When the pressure is high over pacific it tends to be low in Indian ocean from Africa to Australia and vice versa. Under such a situation SST (Sea Surface Temperature) falls in both oceans and the rainfall decreases inversely with pressure. The years of ENSO during past 60 years (1941, 42, 52, 54, 57, 72, 76, 83), although suggest an average period of 3-5 years, but there is no regularity in occurrence of ENSO.

4.0 Monsoon Experiments

To study the flow pattern of South West monsoon over Arabian sea and adjoining Indian Ocean the first International Indian Ocean Expedition (IIOE) was conducted during 1963-65. The observations indicated the existence of low level jet off the Somalia coast as an extension of a jet core originating in southern Indian ocean and crossing equator near Kenya. Indo Soviet Monsoon Experiment (ISMEX) was conducted during summer 1973 for collecting data of arabian sea and equatorial region of southern Indian ocean. The coordinated efforts was also made for collecting more upper air and surface data in arabian sea and bay of Bengal in an experiment called Monsoon 1977. During summer 1979 a major International Experiment called monsoon experiment (MONEX-79) was conducted over arabin sea, bay of Bengal and Indian ocean for studying regional scale aspects of monsoon.

4.1 Moisture Transport

Equatorial regions show minimum precipitable water during active monsoon period. It progressively increases northwards to the maximum in east Arabian sea around 10°N. During weak period equatorial region and southeast parts of Arabian sea have maximum moisture. Zonal transport of moisture (west to east) in Arabian sea is two to three times higher than the moisture transported from southern hemisphere across the equator. (Pant M.C. 1993, Ph.D. thesis). Zonal flow, however undergoes fluctuations during active and weak phases of monsoons. During active phase western coast receives moisture supply in higher quantity. This variation is independent of the cross equatorial flow. Likewise large quantity of moisture is transported east ward (towards Myanmar & Malayasian coasts) zonally in bay of Bengal.

Low level (0.5-1.5 km) westerly jet persists over western Arabian sea during monsoon months between 9-16°N with core wind speed of 60-70 kts. The core wind reduces as the jet reaches over east Arabian sea. It causes low level convergence and transports huge quantity of moisture. This low level strong current, called **Somali jet,** starts from east of Madagaskar, moves to Kenya coast (3°S), crosses equator as southwesterly jet and splits into two branches over west Arabian sea. According to an estimate during monsoon months about 770 million hectare metre (ham) moisture is brought over India from Arabian sea and 340 m ham from Bay of Bengal. About 25% of it falls as precipitation.

Amini (11°N, 75°E) in Arabian sea and Portblair (12°N, 92°E) in Bay of Bengal have annual rainfall of 150 and 295 cm respectively with the following seasonal distribution:

	Rainfall (mm)	
Season	Portblair	Amini
Winter	75	18
Hot weather	433	153
SW Monsoon	1764	1069
Post Monsoon	683	250
Annual	2954	1480

The large difference may be due to the influence of easterly waves and higher sea surface temperature in bay of Bengal causing higher frequency of cyclones and depressions there.

5.0 Monsoon variability

An analysis of 126 year (1871-1996) of seasonal (June-Sept) rainfall data over India brings out the following features of temporal and spatial variabilities in monsoon.

5.1 Inter-annual variability (I V)

The expression $IV = \frac{1}{n-1} \Sigma \left| X_i - X_{i-1} \right|$, X_i being the monsoon rainfall over the country for ith year, works out to be IV = 107 mm, which is 12% of the normal of above 900 mm.

5.2 Decadal variability

The decadal means and coefficient of variations of monsoon rainfall over the whole country are :

Decade	Mean Rainfall (mm)	CV (%)
1871-1880	847	13
1881-1890	879	4
1891-1900	863	12
1901-1910	835	10
1911-1920	852	15
1921-1930	883	5
1931-1940	906	6
1941-1950	917	6
1951-1960	904	9
1961-1970	868	12
1971-1980	845	13
1981-1990	843	12
1991-1996	903	5
Mean	872	

5.3 30-year climatic means of monsoon rainfall over India

30-year period	Mean rainfall (mm)	C.V. (%)
1871-1900	863	8
1901-1930	857	10
1931-1960	909	7
1961-1990	852	12
1991-1996	903	5

The period 1931-60 has been the wettest while 1961-90 the driest.

6.0 SNOW, GLACIER, WEATHER AND MONSOON

Snow and ice cover influence atmospheric circulation on short term (day to week) as well as on long term (month to season) basis. Spatially also these influences vary from local or micro scale (a few Km^2) to synoptic scales (100s to 1000s Km^2) depending on spread of the cover. Major short term influences are (i) production of colder airmass in lower levels of atmosphere. Arctic and Antarctica regions (70-90° lat) are covered with snow and ice. Polar continental region (Canada, North Europe and North Asia above 55°N) are the zones of snow and permafrost. These regions are dominated by permanent anticyclones and are good source of dry, cold and stable airmass. Air is subsiding and high northerly flow prevails. During summer, the arctic source region does not change much, but polar continental zone contracts as a narrow band over north Canada and Siberia. It serves as a thin layer between Arctic air and tropical air of southern latitude. Main meteorological features of these polar continental airmass (CP) are: clear skies because of subsidence, low surface temperature associated with steep ground inversion upto about 1500 m height, very low absolute humidity (Sp. humidity = 1-2 gm/Kg), strong stability and ice crystal fog. When polar airmasses move from their source region, they get modified by absorbing the temperature and humidity of ground underneath. Abrupt change occurs when they leave snow and ice field.

In north and central India modified CP prevails during winter which enters from northeast under the influence of Siberian anticyclonic flow. CP air also occasionally enters north India in the wake up of 'Western Disturbances' during October to May. These are strong and very cold and dry wind which may last for 3 to 6 days in one spell.

Mountain glaciers are usually not capable of generating large scale airmass. Locally a glacier increases stability of adjacent air and changes wind speed above the ground surface. Snow surface has very low roughness height (0.07 cm) as compared grass (.2 to .70 for small grass and 3.7 to 9.0 for large grass). Hence wind speed cover snow is higher than over grass surface.

Generation of baroclinicity at the boundary of ice and bare land due to sharp temperature contrast. For a large spatial extent this effect can cause development of cloud and weather at the boundary. But for mountain glaciers, it can produce some instability and modify wind.

