Large-Scale Droughts/Floods and Monsoon Circulation

H. N. BHALME AND D. A. MOOLEY
Indian Institute of Tropical Meteorology, Pune—411 005, India

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ABSTRACT

An objective numerical drought index based on monthly monsoon rainfall and duration has been developed for assessment of drought intensity. The drought intensity equation serves the dual purpose of assessing the intensity of drought as well as flood. The Drought Area Index (DAI) is defined as the percentage area of India having a mean monsoon index $\leqslant -2$ (i.e., moderate or higher drought severity). Likewise, the Flood Area Index (FAI) is the percentage area of India with mean monsoon index $\geqslant +2$ (i.e., moderate or more severe wetness), where the mean monsoon index is the mean drought index for the four monsoon months. A year is defined as a large-scale drought or flood year when DAI or FAI $\geqslant 25$. Using the evolved criteria, years of large-scale drought and flood over India have been identified during the period 1891–1975. The method adopted for defining large-scale drought or flood does bear out the actual experience. Power spectrum analysis reveals a weak triennial cycle in DAI series and a highly significant quasi-periodicity of 20 years in the FAI series—nearly a double sunspot cycle. The FAI series is in phase with the double sunspot cycle and large-scale floods have been more frequent in the high-amplitude maximum phase of sunspot cycle. Weaker meridional pressure gradients, larger northward seasonal shifts of the monsoon trough, larger numbers of days of breaks in the monsoon, smaller frequencies of depressions and shorter westward extents of depression tracks appear to be the major factors associated with large-scale droughts; opposite features have been observed for large-scale floods. The height of the 200 mb surface in May is found to be abnormally low in the latitude belt 15–30°N, along 70°E during large-scale drought years, in contrast to abnormally high levels during flood years. The 200 mb surface during May seems to have the potential for prediction of extreme abnormality in the following monsoon season.

1. Introduction

The important natural causes of Indian famines are large-scale droughts and floods. Although the onset, persistence and termination of a drought are usually gradual processes, its total impact may be far more disastrous than that of flood. Droughts in successive years or prolonging continuously for more than one or two years have a devastating effect on food production and the country's economy. Various attempts have been made to define and classify droughts. There is no universally acceptable definition of drought, although the word is associated with prolonged and abnormal rainfall deficiency. Various interests have evolved their own definitions according to their specific requirements. An extensive survey of the definitions of drought has been made by Hounam *et al.* (1975).

Rainfall is the most important single factor influencing the incidence of drought and practically all definitions use this variable either singly or in combination with other meteorological elements. Ramdas (1950) defined a drought or flood with reference to the variation of southwest monsoon rainfall only. According to Ramdas, drought occurs when the actual southwest monsoon rainfall is less than the normal by twice the mean deviation or more, and flood occurs when the actual southwest monsoon rainfall exceeds the normal by twice the mean deviation or more. In the India Meteorological Department, an annual rainfall of 75% of normal or less is taken as drought, and 50% or less as severe drought. Both these definitions suffer from the disadvantage that the drought severity is not comparable in space because no account is taken of spatial differences in the variability of rainfall.

The purpose of this paper is to develop an objective numerical drought index comparable in space and time, to evolve criteria for large-scale drought/flood, and to gain causal understanding of such large-scale extreme abnormalities in terms of monsoon circulation features.

2. Data

The present study has been made using monthly rainfall measurements for meteorological subdivisions of India (Fig. 1) for a period of 85 years (1891–1975)—except for the two subdivisions of Bay Island and Arabian Sea Island. About 3000 raingage stations, more or less uniformly dis-

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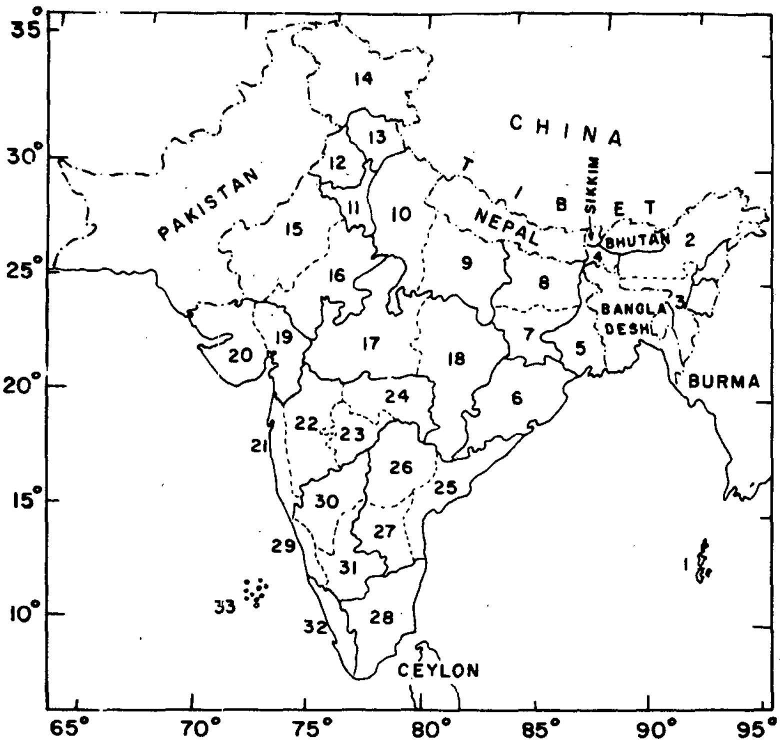


Index to Subdivision numbering

1. Bay Islands
2. North Assam
3. South Assam
4. Sub-Himalayan West Bengal
5. Gangetic West Bengal
6. Orissa
7. Bihar Plateau
8. Bihar Plains
9. Uttar Pradesh East
10. Uttar Pradesh West
11. Haryana
12. Punjab
13. Himachal Pradesh
14. Jammu and Kashmir
15. Rajasthan West
16. Rajasthan East
17. Madhya Pradesh West
18. Madhya Pradesh East
19. Gujarat
20. Saurashtra and Kutch
21. Konkan
22. Madhya Maharashtra
23. Marathwada
24. Vidarbha
25. Coastal Andhra Pradesh
26. Telengana
27. Rayalaseema
28. Tamil Nadu
29. Coastal Mysore
30. Interior Mysore North
31. Interior Mysore South
32. Kerala
33. Arabian Sea Islands

FIG. 1. Meteorological subdivisions of India as of 1 January 1971.

tributed in all subdivisions, have been utilized in obtaining subdivisional rainfall averages. The number of stations for which data are available in a given subdivision may vary from year to year. In order to permit year-to-year comparison of area rainfall, monthly percentage departures from normal for each of the subdivisions based on the data of available stations were computed. Monthly rainfall series were computed from the percentage departures using the monthly normals of subdivisional rainfall. This process eliminates the inhomogeneity due to varying number of stations and enables year-to-year comparison of subdivisional rainfall amounts.

