CHAPTER VIII
SUMMARY AND CONCLUSIONS

A short review of the circulation features connected with the Indian summer monsoon and the rainfall associated with it is given in the introductory chapter. The salient points and conclusions of the author's studies presented in Chapters 2 to 7 are summarised below.

8.1 Onset of the southwest monsoon over Kerala

(i) No objective method exists for fixing the date of onset of the southwest monsoon over Kerala which marks the beginning of the principal rainy season for India. The prime consideration has always been a sustained increase of rainfall at the coastal stations. Upper air circulation features and satellite cloud imagery have been valuable aids since such data became available in later years.

(ii) Kerala has had a dense network of raingauge stations over a long period going back to the last century. The daily rainfall data from this network have been utilised to derive a uniform set of monsoon onset dates over south Kerala (SK) and north Kerala (NK) from as far back as possible up to 1990.

(iii) Examination of the daily area-averaged rainfall series shows a sharp and sustained increase distinguishing the monsoon onset from the pre-monsoon thunderstorm rain. Semi-objective criteria for fixing the date of monsoon onset have been derived from the daily rainfall data series and the onset dates determined for the period 1891 to 1990 for SK and 1870 to 1990 for NK. These are the longest data series relating to the monsoon onset over Kerala up to 1990.
(iv) The mean dates of monsoon onset for SK and NK are 30 May and 1 June. The standard deviation of both the data series is ~8.5 days. The total dispersion of the onset dates is 45 days; the earliest and latest onset dates were 7 May in 1918 and 22 June in 1972 respectively.

(v) The dates of onset for the period 1900 to 1990 have been compared with the dates as per IMD records and comments are offered where substantial discrepancies are noticed pointing out the need for revision of the IMD onset dates in such cases.

(vi) The onset dates do not show any long term trend; however, there are clear epochs of early and late onsets.

(vii) The onset spell that brings the monsoon to Kerala has large variations in respect of its duration and mean daily rainfall. Statistically significant decreasing trend is found in both these features in recent years.

(viii) The steep and sudden increase of rainfall associated with the monsoon onset is strikingly brought out when the daily rainfall data are combined by superposed epoch method centered on the onset dates for the individual years.

(ix) Because of the dispersion of the onset dates in individual years, the increase in rainfall associated with the onset appears gradual when the rainfall data are combined chronologically. This gives the impression of merging of the monsoon rains with the pre-monsoon thundershowers as stated in some earlier studies.
The two major contributions of the studies presented in this Chapter are: (a) fixing of monsoon onset dates over Kerala going as far back as possible on the basis of uniform criteria based on rainfall records; and (b) showing the distinct increase in rainfall that characterises the monsoon onset by the superposed epoch method.

8.2 Evolution of upper-air circulation and moisture fields over India associated with the onset of summer monsoon over Kerala

(i) The synoptic features associated with the onset of the summer monsoon over Kerala during individual years have broad similarities with super-imposed interannual variations. The similarities are brought out by making a composite study of the meteorological features during the onset phase, taking the date of onset over south Kerala as the key date.

(ii) The rainfall composites are prepared by using daily data of the 80-year period 1901-1980. The wind and the moisture related parameters are worked out for 23 RS/RW stations over India for the period 1971-1985. The Outgoing Longwave Radiation (OLR) data for the period 1974-1987 were utilised to examine the convective activity during the onset phase.

(iii) The composite rainfall diagrams show sharp increase over stations along the west coast with progressive lag from south to north. Stations like Calcutta and Nagpur whose normal onset dates are within 20 days of Kerala onset also show this increase. However, for stations in the southeast coast of India, the important factor for deciding the onset of southwest monsoon is circulation rather than rainfall.
(vi) In the wind field, the gradual strengthening of the equatorial easterlies in the upper troposphere is the first indication of the approach of the summer monsoon. The easterlies attain a strength of 20 ms\(^{-1}\) in the layer between 300 to 100 hPa levels over the southern parts of the peninsula at the time of the onset over south Kerala.

(v) The subtropical westerlies in the upper troposphere over north India start weakening from about 30 ms\(^{-1}\) to 20 ms\(^{-1}\), slowly at first and more rapidly as the onset date approaches. It was noticed that the ridge line separating the easterlies and westerlies above 700 hPa level at about 17\(^\circ\)N latitude does not move northward until the onset. After the onset over Kerala it moves rapidly northward but the core of the westerlies retains the strength of about 20 ms\(^{-1}\) for about 2 weeks.