Long term effects may change surface albedo and consequently modify energy regime around the boundary layer. For example, increase in surface of snow and ice may cause increase in albedo, atmospheric cooling, formation of cold trough aloft and hence increase in quantity of snowfall resulting into further glaciation (Schlesinger et al 1986, Glaciological data, p. 11). To illustrate the changes in surface albedo due to seasonal variation in snowcover, the following data of north America are relevant.

Lat.(°N)	North America : Albedo (%) Mid Winter	Mid Summer
60-65	67	16
50-55	50	15
40-45	38	16
30-35	19	17
20-25	16	16
Mean	43	16

Net radiative deficit due to increased surface albedo over western Himalayas may affect adversely the development of summer low pressure are over northwest India, which is a driving force for Indian southwest monsoon.

Zhao Zongei (Glacial data - 1976) observed (i) a negative correlation between snowcover over N.hemisphere in winter and its temperature in following summer; (ii) a significant relationship between Eurasian snowcover in 'winter and several characteristic features of 500 hPa circulation over east Asia in the following spring or summer.

7.0 HIMALAYAN SNOW AND SOUTHWEST MONSOON OVER INDIA

Blendford (1884) and Walker (1910) were first to show the inverse relationship between snowcover over Western Himalayas at the end of winter and monsoon rainfall over plains of north-west India. Walker used qualitative point source snowcover and rainfall data (Normal =0, above/below normal = ±1, appreciably above/below normal = ±2 and markedly above/below normal = ±3) for the period 1876-1908 and worked out a correlation coefficient of -.31 between snowcovr over western Himalayas at the end of May and monsoon rainfall over NW India. Hahn and Kukla (1976), using satellite data (1967-75) observed inverse relationship between winter snowcover over Eurasia (south of 52°N) and monsoon rainfall over India. Chen and Yen (1978), Dey et.al. (1984) and Upadhyay & Kaur (1986) reported similar inferences (delay in onset or reduction in monsoon rainfall in relation to increased snow cover).

This inference can provide a useful tool for long range forecasting of monsoon rainfall because maximum build up of snowcover in Feb.-March is known 2 to 3 months in advance of onset of monsoon (June). However, the correlation is very weak and often unstable. Besides, there are many other factors governing land and sea surface or upper air processes, which influence the onset and progress of monsoon circulation over Indian subcontinent.

8.0 PREDICTABILITY

Spatial and temporal distributions of monsoon rainfall are characterised by delay in onset, prolonged breaks, weak currents and absence of depressions. These events are associated with specific synoptic features and can be identified on weather charts. For example strength of cross equatorial flow, intensity of inter tropical convergence zone, development of upper air easterlies and formation of upper air anticyclone over Tibetan plateau are good indications for the onset of monsoon over southern and eastern parts of India.

Breaks are indicated by downward shift of westerly jet, weakening of upper air easterlies over central and south India and shifting of the axis of trough towards food hills of Himalayas.

Loose pressure gradients on surface weather charts indicate weaker currents.

With present day's knowledge of synoptic meteorology assisted with radar and satellite observations, the features and pressure systems can be identified 2-3 days in advance and changes in their positions and strength can be followed. This enables us short range prediction of rainfall distribution.

For predicting seasonal or long term performance of monsoon there are two approaches (i) statistical - which depends on teleconnections of distant phenomena (parameters) like Elnino, Himalayan snow etc. with monsoon performance. Search of logical and stable parameters is a continuing effort in this exercise. (ii) General Circulation Models - slow changes in boundary layers affect the weather months in advance. These indications can be used in medium and long range predictions. Monsoon prediction actually relates to forecasting onset in different parts, breaks, and active phases in medium time range of 5 to 10 days and total quantity received during the entire seasons by different subdivisions.