3. Drought index

Weather events in the tropics are chiefly reflected in rainfall activity. Fortunately, rainfall is an accurate and more commonly available element over a long period of record. The southwest monsoon rainfall is the most important single factor in the agricultural economy of India. Hereafter we shall be referring to the southwest monsoon (June–September) as the monsoon. During the Indian monsoon more than 75–90% of the annual rainfall occurs over a large area of the country, droughts or floods are determined primarily by the amount of monsoon rainfall alone. Therefore, a drought index is developed by taking into account rainfall during the four months of the monsoon. A basic assumption in the development of the index is that plant life and established human activities are geared to the long-term mean rainfall of the area in the specific period. The procedure for development of an index consists of the following steps.

a. *Statistics of rainfall*

Statistical analysis of a long record is carried out to derive long-term mean monthly rainfall, and the standard deviation (SD) and coefficient of variation (SD/mean) of each of the four months of monsoon for the area of interest.

b. *Rainfall anomaly*

The rainfall anomaly is the percentage departure of monthly rainfall from the long-term mean; this provides a dimensionless measure of the abnormal precipitation.

c. *Moisture index*

The moisture index is the rainfall anomaly weighted by the reciprocal of coefficient of variation (SD/mean) of the corresponding month. This moisture index, within reasonable limit, permits comparison of rainfall anomaly in space and time.

d. Drought index equation

According to the American Meteorological Society (Huschke, 1959), drought is defined as abnormal moisture deficiency of a prolonged duration. Thus, no rational index of drought severity can dissociate itself from the duration of the abnormal moisture deficiency. The procedure given by Palmer (1965) has been used here to account for the duration factor of the abnormal moisture deficiency. To develop the drought intensity equation, averages of the highest accumulated values of the negative moisture index during various intervals of months were obtained from five drought-prone subdivisions: Bihar Plains, Rajasthan East, Gujarat, Marathwada and Rayalaseema. These data are shown in Fig. 2. The solid line was fitted to the plotted data by least-squares and represents extreme drought. The distance (ordinate) between the extreme drought line and the top of the chart was then divided into four equal lengths and the body of the graph was correspondingly divided by three more lines, labeled severe, moderate and mild drought. Numerical values are assigned to these lines, *viz.*, −4 for extreme drought, −3 for severe drought, −2 for moderate drought and −1 for mild drought. The equation for these lines is

$$I_k = (\sum_{t=1}^{k} M_t)/(24.26k + 24.29), \qquad (1)$$

where I_k is the drought intensity of kth month and $\sum M_t$ the accumulated moisture index over a duration t in months. This expression for intensity of drought provides only a partial solution because it is based on cumulative sums of moisture index M. This cumulative procedure of accounting for the duration of the dry period can be misleading. Thus, Fig. 3 clearly shows how the cumulative procedure can produce misleading results. Fig. 3a was constructed by assuming that $M = -50$ each month for two months and then $M = -150$ each month for following two months. The total accumulated M becomes −400 in four months. The fourth month value of M does not reach the extreme drought line. Fig. 3b was drawn by assuming that the first two months were wet and that remaining two months each had $M = -150$ as before. In this case the dry period begins with the first month in which $M = -150$ and the two months give the value $M = -300$. It may be noted that the value for the second month falls below the extreme drought line. Thus, Fig. 3b shows that two very dry months following wet months can produce more severe drought conditions than are produced by the same two very dry months following (Fig. 3a) two months of relatively dry weather.

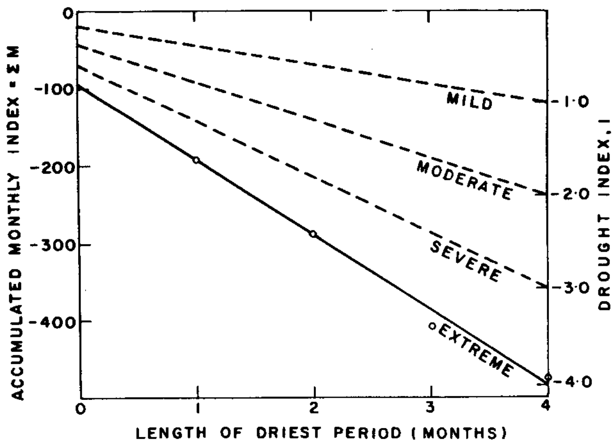


FIG. 2. Accumulated moisture index during the periods of various lengths.

Obviously, this is unrealistic. The cumulative procedure is misleading and cannot be used as a method of taking account of the duration of the dry period. The matter of drought intensity must be considered on an incremental basis such that each successive month is evaluated in terms of its contribution to the intensity of the drought. As a result of this

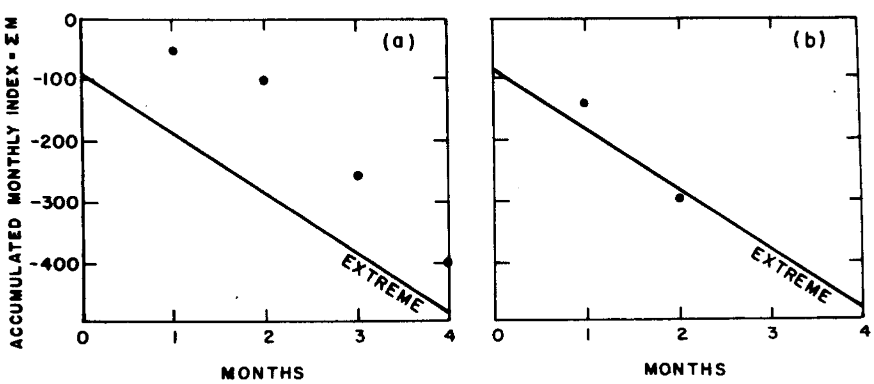


FIG. 3. An illustration of misleading cumulative procedure. (a) Two relatively dry months followed by two very dry months; (b) two very dry months alone.

TABLE 1. Description of monthly drought (−)/flood (+) index.

Index	Character of the weather
4.00 or more	Extremely wet
3.00 to 3.99	Very wet
2.00 to 2.99	Moderately wet
1.00 to 1.99	Slightly wet
0.99 to −0.99	Near normal
−1.00 to −1.99	Mild drought
−2.00 to −2.99	Moderate drought
−3.00 to −3.99	Severe drought
−4.00 or less	Extreme drought

treatment, the effect of duration is only indirectly included but this approach eliminates the other problem which is more serious.

The contribution of each month can be obtained by setting $k = 1$ in Eq. (1) to obtain

$$I_1 = M_1/48.55. \qquad (2)$$

For the initial month, $I_0 = 0$,

$$I_1 - I_0 = \Delta I_1 = M_1/48.55. \qquad (3)$$

In successive months, a negative value of M will be required to maintain the existing dry spell. The rate at which the moisture index M must increase to maintain a constant value of I, as evident from Eq. (1), depends on the value of I that is to be maintained. This suggests that for all months following the initial dry month, there should be an additional term. The equation then becomes

$$\Delta I_k = (M_k/48.55) + CI_{k-1}, \qquad (4)$$

where,

$$\Delta I_k = I_k - I_{k-1}.$$

Now a constant C is to be determined. Using Eq. (1) we can compute M_k from two successive months for a constant value of I. We set $k = 4$ and $I_4 = -1$ in Eq. (1) to obtain

$$\sum_{t=1}^{4} M_t = -121.33.$$

Likewise setting $k = 3$ and $I_3 = -1$, we have

$$\sum_{t=1}^{3} M_t = -97.07.$$

Hence

$$M_4 = \sum_{t=1}^{4} M_t - \sum_{t=1}^{3} M_t = -24.26.$$

Substituting these values in Eq. (4) yields $\Delta I = 0 = (-24.26/48.55) - 1.0C$, i.e., $C = -0.50$. Even with other values of intensity, the resulting value of C will come out to be the same. Thus, Eq. (4) becomes

$$\Delta I_k = (M_k/48.55) - 0.50I_{k-1}, \qquad (5)$$

or

$$I_k = I_{k-1} - 0.50I_{k-1} + (M_k/48.55)$$
$$= 0.50I_{k-1} + (M_k/48.55). \qquad (6)$$

Eq. (6) is the drought intensity equation, where I is the drought intensity, M the moisture anomaly index and the subscript k refers to the current month. The monthly rainfall anomaly can be negative as well as positive. Likewise, (6) gives negative or positive values of the index and thus provides a measure of dryness or wetness. It is reasonable to assume that the abnormal moisture deficiency which could result in moderate drought conditions would have resulted in moderate wet conditions had the moisture departures been positive rather than negative. Thus the index serves the dual purpose of assessing the intensity of drought, as well as flood. The monthly index values generally range from −4 to +4. Table 1 lists the descriptive terms which have been assigned to describe the character of the weather represented by various intervals of the index.