(vi) At the lower levels the circulation does not show any appreciable change from -20 day to the onset date. The surface westerlies deepen to about 400 hPa level rapidly with the onset. The strength also increases to 10 / 15 ms\(^{-1}\) between 800 and 700 hPa levels.

(vii) In the composite flow charts, a stationary east-west trough line appears about 10 days before the onset at the tip of the peninsula from 700 to 400 hPa levels. After the onset, the trough line moves rapidly northward along the west coast to about latitude 22\(^\circ\)N. This trough in the composite may be regarded as the manifestation of the onset vortex noticed over eastern Arabian sea during the onset in many years.

(viii) The vertical distribution of relative humidity shows rapid deepening of the moist layer a few days before
the onset at the respective stations. The study brings out the large-scale increase in atmospheric moisture content over the Indian land mass before the strengthening of the monsoon flow, similar to the increase noticed over the Arabian sea.

(ix) The composite vertically integrated transport of moisture also shows rapid increase with the onset over peninsular India. In the composite, the transport across Bombay changes from westward to eastward on the sixth day after the onset over south Kerala consistent with the increase in rainfall at this station six days after the Kerala onset. Comparison of moisture transport over Madras and Mangalore, which are located practically at the same latitude, shows simultaneous increase in the transport suggesting simultaneous onset over both these stations.

(X) The OLR composites show the rapid development and northward movement of convective activity over the southeast Arabian sea and west coast. The main convective area before the monsoon onset is over northeast Indian Ocean. A convective area develops close to the equator near 70°E about 5 days before the onset over south Kerala. The intensification and northward movement of this convective zone brings the first monsoon rains over Kerala. After the onset over Kerala, deep convection again shifts to the north central and eastern Bay of Bengal.

8.3 The normalised daily rainfall distribution

(i) The daily rainfall at stations from which monthly/seasonal/annual rainfall data are derived has a highly skewed distribution. When the daily rainfall data are arranged in the ascending order of rain amount, a small number of days with large rain
amount account for half the total rain from the upper end of the rainfall series.

(ii) The association between the cumulated percentage rain amount \((x)\) and cumulated percentage number of rain days \((y)\) in the ordered daily rainfall series is referred to here as the normalised rainfall curve (NRC). Both \(x\) and \(y\) are non-dimensional parameters varying from 0 to 100%.

(iii) There are earlier studies relating to the nature of the NRC utilising daily rainfall data of certain countries. The results of these studies are conflicting. A brief review is presented.

(iv) A fresh study of the problem has been made making use of the daily rainfall data of 15 Indian stations with widely different rainfall regimes. This study has brought out that the NRC is uniquely related to the coefficient of variation (CV) of the rainfall series. This had not been realised by the earlier workers. It is shown that there is no universal NRC (as had been claimed by some authors) that can represent all rainfall regimes.

(v) It is found that the equation \(x = y \exp \left[ -b(100-y)^c \right]\) where \(b\) and \(c\) are empirical constants, gives a good analytical representation of the NRCs over a wide range of CV values of the rainfall series.

(vi) This analytical equation is able to account for the occurrence of high daily rainfall amounts for rainfall series with large values of CV. Various properties of the equation are discussed.

(vii) The rain intensity (daily rain amount) corresponding to any point on the NRC is inversely proportional to the slope of the tangent at that point. The point
where the slope is 45° corresponds to the mean rain amount per rain day (r) of the rainfall series.

(viii) Days with rain amount greater than r (designated as days of significant rainfall) constitute about 30% of the rain days and contribute about 75% of the total rain amount at almost all stations.

(ix) The unique association between the NRC and the CV of the rainfall series is a significant new finding of the present study which explains the conflicting earlier results. The analytical equation with two empirical constants for the NRC is also a new contribution.

8.4 Statistical aspects of daily rainfall during the summer monsoon

(i) A detailed analysis of several features of the daily rainfall at 365 stations distributed over India for the period 1901-1980 is carried out to understand the climatology of daily rainfall during the southwest monsoon season.

(ii) The mean daily rainfall (r) per rain day at Indian stations varies from 10 mm/day to more than 30 mm/day during the summer monsoon. The lowest values occur over the rain-shadow regions east of the Western Ghats and the highest value along the west coast and some parts of northeast India.