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SOUTH WEST MONSOON

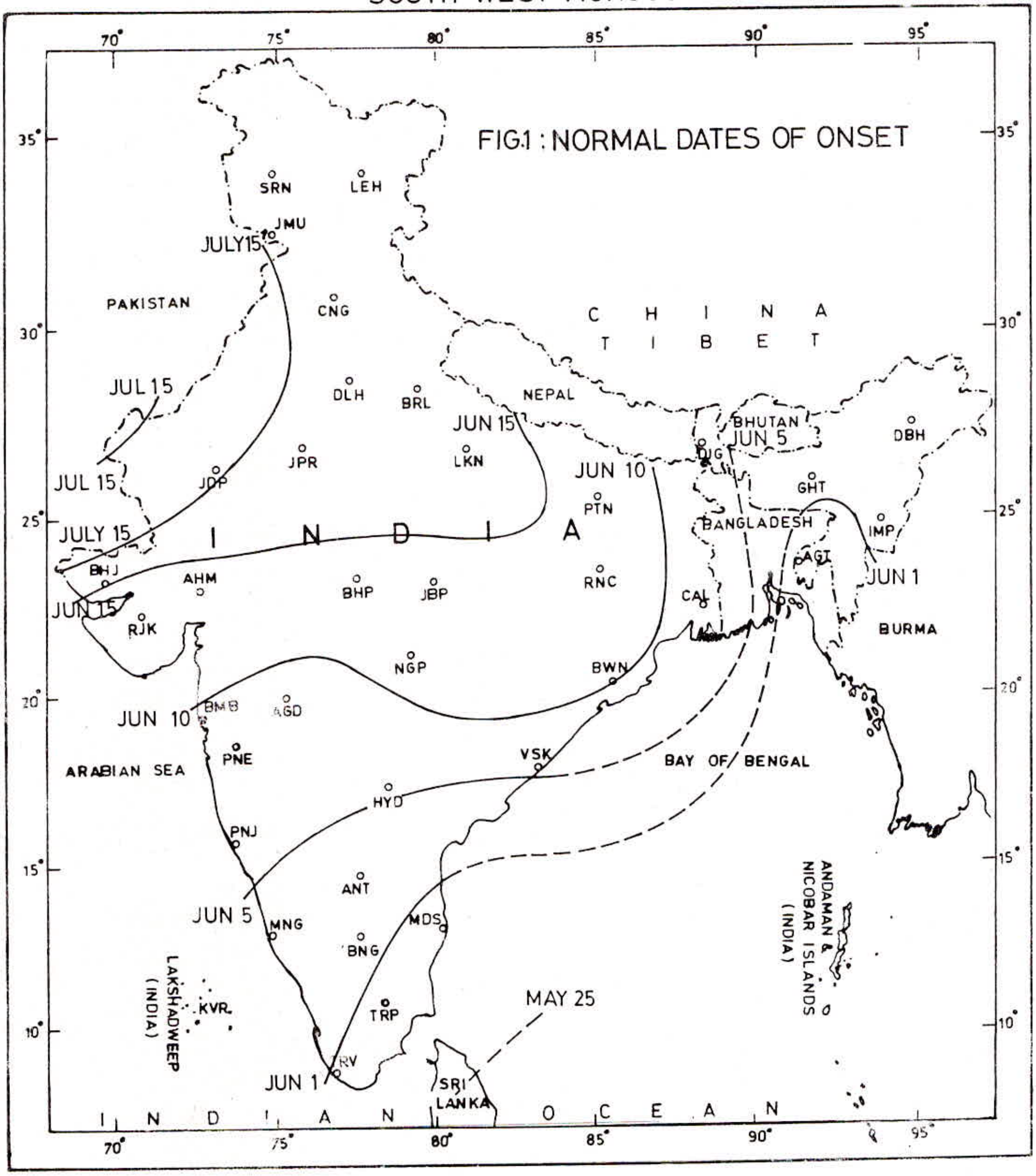


FIG.1 : NORMAL DATES OF ONSET

SOUTH WEST MONSOON