4. Large-scale droughts/floods

Using this drought index equation, monthly index computations were carried out for each monsoon month, June–September, for each of the 31 meteorological subdivisions of India (Fig. 1), for the years 1891–1975. From these monthly indices, the mean index for the four monsoon months (hereafter referred to as the mean monsoon index) was calculated for each of the years and for each of the subdivisions. The Drought Area Index (DAI) of a year is defined here as the percentage area of India having a mean monsoon index ≤ -2, i.e., moderate or higher intensity of drought during that year. Similarly, the Flood Area Index (FAI) of a year is the percentage area of India with mean monsoon index $\geq +2$, i.e., with moderate or more severe wetness during that year. A year with DAI ≥ 25 is defined as a large-scale drought year and a year with FAI ≥ 25 as a large-scale flood year.

a. Drought/flood magnitudes

The values of DAI and FAI were calculated for each of the years from 1891–1975 and, using the preceding criteria, the years of large-scale drought and flood in India were identified. The DAI and FAI series from 1891–1975 are presented in Figs. 4 and 5. The years of large-scale droughts and floods, their relative ranking and area affected are shown in Table 2. The years of large-scale drought/flood, identified by these criteria, have been supported by independent information. Appendices A and B give past accounts of droughts and floods that have occurred over India. The years of large-

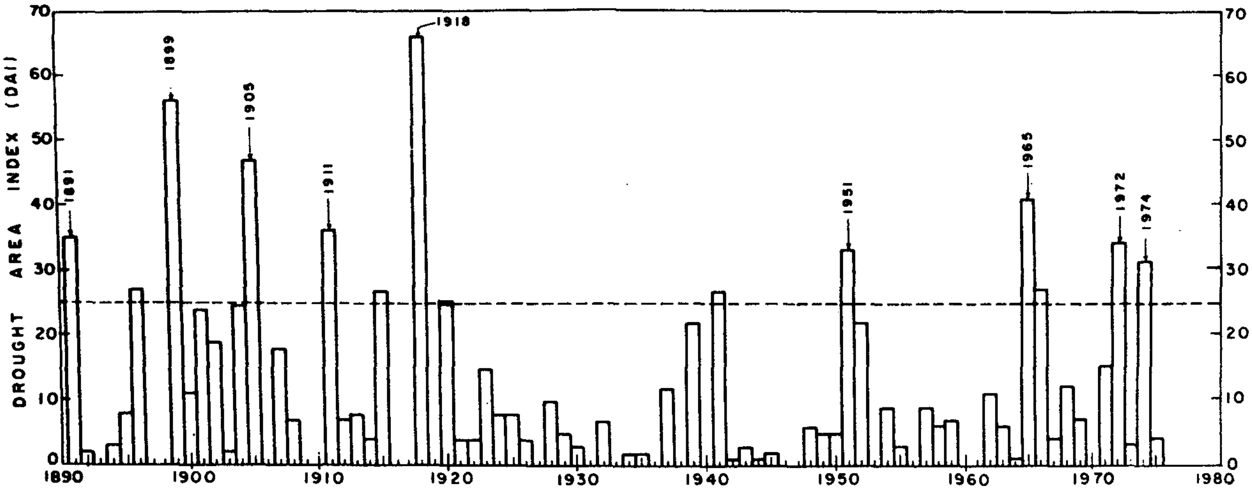


FIG. 4. Drought Area Index (DAI) from 1891–1975.

scale drought/flood identified by the method show satisfactory agreement with the past accounts. It may be seen from Fig. 4 that the year 1918 stands out as a great drought year for India. The unprecedented drought of 1918 resulted in famine of both food and fodder over practically the whole of the country. Fig. 5 shows that the year 1961 was a great flood year. Many states experienced the fury of floods with heavy damage to life, property and standing crops during the unparalleled flood of 1961. The past accounts from independent sources have also shown quite good agreement with these years. Thus the method adopted for defining large-scale droughts/floods generally bears out the actual experience.

The interesting feature to note from the Table 2, and also from Figs. 4 and 5, is that the number of large-scale droughts and floods tends to equalize. On the basis of Table 2, one may conclude that such large-scale droughts/floods may occur around 15 times each in a century. Then about 70 years in a century may be expected to be near normal. The years 1965 and 1966 afford the only instance of large-scale drought that occurred in consecutive

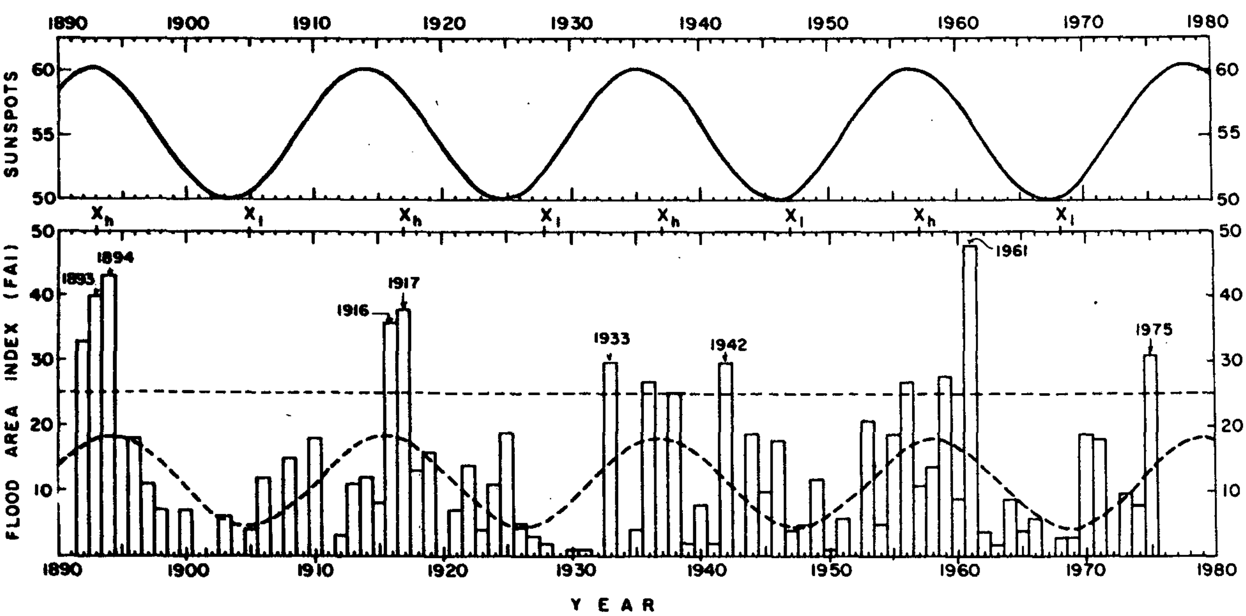


FIG. 5. Lower: Flood Area Index (FAI) from 1891–1975, the years of high-amplitude sunspots maximum (X_h), the years of low-amplitude sunspots maximum (X_l), and a wave of 21-year period in the FAI series. Upper: A wave of 21-year period in sunspots from 1891–1975.

TABLE 2. Large-scale drought/flood years over India from 1891–1975.

Large-scale droughts					Large-scale floods				
No.	Year	Interval between droughts (years)	Area affected (percent)	Ranking	No.	Year	Interval between floods (years)	Area affected (percent)	Ranking
1	1891	—	35	6	1	1892	—	33	6
2	1896	4	27	11	2	1893	0	40	3
3	1899	2	56	2	3	1894	0	44	2
4	1905	5	47	3	4	1916	21	36	5
5	1911	5	36	5	5	1917	0	38	4
6	1915	3	27	10	6	1933	15	30	9
7	1918	2	66	1	7	1936	2	27	11
8	1920	1	26	14	8	1938	1	25	13
9	1941	20	27	12	9	1942	3	30	8
10	1951	9	33	8	10	1956	13	27	12
11	1965	13	41	4	11	1959	2	28	10
12	1966	0	27	13	12	1961	1	48	1
13	1972	5	34	7	13	1975	13	31	7
14	1974	1	31	9					

years, whereas the years 1892, 1893, 1894 and 1916, 1917 are two instances of large-scale floods in consecutive years. The pairs of years 1891–1892, 1917–1918 and 1941–1942 show instances of successive years of large-scale contrast in moisture conditions.