(iii) The CV of the daily rainfall amounts varies from 100 to 230 percent over different parts of the country, with many stations in the interval 120-160 percent. The maximum values of CV of the daily rainfall series are found over Gujarat state and northern parts of west coast, where very heavy rainfall of more than 500 mm/day have been recorded.
(iv) The average number of rain days (n) over the stations range from less than 10 to more than 100 (out of a seasonal total of 122 days). The coefficient of variation of n ranges from 10 percent to 60 percent, the larger values being associated with stations with smaller values of n.

(v) Heavy rainfall in 10 to 20% of the total number of rain days accounts for 50% percent of the seasonal rainfall at the individual stations.

(vi) The computed rain intensities below/above which 50% of the seasonal rainfall is received at different stations vary from about 20 mm day$^{-1}$ to more than 60 mm day$^{-1}$.

(vii) Based on the equation for the NRC, the rain intensities likely to be exceeded once in 100 rain days and once in 1000 rain days have largest values over the Gujarat region and adjacent parts of West Coast.

(viii) The average contribution by the last 1 per cent of the cumulated rain days to the total seasonal rainfall varies from 6 to 16%, the larger amounts being associated with stations with large CV values for the rainfall series.

(ix) Days of significant rainfall defined as rain days with amounts not less than the mean daily rainfall (r) constitute about 30% of the total number of the rain days and contribute nearly 75% of the total seasonal rainfall at most of the stations. This appears to be a general feature of tropical rainfall.

(x) A rain day is defined as a day with any measurable amount of rainfall (0.1 mm or more) while a rainy
A day is defined according to IMD criterion as a day on which 2.5 mm or more of rain is recorded. Over the central parts of the peninsula and the coastal regions of Tamil Nadu and Gujarat states, the number of rain days exceeds the number of rainy days by 30-50 percent; along the west coast and western parts of Rajasthan this difference is about 10 to 20 percent while over the rest of the country the values range 20 to 40%.

8.5 Intra-seasonal oscillations in the daily rainfall series

(i) A brief review is given of the observational studies relating to the 30-60 day period oscillation over the tropics and the meteorological features associated with it over the Indian summer monsoon region. Formation of convective cloud bands over the equatorial Indian Ocean and their northward progression across India towards the Himalayas in about 40 days have been found from the analysis of satellite cloud data. Similar progression of trough/ridge systems in the zonal winds has also been noticed. These features have been associated with the active/break phases of the summer monsoon. It is known that there are inter-annual variations in these features. These also need detailed examination.

(ii) The progression of convective cloud systems as stated above should be reflected in the analysis of the daily rainfall series over selected areas of the country which should show similar quasi-periodicity.

(iii) A limited study has been made in this Chapter utilising the daily area-averaged rainfall data for a period of 80 years (1901-1980) over three areas, two in the extreme south and the third over the central part of India. The three areas are south Kerala
(SK), north Kerala (NK) and the Upper Narmada catchment area (NC). The method of harmonic analysis has been utilised for the analysis of the data series.

(vi) The rainfall series were analysed for three periods: (a) for 360 days from 1 January to 26 December; (b) for 200 days from 10 April to 26 October; (c) for 120 days from 1 June to 28 September.

(v) As a first step, the 80-year normal rainfall data series were constructed for each of the three regions. Harmonic analysis of the normal rainfall data series for 360 and 200 day shows that less than 1% of the variance of the series is contained in the harmonics of the 30-60 day period range for all the three regions. For the series of 120 days covering the summer monsoon season, the variances in the 30-60 day period range are about 9% for SK, 3% for NK and 13% for NC.

(vi) Similar analysis of the rainfall series for the individual years 1901-1980 was carried out. This analysis was done for the original data series containing the annual rainfall variation as well as on the series resulting after removal of the annual variation, making use of the 80-year daily normals for this purpose, following the standard procedures. One such method is to utilise the departure of the actual from the normal daily rainfall. The other method is to take the ratios of the actual to the normal for the day. Both methods have been employed. The results of the analysis for 360 days are presented in detail. Large inter-annual variations have been found in the amplitude of the 30-60 day oscillation over all the areas.

(vii) Analysis of the departure series for the individual years has been made to estimate the percentage
variance associated with the individual harmonics of period exceeding 10 days. The 80-year mean values, the standard deviations and extreme values of the variance were evaluated for all such harmonics.

(viii) In all cases the mean values and standard deviations are of the same order. The highest values are about 4 to 6 times the mean and the lowest values close to zero. This illustrates the large inter-annual variation in the contribution of variance by these harmonics.