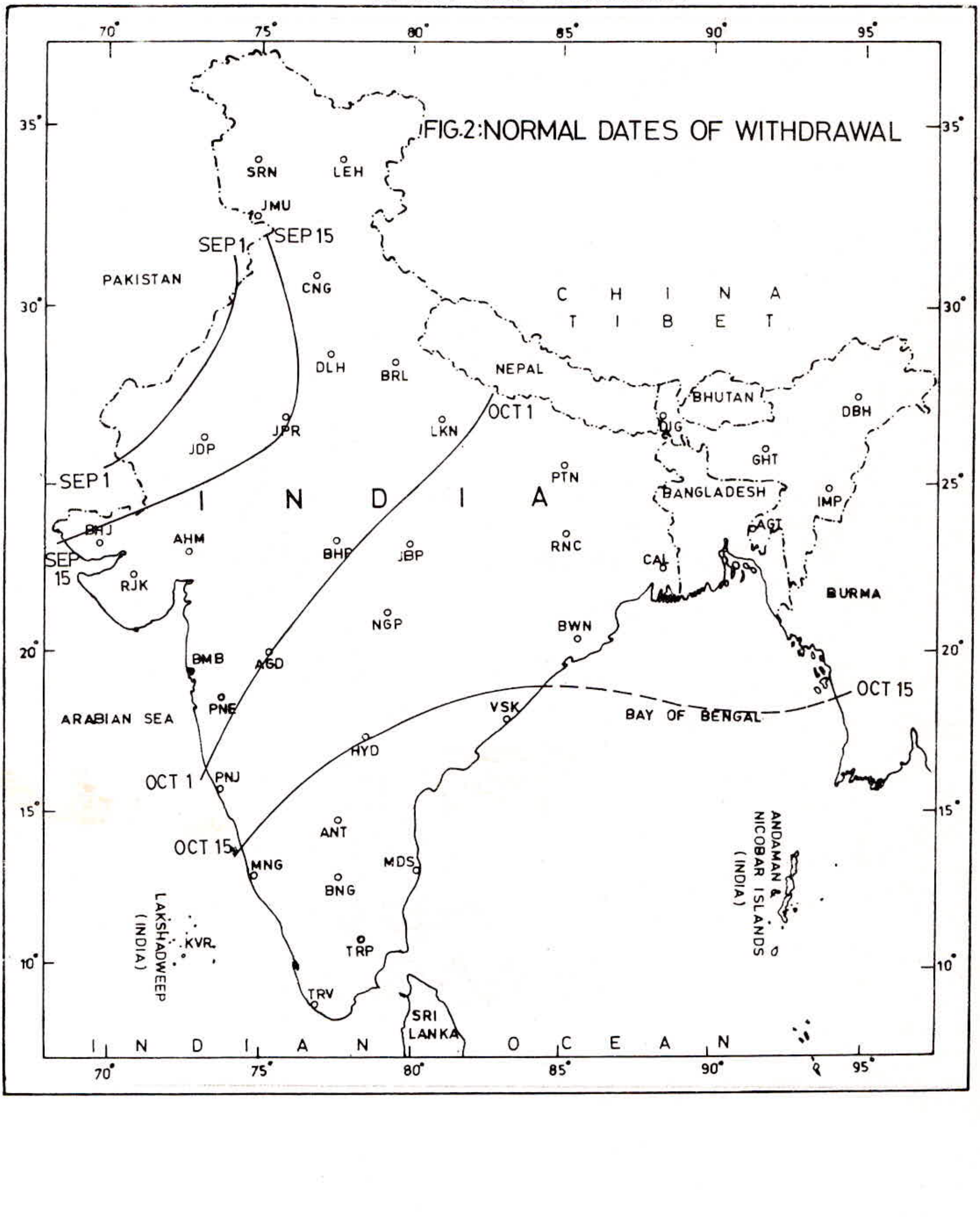


FIG.2: NORMAL DATES OF WITHDRAWAL

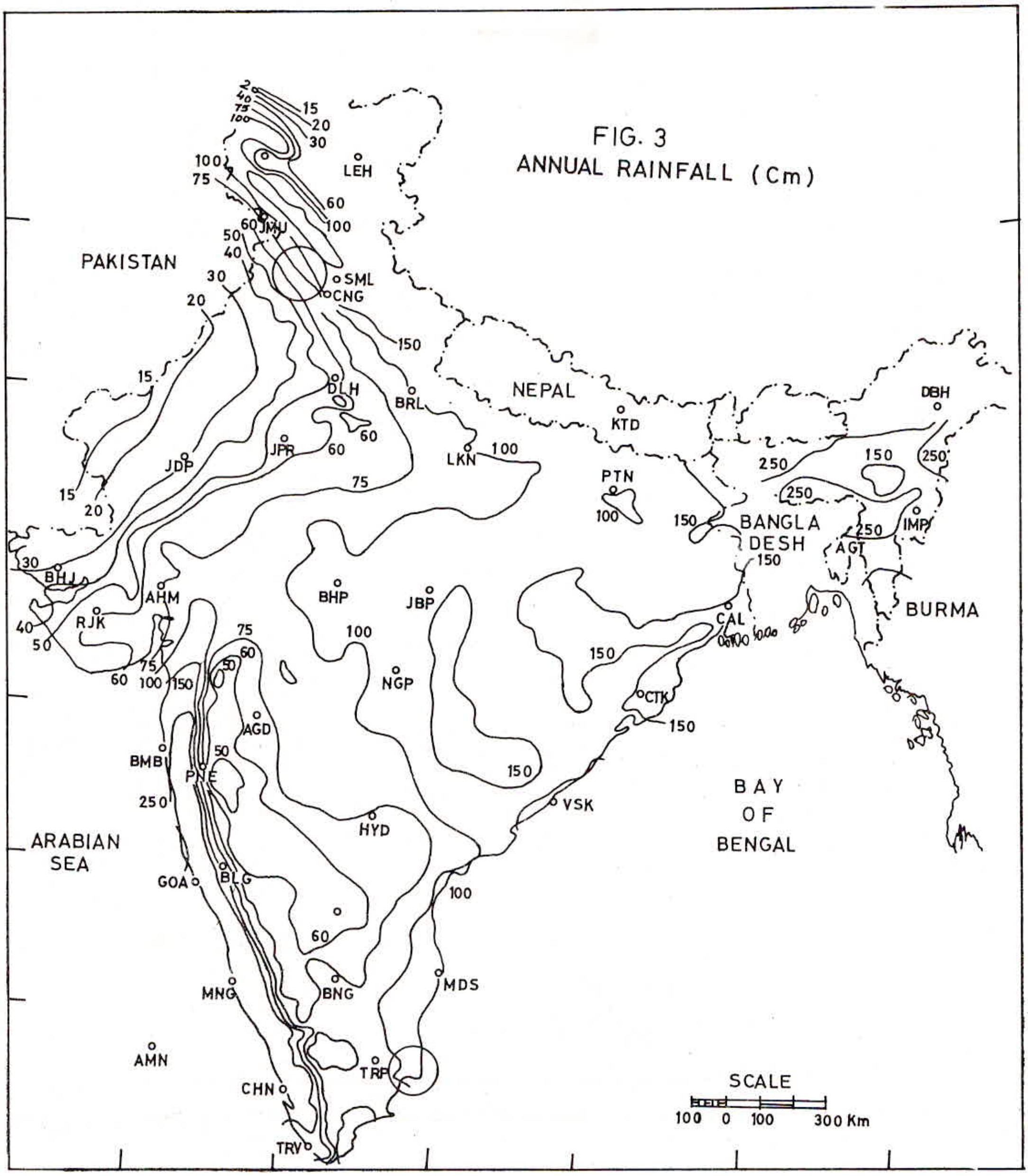


FIG. 3
ANNUAL RAINFALL (Cm)