An examination of Fig. 4 for the DAI series reveals that there have been greater frequencies of large-scale droughts during the two periods 1891–1920 and 1961–1975, with only a few years of large-scale drought in the long intervening period. The striking feature of Fig. 5 for FAI is that the series shows a cyclic change with a period of about 20 years. Large-scale floods occurred at an interval of about 20 years. This is also confirmed by power spectrum analysis as discussed in the following section.

5. Cycles of drought/flood

The time series of DAI and FAI for 1891–1975 were subjected to power spectrum analysis with a maximum lag of 20 to find out significant periodicities, if any. The computational procedure used is the same as outlined in WMO Technical Note No. 79 (WMO, 1966). The power spectra for the DAI and FAI series are shown in Fig. 6. The spectrum analysis shows a quasi-periodicity of 2.7–2.9 years significant at 90% confidence level (CL), suggesting a weak quasi-periodicity at or about a triennial cycle, in the DAI series. A similar triennial cycle in the total area of India under deficient monsoon rainfall and in the monsoon rainfall index with a shorter period of record was reported by Mooley (1975) and Joseph (1976), respectively. Bhalme (1972) also noticed an oscillation near this period in monsoon depressions/storms over India.

The power spectrum for the FAI series reveals a well-defined concentration of power at a period of 20 years, significant at 95% CL and very close to 99% CL, near a double sunspot cycle (it has averaged 21 years during the period under study). Fig. 5 displays the years of high-amplitude sunspot maximum (X_h), the years of low-amplitude sunspot maximum (X_l), and a wave of 21-year periods in sunspots and in the FAI series obtained by applying harmonic analysis to the data series. Fig. 5 clearly shows that the FAI series is in phase with a double sunspot cycle and that large-scale floods have been more frequent in the high-amplitude maximum phase of sunspot cycle. Jagannathan and Bhalme (1973) have shown evidence that southwest monsoon rainfall is influenced by sunspot activity. A cycle of 20 years has been found by Palmer (1965) in severe drought of western Kansas. Mitchell and Stockton as explained by Siscoe (1978) found a double sunspot cycle in the drought index over the central Great Plains of the United States.

6. Monsoon circulation associated with droughts and floods

Large variations in the monsoon rainfall are observed from year to year. These are evidently caused by the large-scale fluctuations in the atmospheric circulation during the monsoon. Monsoon rainfall variations are determined by the behavior of the monsoon trough (ITCZ). The most prominent feature of the Indian monsoon is a periodic shift of the monsoon trough. Rainfall areas also frequently shift in association with changes in the location of monsoon trough. A more southerly position of the monsoon trough is generally favorable for an active monsoon. During the most active monsoon months, July and August, the monsoon trough lies over the Gangetic Plains

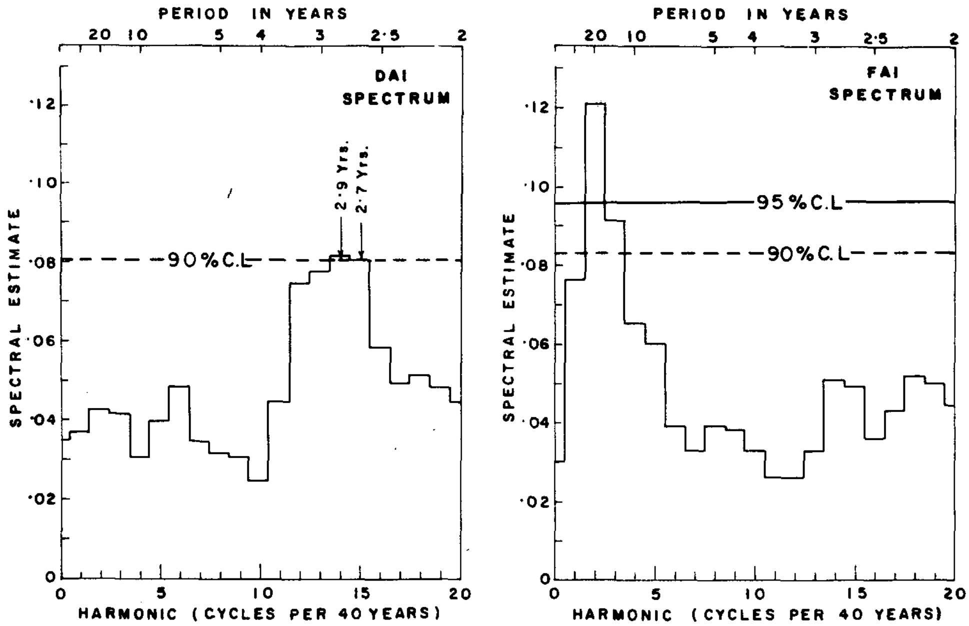


FIG. 6. Power spectra of DAI and FAI series.

roughly 30°N, 75°E to 23°N, 88°E, causing good rainfall in the plains of India and low rainfall near the foot of the Himalayas and in the southeast peninsula. On the other hand, the position of the axis of the monsoon trough close to the foot of the Himalayas results in a striking decrease of rainfall over most of the country but heavy rainfall along and near the foot of the Himalayas and an increase in rainfall in the southeast peninsula. This type of situation is known as a monsoon "break" (Ramamurthy, 1969; Raghavan, 1973). Sometimes these breaks are prolonged. Conditions then become favorable for continuous heavy rain in the catchment of the Himalayan river system causing floods along these rivers, although there may be very little rain in the plains of northern India.

The information on surface pressure, frequency of breaks and tracks of storms/depressions is available over a long period of record. This information has been examined by preparing composite maps for large-scale drought and flood regimes to gain causal understanding of such major abnormalities in terms of persistent large-scale aberrations of the monsoon circulation. The years of droughts (1899, 1905, 1911, 1918, 1951, 1965, 1972, 1974) and years of floods (1893, 1894, 1916, 1917, 1933, 1942, 1961, 1975) were chosen for the preparation of the composites.

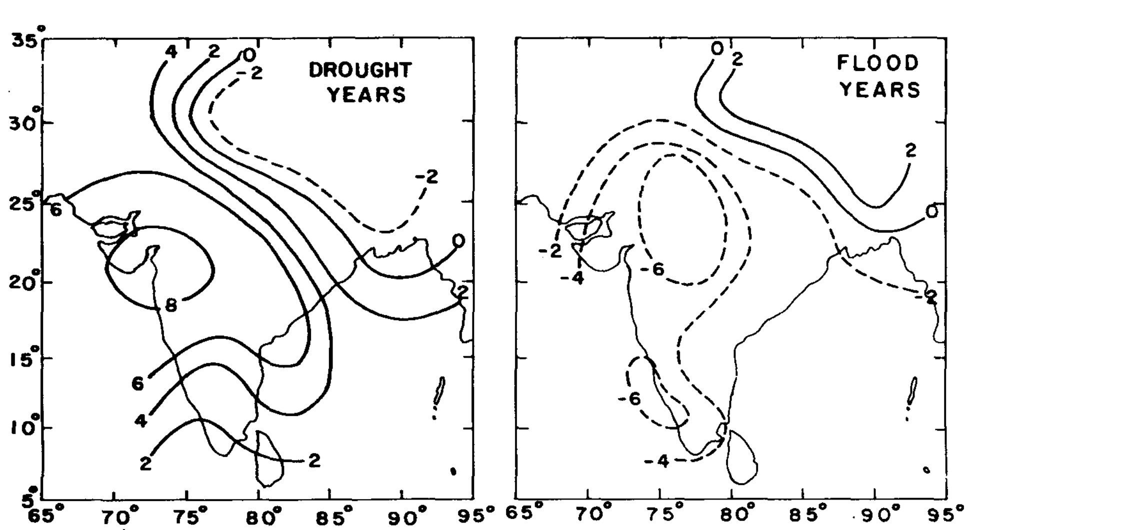


FIG. 7. Surface pressure departure (10^{-1} mb) during the southwest monsoon season.