(ix) In the mean values for the 80-year period, there is a maximum in the 30-60 day range which is more pronounced in the 120 day series covering the southwest monsoon season. But the large inter-annual variability persists in the amplitude of the oscillation.

(x) Auto-correlation studies of the rainfall series for the monsoon season were made with lags up to 60 days for all the three areas. Significant correlations in the range of 30-60 days were found for about half the number of years with large inter-annual variations in the periodicity of the oscillations.

(xi) Cross correlation studies were made between the rainfall series of SK and of NC which is about 12 degrees to the north of SK, to examine the northward progression. With a northward progression speed of about a degree per day, significant correlation should be expected with lags around a fortnight. This was found in less than half the number of years.

(xii) Results of the detailed analysis of the daily rainfall series presented in this Chapter show that while there is a maximum in the variance explained in the 30-60 day mode on the average in a large data set,
there is large inter-annual variability in the amplitude, periodicity, and the northward propagation speed of this oscillation. This variability limits the utility of this long period oscillation as an aid for rainfall prediction over the Indian region.

8.6 Thermodynamic structure of the atmosphere in relation to rainfall activity

(i) Monsoon rainfall is of a pulsating nature; over any given area there are periods of good rainfall alternating with periods of little rain.

(ii) Daily 00 UTC aerological data of 23 stations for three years for peak monsoon months of July and August have been examined in relation to the rainfall activity after classification of data in two complementary ways.

(iii) In the first method the days were sorted out into three types (A, B, C) on the basis of criteria fixed for the preceding 24-hourly rainfall corresponding approximately to active, normal and weak monsoon conditions. The mean vertical profiles of dry bulb temperature (T), relative humidity (RH), and mean daily rainfall (r) were evaluated for each of the three types for the individual stations.

(iv) In the second method the daily soundings were classified into three types (X, Y, Z) on the basis of criteria fixed for dew point depression at 700 and 500 hPa levels without prior consideration of rainfall. In X-category the RH is ~90% up to midtropospheric levels while in the Z-category there is rapid decrease of RH above 700 hPa; the remaining days belong to the Y-category. As in the previous case, the vertical profiles of T and RH and the mean
daily rainfall (r) were evaluated for the three types of days.

(v) Comparison of the results of the two types of classification of the same data shows some unexpected results. The mean RH profiles of the X, Y, Z types have larger variations in the vertical than those for A, B, C types. Despite this, the mean daily rainfall of the latter type differ much more than those of the former type. Thus the X-category with RH -90% up to mid-tropospheric levels shows smaller values of r than the A-category in which RH decreases more rapidly in the vertical; also the Z-category in which RH decreases very rapidly above 700 hPa shows higher values of r than the C-category in which the RH decreases less rapidly in the vertical.

(vi) Both types of classification are attempts to associate the preceding 24-hourly rainfall and the vertical variation of RH at 00 UTC, in two complementary ways. The study shows that while there is qualitative agreement there are substantial differences in the results. This arises from the fact that the RH profile from a single sounding at 00 UTC has no unique association with the preceding 24-hourly rainfall at the station and its surroundings although a broad association exists in a large data sample.

(vii) The mean vertical profiles of dry bulb temperature show only small variations even for large variations of rainfall and RH profile at the stations. On the average the temperatures are lower by less than 1°C below 600 hPa and warmer by about the same order in the upper troposphere for soundings associated with larger rainfall and higher RH.
(viii) The RH variations in the vertical are reflected in the profiles of the pseudo-equivalent potential temperatures ($\theta_e$) which have a minimum between 700 and 500 hPa levels for all categories of soundings.

(ix) The analysis shows that more extreme variations of RH occur in the monsoon field than what is brought out by the mean data of soundings associated with active, normal and weak monsoon conditions on the basis of preceding 24-hourly rainfall.

(x) Data relating to the vertical variations of the specific humidity and precipitable water vapour and variation of total static energy have also been presented and discussed.

(xi) The two complementary methods of analysing the same data sample to find out the association between the thermodynamical structure of the atmosphere based on the routine aerological soundings and the preceding 24-hourly rainfall have been done here for the first time. Earlier studies and conclusions are based on classification utilising preceding 24-hourly rainfall as active/ normal/ weak. The results of the complementary study show more extreme variations in the profiles of RH and less variations in the associated rainfall as compared with the earlier method. This was an unexpected result. It shows the limitations of associating the thermodynamical structure of the atmosphere based on the routine aerological soundings with the preceding 24-hourly rainfall which is an integrated effect of atmospheric process over the total interval.