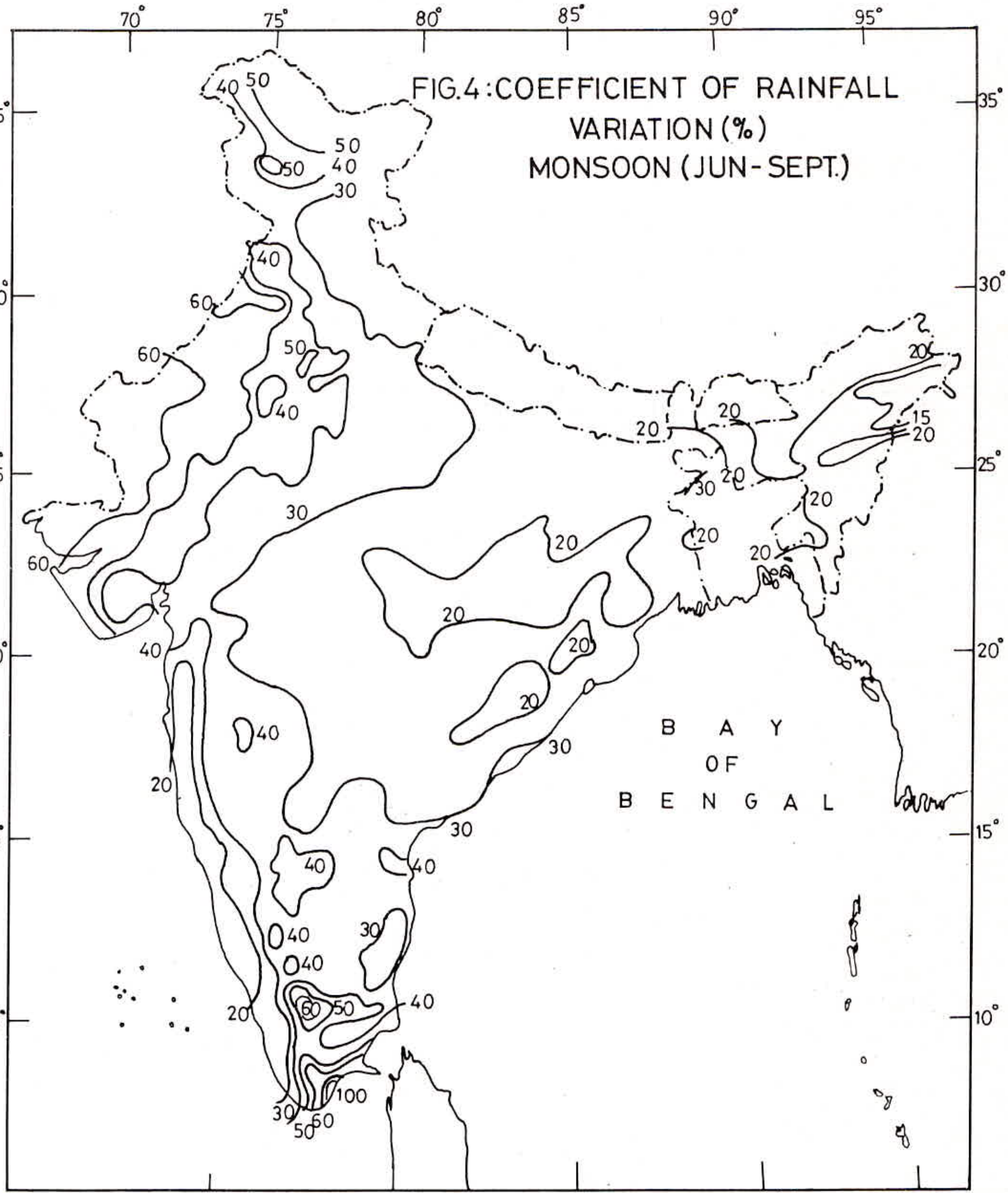
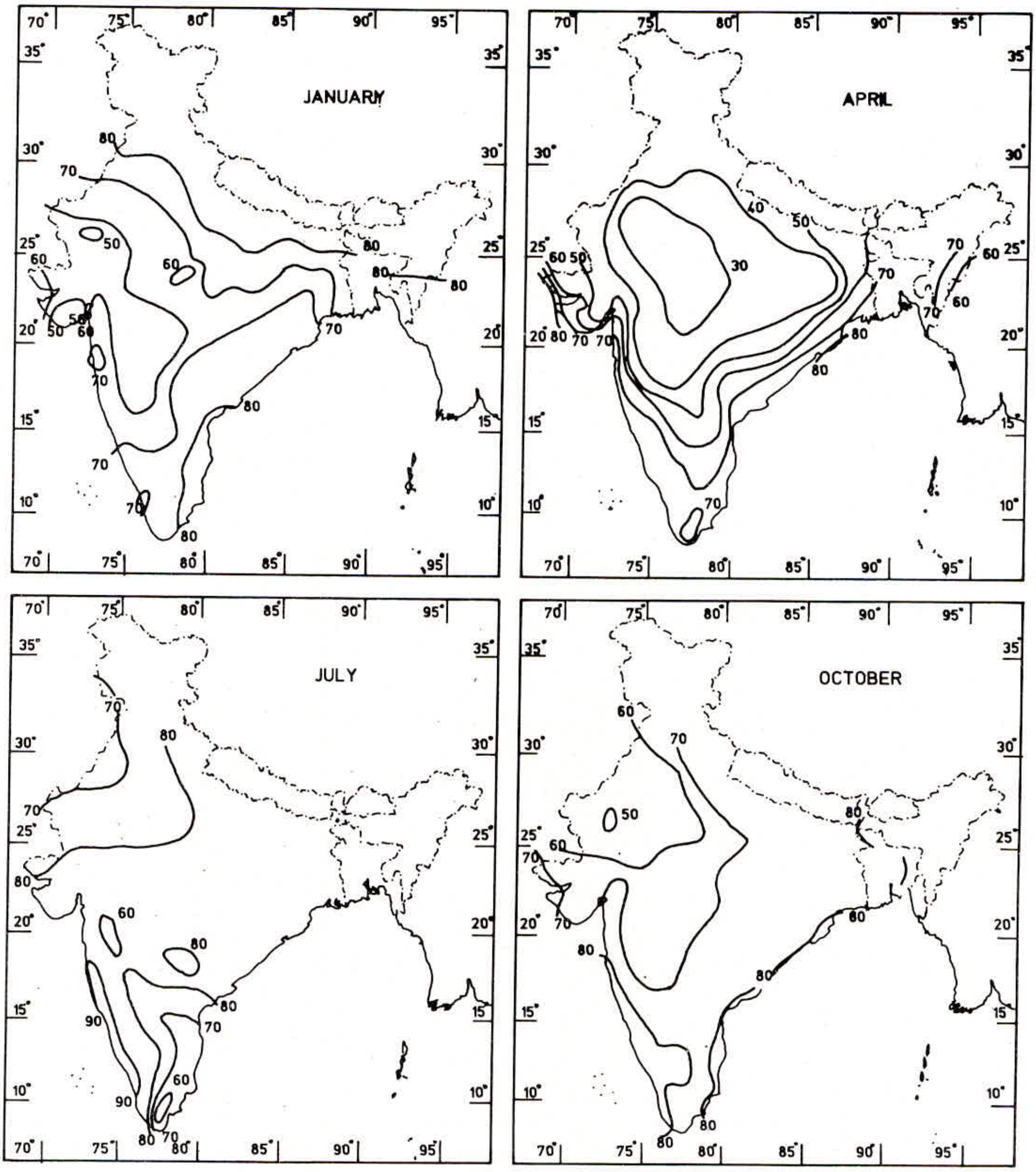


FIG.4: COEFFICIENT OF RAINFALL VARIATION (%)
MONSOON (JUN-SEPT.)