TABLE 3. Number of days of break in monsoon.

Large-scale droughts		Large-scale floods	
Year	Days	Year	Days
1899	23	1893	19
1905	13	1894	9
1911	11	1916	3
1918	23	1917	10
1951	15	1933	8
1965	15	1942	4
1972	14	1961	0
1974	15	1975	4
Total	129		57

a. Surface pressure anomalies

The composite surface pressure departure fields during the monsoon season associated with the large-scale drought and large-scale flood regimes are displayed in Fig. 7. The surface pressure field during drought years shows that 1) the core of the negative pressure anomalies lies near the foot of the Himalayas, a condition usually associated with breaks in the monsoon, and 2) relatively high positive anomalies occur over the west coast of India between 15 and 20°N indicating a weaker meridional pressure gradient over India which results in a weak monsoon current over the west coast. During the flood years, the core of high negative pressure anomalies is situated further south over Rajasthan, Gujarat and Madhya Pradesh, and there is an indication of steeper meridional pressure gradient as in active monsoon conditions. The significant features brought out by the composite pressure fields are consistent with the observations made by Simpson (1921), Desai and Rao (1976) and Mooley (1976) during individual disastrous drought years.

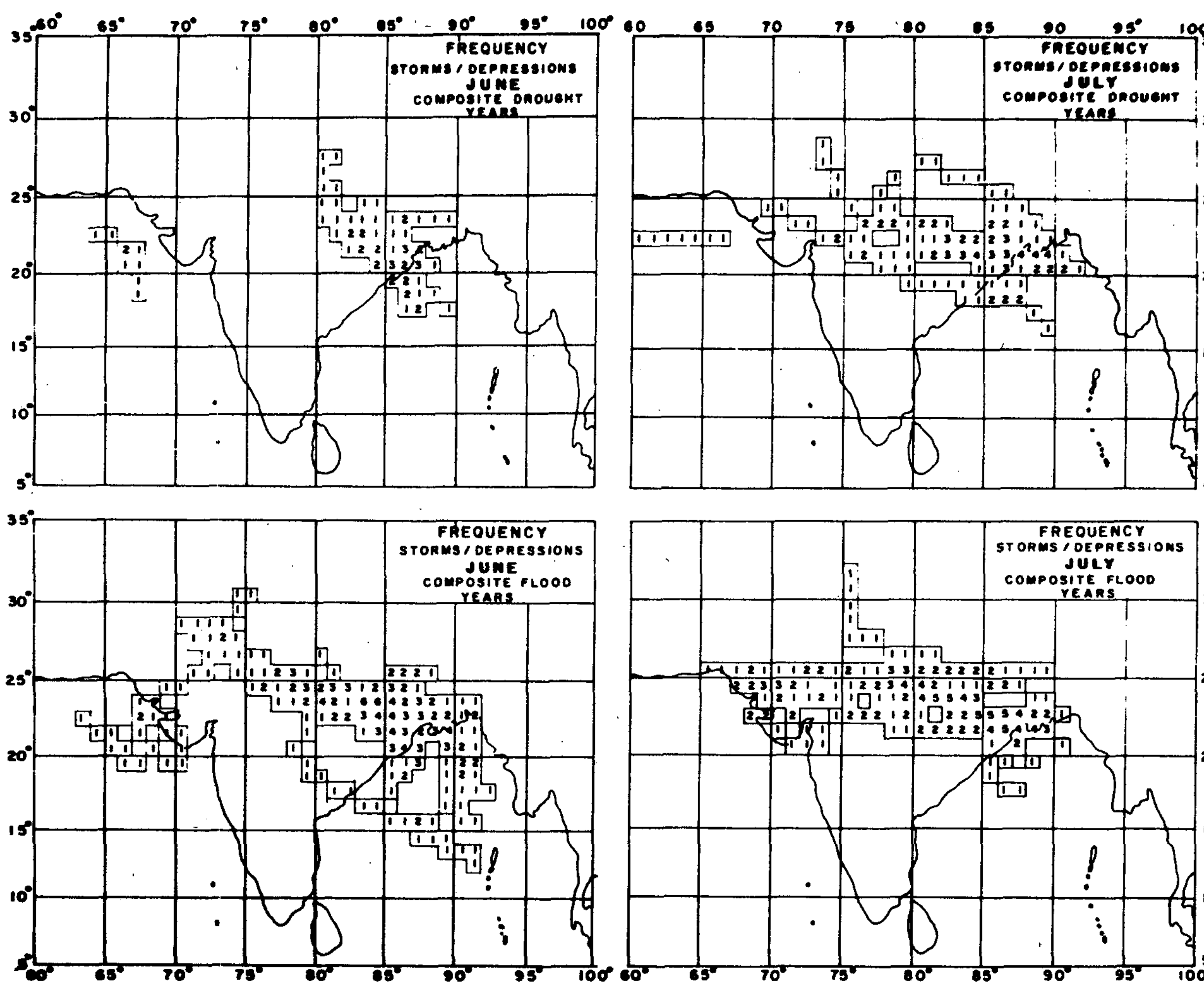
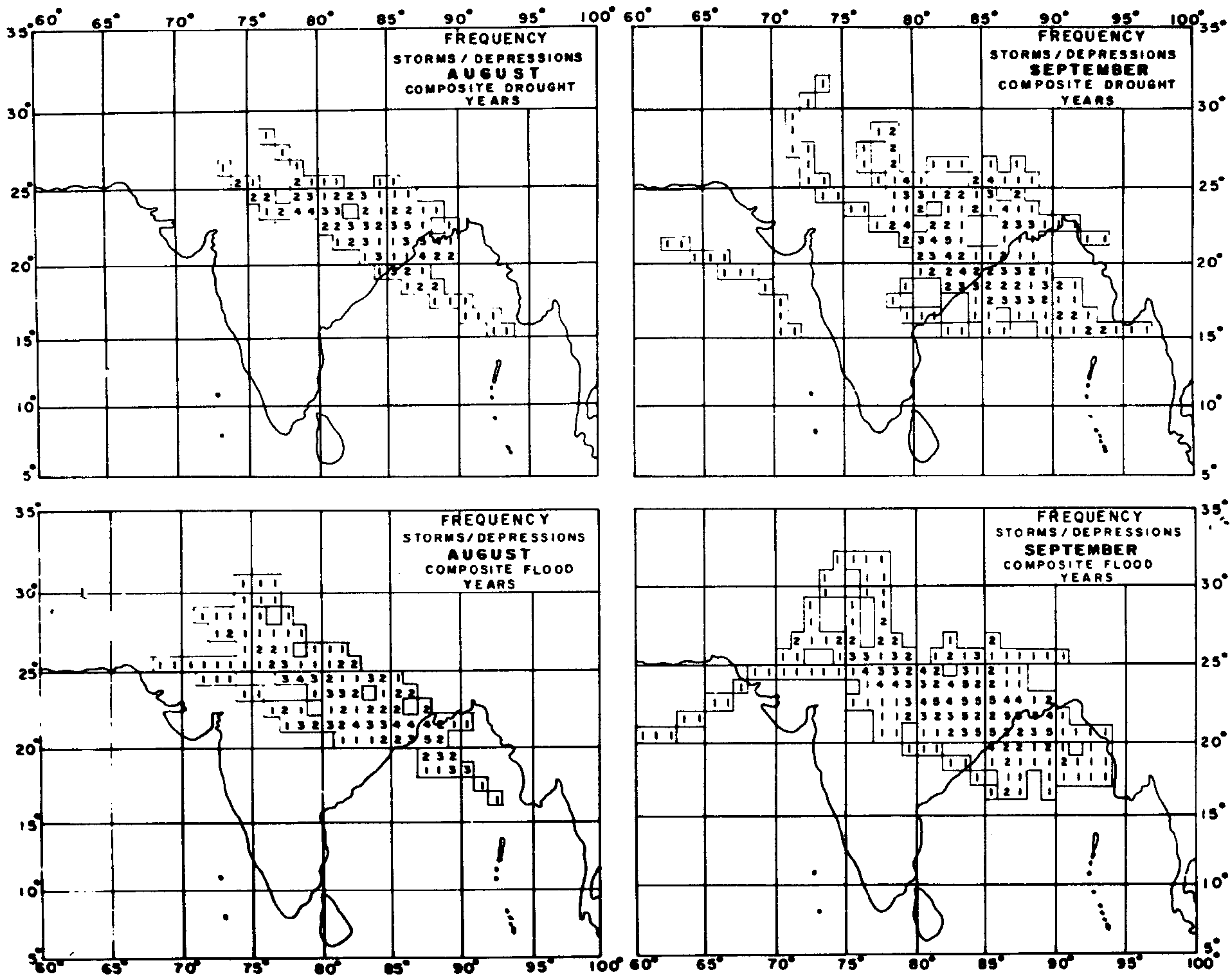


FIG. 8a. Frequency of storms and depressions (June and July).



b

FIG. 8b. As in Fig. 8a except for August and September.

b. Breaks in the monsoon

Table 3 [extracted from Ramamurthy (1969) and Indian Daily Weather Reports (1972, 1974 and 1975)] shows the relative frequency of breaks in the monsoon during July and August of different years of large-scale drought and flood. Note that the total number of days of breaks is significantly larger during droughts than during floods.

c. Monsoon storms/depressions

It is well known that the fluctuations in the intensity of rainfall during the monsoon season are to a large extent associated with the frequency, intensity and tracks of monsoon storms/depressions. The number of storms/depressions that crossed each 1° square of drought and flood regimes is shown in Figs. 8a and 8b. The information was extracted from the *Atlas of Storm Tracks* (India Meteorological Department, 1964) and from the unpublished tracks available at the Deputy Director General of Meteorology (Forecasting), Pune. It can be seen that the frequency of storms/depressions during droughts is much smaller than that during floods. Furthermore, the westward extent of the tracks is shorter during drought years than during flood years, and the belt in which the tracks lie converges westward during drought years. This contrast is most conspicuous for the years of drought during the month of June. Storms/depressions are confined to the east of 80°E during this month.

7. Atmospheric circulation antecedent to droughts and floods

Surface pressure departure fields over India during the pre-monsoon months of March to May were examined in an attempt to relate them to the general behavior of the following monsoon season. But the

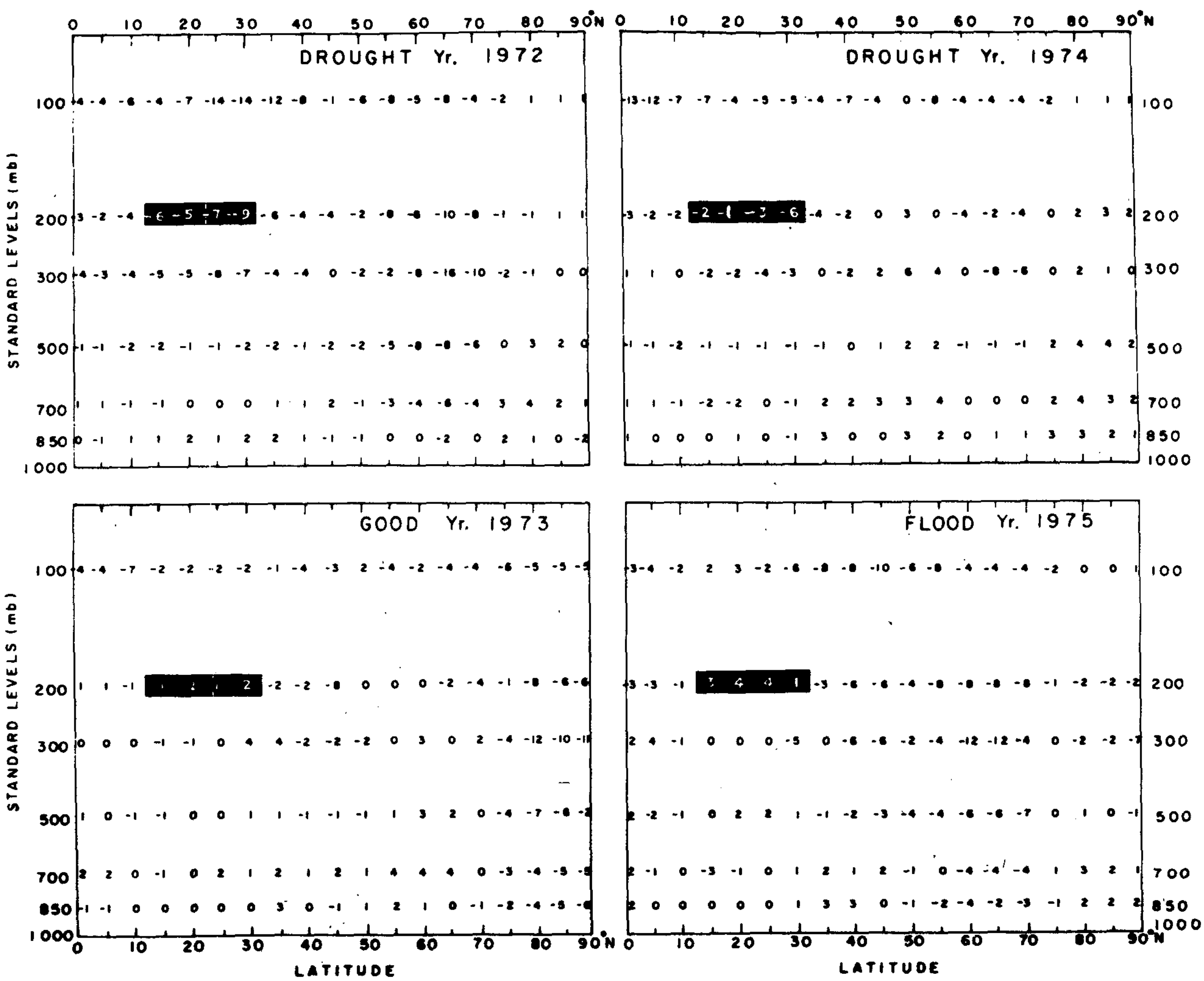


FIG. 9. Height departures (dam) of different isobaric levels from 0–90°N along 70°E, during May.

surface pressure field during pre-monsoon months was not found to give any indication of the behavior of the following monsoon season. Jagannathan and Khandekar (1962) examined the contour heights in the lower troposphere for the premonsoon months with reference to the subsequent monsoon rainfall over Peninsular India. They found that contour heights of the 500 mb surface for Delhi and Allahabad in March are significantly positively correlated to the Peninsular monsoon rainfall. Ananthakrishnan and Krishnan (1962) and Wright (1967) have drawn attention to the abrupt changes that take place in the upper troposphere during May almost simultaneously with the onset of the monsoon.