0830 IST
MEAN DAILY %

FIG. 5a : RELATIVE HUMIDITY



1730 IST
MEAN DAILY (%)

FIG. 5(b): RELATIVE HUMIDITY

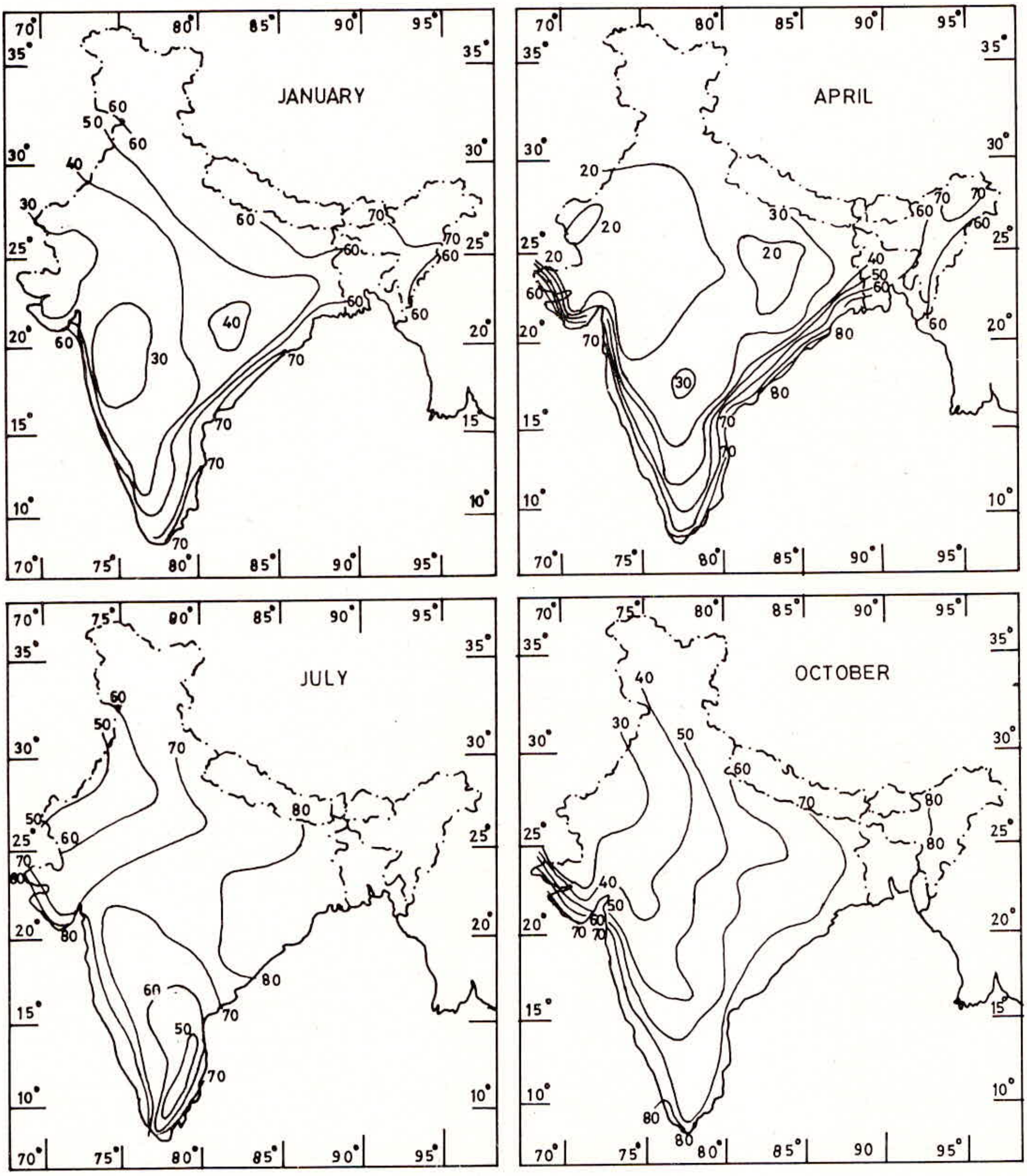


FIG.6(a) :EVAPORATION

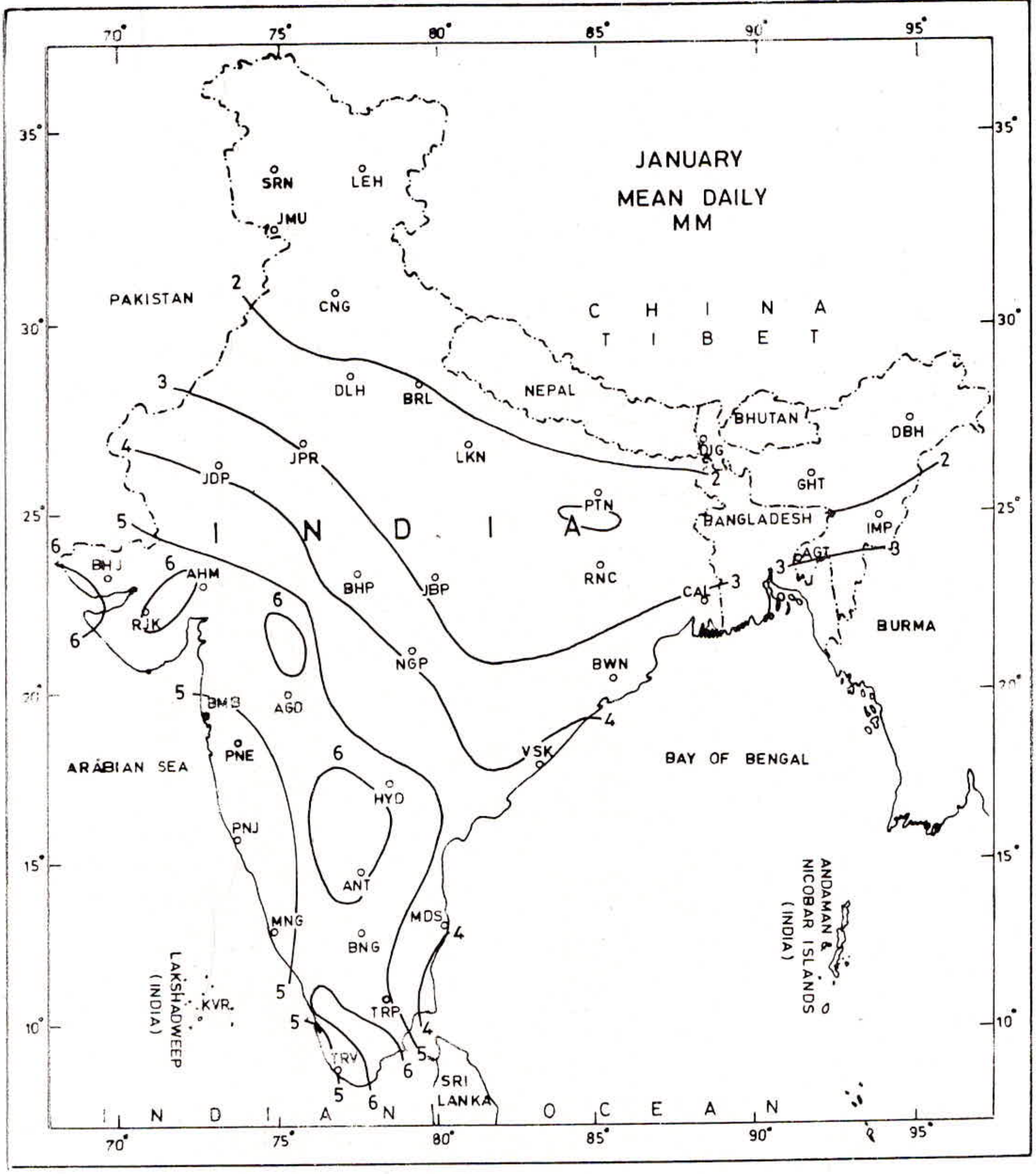


FIG. 6 (b): EVAPORATION

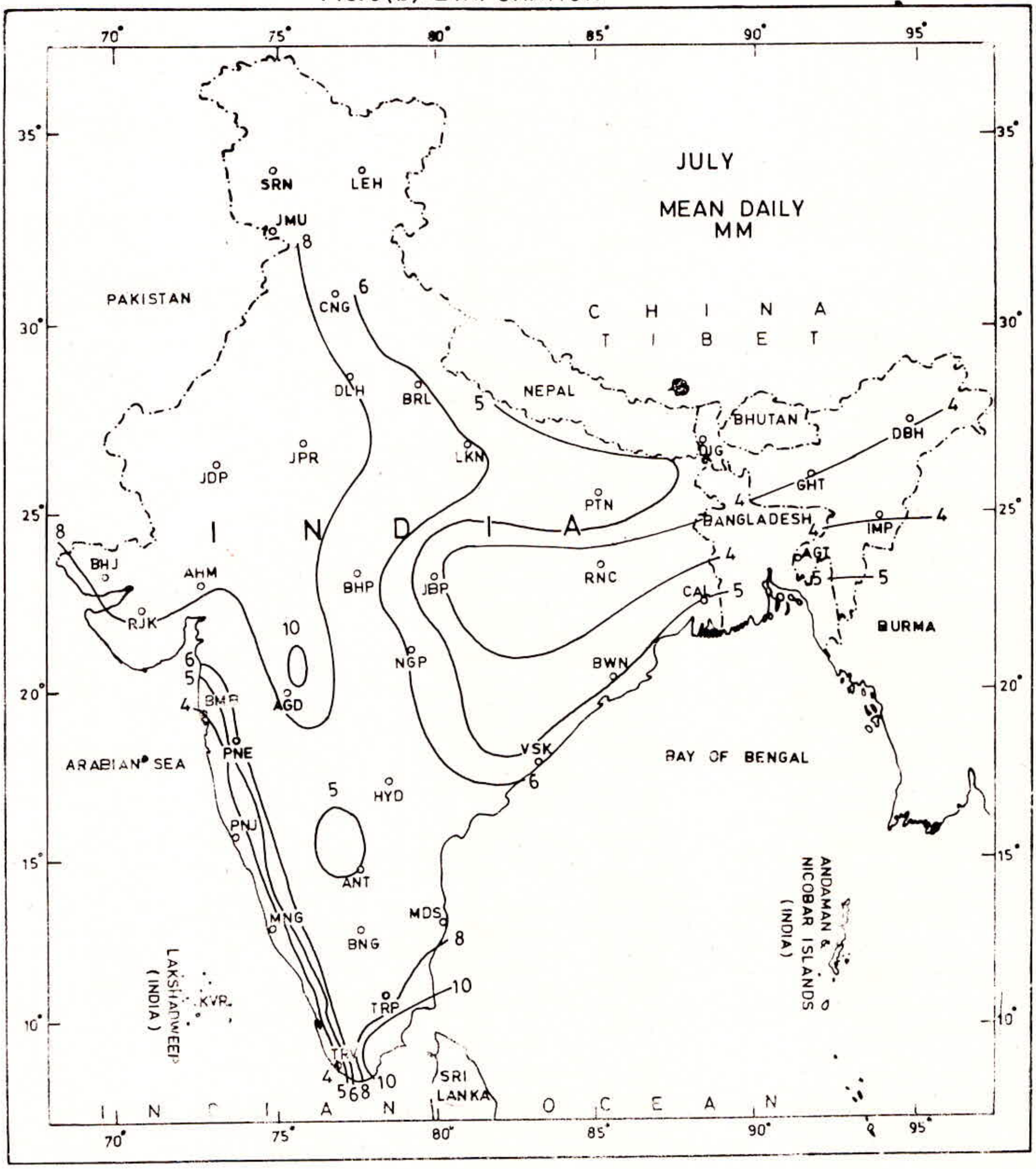


FIG. 7(a): AIR TEMPERATURE

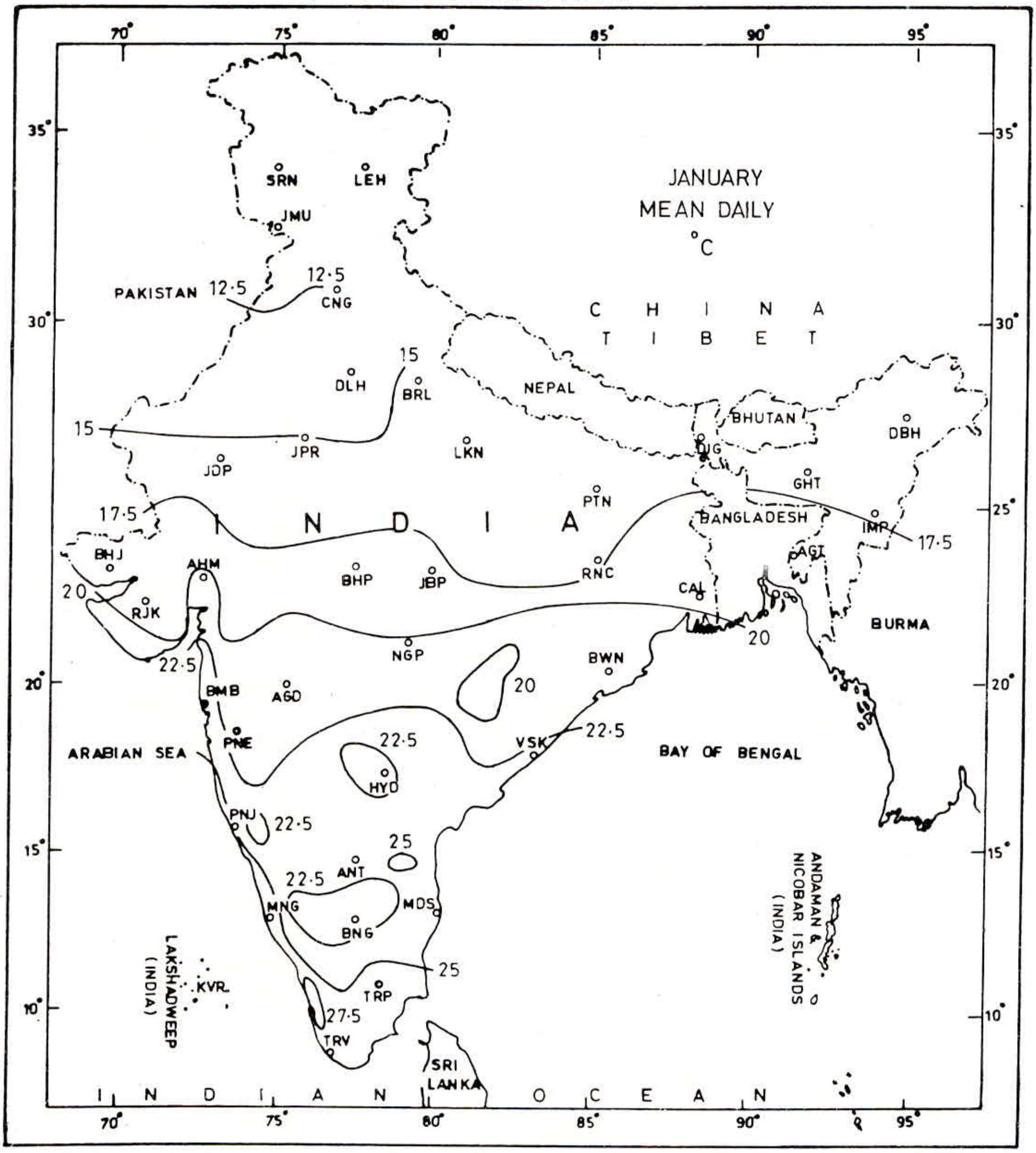
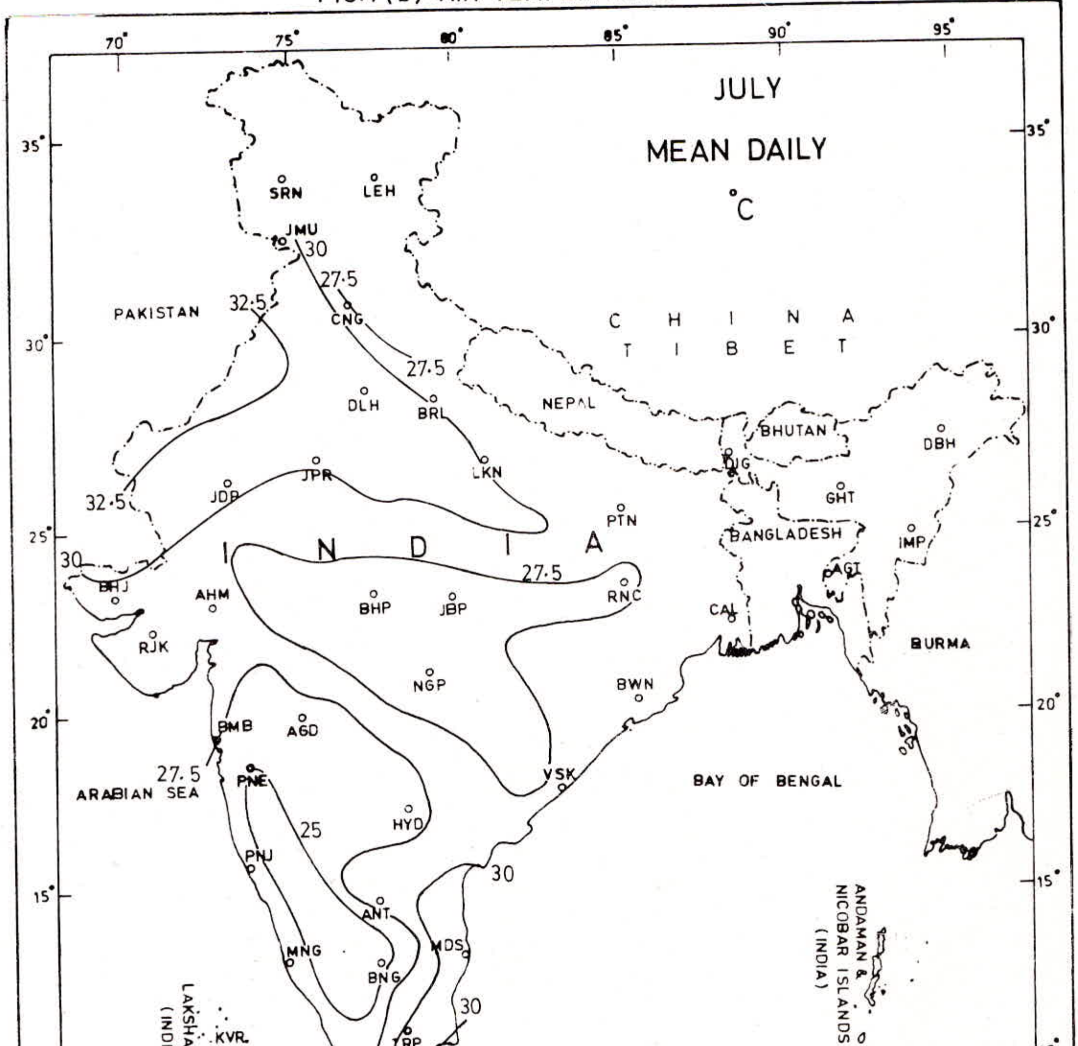


FIG. 7(b): AIR TEMPERATURE



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Dr. D.S. Upadhyay, is Director (Hydrometeorology) in the India Meteorological Department. He has worked extensively (over 25 years) in the areas is snow Hydrology, Hydrometeorology, Data analyses processing and management and rainfall forecasting. He has also worked in snow bound regions of western Himalayas for a number of years and carried out research on many aspects of snow, glaciers and avalanches under Indian conditions.

Dr. Upadhyay obtained his M.Sc degree and Ph.D. in Snow Hydrology from Banaras Hindu University, where he also worked as a lecturer during initial part of his career. The author's Research publications, over 75 in number, cover a wide range of topics such as Snow Hydrology, Avalanche forecasting, frequency and intensity analyses, water and energy balance, floods and drought, network design, climatology,quantitative precipitation forecast (QPF), design storm studies, technology transfer etc. He has also coauthored 3 books earlier in Engineering Mathematics, Meteorology and Statistics.

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