We present here a contrast of the height departures of tropospheric standard isobaric levels in the month of May during large-scale drought years (1972, 1974) with those of the normal year 1973 and the large-scale flood year of 1975. Prior to these years, the Indian region was not fully covered in Northern Hemisphere charts and hence could not be examined for other drought years such as 1965 and 1966. USSR Northern Hemispheric synoptic charts (1972–75) of tropospheric standard isobaric levels for the month of May for these four years were examined to see if any of these isobaric levels indicated anything unusual in the following monsoon season. The height departures of different isobaric levels from the Equator to the North Pole at an interval of 5° latitude along 70°E were calculated for these four years. The data are shown in Fig. 9. The abnormally large mean negative departures of −67 and −30 gpm between 15–30°N (shaded in Fig. 9) for the 200 mb surface is conspicuously noticeable during the large-scale drought years of 1972 and 1974, respectively. In contrast, abnormal positive departures (15 and 30 gpm) are observed in the same belt and for the same isobaric surface for the normal year 1973 and the large-scale flood year 1975, respectively. Large negative departures, during large-scale drought year in latitude belt

15–30°N along 70°E is a significant feature of 200 mb surface in contrast to positive departures during a normal or large-scale flood year. This suggests that the conditions in May are adverse for building up of the Tibetan high in years with large-scale drought. Kanamitsu and Krishnamurti (1978) found a weaker Tibetan high during monsoon months of the drought year 1972 as compared to the normal year 1967.

8. Concluding remarks

1) The method developed for assessment of drought intensity is found to produce realistic results over a tropical country such as India. The resulting drought index equation serves the dual purpose of assessing the intensity of drought as well as flood. The criteria evolved for defining large-scale drought or flood over India do bear out the actual experience. It is felt that this index could be applied to any other tropical country of a comparable size where most of the annual rain is concentrated in a season.

2) The number of large-scale droughts and floods tends to equalize over a long period of record. Large-scale droughts and floods over India may occur around 15 times each in a century.

3) There have been frequent large-scale droughts during the two periods 1891–1920 and 1961–75, which is separated by a long period with only a few years of large-scale drought.

4) Power spectrum analysis reveals a weak triennial cycle in the Drought Area Index series and a highly significant quasi-periodicity of 20 years in the Flood Area Index series. The Flood Area Index seems to expand and contract with a period near a double sunspot cycle. The FAI series is in phase with a double sunspot cycle and large-scale floods have been more frequent in the high-amplitude maximum phase of sunspot cycle.

5) Weaker meridional pressure gradient, larger northward seasonal shift of the monsoon trough, larger number of breaks in the monsoon, smaller frequency of depressions and shorter westward extent of their tracks appear to be the major factors associated with large-scale droughts. Features opposite to this have been observed for large-scale floods. The height of the 200 mb surface in May is found to be abnormally low in the latitude belt 15–30°N along 70°E during large-scale drought years in contrast to abnormally high level during flood years. The 200 mb surface during May seems to have the potentiality for the prediction of extreme abnormality in the following monsoon season; however, this needs to be investigated in detail.

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APPENDIX A

Accounts of Drought over India

The following accounts from different sources give details associated with the years of large-scale droughts over India. The river-discharge data for 1901–60 are available only for two peninsular rivers, *viz*., Godavari and Krishna (UNESCO, 1971). The area covered by the basins of these rivers is equivalent to 60% of the peninsular India and ~20% of the whole of India. Since the river discharge data pertain only to a small portion of India, they are not fully representative of abnormalities of weather over the country. However, this record has been used as a rough indication of weather abnormalities over peninsular India.

1. The drought of 1891

The monsoon of 1891 was late and was deficient over many parts of India but more seriously deficient in northeast India, comprising Assam, Bengal, Bihar and Orissa (Meteorological Department, 1891). Rainfall deficiency led to large failure of crops. Scarcity and famines were experienced in different parts of the country. A drought of great severity affected Bengal, Bihar, Orissa, Rajasthan, Madhya Maharashtra, Andhra Pradesh, Tamil Nadu and Karnataka [Indian Famine Commission Report, (Government of India, 1898)].

2. The drought of 1896

The rainfall of the monsoon period in 1896 was considerably below normal over the whole of northern and central India (Meteorological Department, 1896). The deficiency in monsoon rainfall led to partial failure of the crops over an unusually large area. The loss of crops was estimated to be one-third of the normal yearly production [Indian Famine Commission Report (Government of India, 1898)].

3. The drought of 1899

The monsoon of 1899 started on time but by the end of June showed signs of failure in several parts of India. The monsoon rainfall of this year failed almost over the entire country. The Meteorological Department declared the drought to be unique. The year was described at the time as the driest on record (Meteorological Department, 1899). The autumn harvest was a failure and few spring crops were sown. The famine was more widespread and severe than any the country had ever experienced. It was not merely a food famine but also one of fodder and water. Cattle died by the millions, and the Government helped farmers by very large appropriations of funds [Indian Famine Commission Report (Government of India, 1901)].

4. The drought of 1905

The monsoon rainfall of 1905 was inadequate over a large part of the country, the deficiency in rainfall being great in West Uttar Pradesh, Haryana, Punjab, Himachal Pradesh, Rajasthan, Maharashtra and Interior Karnataka (Meteorological Department, 1905). The river discharges over the Godavari and Krishna basins were ~40% below average (UNESCO, 1971). The crops failed in the autumn of this year. However, there was scarcity and suffering over Maharashtra and certain other states (Bhatia, 1967).

5. The drought of 1911

The monsoon of 1911 was characterized by its extreme weakness and unsteadiness from about the middle of June to the middle of August. It was almost a complete failure in Rajasthan, Gujarat, Saurashtra and Kutch. During the second half of August, the monsoon, which at one time threatened to prove as serious as in 1877, revived, with the result that the drought mitigated considerably (Meteorological Department, 1911). The river discharges of the Godavari and Krishna basins were 30% below average (UNESCO, 1971). The famine, however, was severe only in Maharashtra (Srivastava, 1968).

6. The drought of 1915

The most marked features of the monsoon of 1915 were its late arrival, its weakness and unsteadiness in July and August, and its failure to penetrate into northwest India before the middle of September. The deficiency in monsoon rainfall was most pronounced in northwest India which barely received half of its normal supply (Meteorological Department, 1915). The river discharges of the Godavari and Krishna basins were ~5% below average (UNESCO, 1971). The deficiency in monsoon rainfall led to famine, especially of fodder, over Bihar, Punjab, Rajasthan, Gujarat, Saurashtra and Kutch (Srivastava, 1968).

7. The drought of 1918

The monsoon of 1918 was exceptionally feeble and rainfall was seriously deficient over the whole of the country with the exception of northeast India (Meteorological Department, 1918). The river discharges of the Godavari and Krishna basins were 60% below average (UNESCO, 1971). The crops consequently failed. The drought in the year 1918 was more widespread and severe than the country had experienced in the last two centuries. The seriousness of the drought conditions over India is indicated in the comments from the Progress Report in Agriculture for 1918–1919 (Government of India, 1920) and the weekly *Kesari* from Pune, 1 October 1918. Reports clearly indicate that there was an almost unprecedented drought which resulted in the famine of both food and fodder over practically the whole of the country.

8. The drought of 1920

After making a good start the monsoon in the end proved disappointing. The deficiency in monsoon rainfall was considerable over Punjab, Jammu and Kashmir, West Rajasthan and Andhra Pradesh (Meteorological Department, 1920). The river discharges of the Godavari and Krishna basins were ~70 and 25% below average, respectively (UNESCO, 1971). The comparative failure of the rains in September not only seriously affected the standing monsoon season crops but was responsible for a large decrease in area in the succeeding winter crops (Government of India, 1922).

9. The drought of 1941

Monsoon rains were 25–40% below normal over large parts of Uttar Pradesh, Haryana, Madhya Pradesh, Maharashtra and Telangana (Meteorological Department, 1941). The river discharges of the Godavari and Krishna basins were 60 and 30% below average, respectively (UNESCO, 1971).

10. The drought of 1951

The chief features of the monsoon of 1951 were weak monsoon conditions, in general, throughout the period, with continued drought conditions over Rajasthan, Gujarat, and Saurashtra and Kutch from about the middle of August onward, resulting in famine conditions there (India Meteorological Department, 1952). The river discharges of the Godavari and Krishna basins were ~25% below average (UNESCO, 1971).

11. The drought of 1965

The monsoon of 1965 was deficient over the whole of the country, being appreciably so in northwest India, central parts of the country and part of eastern India (India Meteorological Department, 1966). During 1965–66 India witnessed one of the severest droughts in recent history, the worst affected areas being Bihar and east Uttar Pradesh, where special measures were taken to provide relief to the drought-stricken people. To meet the heavy short-fall in foodgrains production in the country, the Government intensified internal procurement and arranged for massive imports (Research and Reference Division, 1967).

12. The drought of 1966

The monsoon rainfall was characteristic of drought conditions over most of the northern parts of the country. This happened for the second year in succession, the worst affected areas being Bihar and east Uttar Pradesh (India Meteorological Department, 1967). The food situation in the country continued to be extremely difficult due to widespread drought and the consequent failure of crops for the second year in succession (Research and Reference Division, 1968).

13. The drought of 1972

The delayed onset of monsoon of 1972 and a prolonged break in July led to drought conditions over the country, particularly in many parts of north India and north Peninsula (India Meteorological Department, 1973). The food situation in the country was rather difficult in 1972 because of extensive damage to monsoon season crops resulting from erratic and scanty rainfall and drought conditions in several parts of the country. Scarcity conditions were experienced in varying degrees in a number of States, the worst affected areas being Maharashtra, Gujarat, Rajasthan and Andhra Pradesh. Toward the end of 1972, arrangements were made to import 2 million metric tons of foodgrains to replenish the buffer stocks and to ensure uninterrupted flow of supplies through public distribution (Research and Reference Division, 1974).

14. The drought of 1974

The monsoon of 1974 proved erratic. Rains were 20–59% below normal over large parts of Gujarat, Rajasthan, Orissa, West Bengal, Bihar, Haryana and Punjab. Consequently, a shortage of 7 million metric tons in the monsoon season crop of foodgrain was feared. The possibility of importing large quantities of grains was also restricted owing to the high world prices. In the climate of scarcity, many growers held on to their stocks and there was also a considerable amount of clandestine trading. In Orissa and West Bengal low stocks of grains and lack of purchasing power led to famine conditions in rural areas. The Government adopted a series of measures to curb money supply, curtail expenditure and raise more revenue [*Britannica Book of the Year* (University of Chicago, 1975)].

APPENDIX B

Accounts of Floods over India

The word floods used in the this paper pertains to excessive rainfall over large parts of the country. The following information from different sources gives details of flood occurrence over India.

1. The flood of 1892

The monsoon rainfall of 1892 was normal or in excess over the whole of India. It was in large excess in Haryana, Punjab, Jammu and Kashmir, Rajasthan, Gujarat, Andhra Pradesh, Tamil Nadu and Karnataka. India Meteorological Department (1962b) described 1892 as flood year in which floods or excessive rainfall occurred over large parts of the country.

2. The flood of 1893

The monsoon rainfall of 1893 was excessive over all of northern and central India, with the greatest excess being in Bihar, Haryana, Punjab, Jammu and Kashmir, Rajasthan and Gujarat. Monsoon rain was more abundant and frequent than usual (Meteorological Department, 1893).

3. The flood of 1894

The monsoon rainfall of 1894 was normal or in excess over the whole of India. It was in considerable to large excess in Punjab, Himachal Pradesh, Jammu and Kashmir, Rajasthan, Gujarat, Saurashtra and Kutch (Meteorological Department, 1894).

4. The flood of 1916

The monsoon rains were exceptionally heavy in this year which is one of the wettest on record, a greater excess than this having occurred only twice before in 1878 and 1893 (Meteorological Department, 1916). The river discharges of the Godavari and Krishna basins were 15 and 30% above average, respectively (UNESCO, 1971).

5. The flood of 1917

The monsoon of this year was phenomenally vigorous, the total rainfall during the monsoon period being by far the highest on record (Meteorological Department, 1917). India Meteorological Department (1962b) described this year as one of the big flood years over a large part of the country. The river discharges of the Godavari and Krishna basins were 40 and 10% above average, respectively (UNESCO, 1971).

6. The flood of 1933

The monsoon of 1933 provided abundant and well-distributed rainfall over a large part of the country. The total rainfall during the monsoon was in large excess in Pubjab, Rajasthan, Gujarat, and Saurashtra and Kutch. The river discharges of the Godavari and Krishna basins were ~35% above average (UNESCO, 1971). Excessive rains and flooding damaged crops (Meteorological Department, 1933; Government of India, 1936).

7. The flood of 1936

The monsoon of 1936 had no pronounced breaks. The rainfall of the period June–September was unevenly distributed, with several spells of heavy rain in the Gangetic Plain, giving rise to serious floods, and scanty rains in the Gujarat and Maharashtra (Meteorological Department, 1936). The river discharges of the Godavari and Krishna basins were 25% above average and 20% below average, respectively (UNESCO, 1971).

8. The flood of 1938

The monsoon of 1938 was marked by spells of heavy rains which resulted in floods in Brahmaputra valley in July and in the Uttar Pradesh in August. According to press reports, large areas were submerged and breaches in railway lines caused serious dislocation of traffic in parts of Assam and Bengal (Meteorological Department, 1938). The river discharges of the Godavari and Krishna basins were 25% above average and normal, respectively (UNESCO, 1971).

9. The flood of 1942

During the monsoon of 1942 there was abundant and well-distributed rainfall in the country, and it was in great excess in west Uttar Pradesh, Punjab, Himachal Pradesh, Jammu and Kashmir, east Rajasthan, west Madhya Pradesh and Gujarat (Meteorological Department, 1942). The river discharges of the Godavari and Krishna basins were 30% above average and near-normal, respectively (UNESCO, 1971).

10. The flood of 1956

The monsoon of this year over a major part of the country extended for a period of five months, from mid-May to mid-October, instead of the usual four months, June–September. Also, the activity of the monsoon was being reinforced by successive depressions both in the Bay of Bengal and the Arabian Sea areas, resulting in the total season's rainfall being generally above normal, many areas getting an abundance of it. The excessive rainfall gave rise to the severe floods in parts of Assam, West Bengal, Bihar, Uttar Pradesh and the Punjab and minor floods in several other parts (India Meteorological Department, 1957). The river discharges of the Godavari and Krishna basins were 30 and 60% above average, respectively (UNESCO, 1971).

11. The flood of 1959

The monsoon of 1959 will be particularly remembered for the devastating floods it caused in Assam in June, Jammu and Kashmir, and Saurashtra and Kutch in July and the unprecedented floods in Gujarat and coastal Andhra Pradesh in September (India Meteorological Department, 1960; Research and Reference Division, 1961). The river discharges of the Godavari and Krishna basins were 125 and 55% above average, respectively (UNESCO, 1971).

12. The flood of 1961

Many states experienced heavy floods during the monsoon of 1961. A special feature of this year's floods was that states like Kerala, Tamil Nadu, Karnataka, Madhya Pradesh and Rajasthan which are normally not subject to appreciable floods, experienced heavy floods as a result of heavy and concentrated rainfall. Many rivers recorded the highest ever levels this year (Research and Reference Division, 1962). The suffering and losses of life and property due to the floods caused by the bursting of protective dams designed to control floods or regulate other projects were so alarmingly high that the economics of flood control measures had to be reviewed by agencies like Central and State Flood Control Boards, the Central Water and Power Commission, Ministry of Irrigation and Power, etc. (India Meteorological Department, 1962a).

13. The flood of 1975

During the vigorous monsoon of 1975, west Bengal, Bihar, Orissa, Uttar Pradesh, Kerala and some other states experienced the fury of floods with heavy damage to life, property and standing crops (Research and Reference Division, 1976).

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