STUDIES ON SOME ASPECTS OF THE RAINFALL AND UPPER AIR
FEATURES ASSOCIATED WITH THE INDIAN SUMMER MONSOON

ABSTRACT

Most parts of India receive the bulk of annual rainfall during the four months (June - September) of the summer monsoon season. The space-time distribution of this rainfall is intimately linked to the national economy and social welfare of the country. From the early days of Indian meteorology a large number of studies have been addressed towards elucidation of various facets of the summer monsoon and the rainfall associated with it. The tropics constitute the heat source for driving the general circulation of the atmosphere and there are close links and tele-connections between the meteorology of the tropics and the extra-tropics. In recent years there has been much interest in problems connected with tropical meteorology including the monsoons among scientists of the extra-tropics. A general over-view of the salient aspects of the Indian summer monsoon and some of the recent studies in this area is presented in Chapter I of the Thesis. The rest of the Thesis deals with the author's original studies and contributions.

Chapter II deals with the dates of monsoon onset over Kerala for the period 1870-1990. This date marks the beginning of the principal rainy season for the country. Its long term mean is 1 June, but there are variations from year to year. No objective criteria are available for fixing the date of monsoon onset announced by the India Meteorological Department (IMD) year after year. Although there are broad guidelines, some degree of subjectivity is inevitable under operational conditions.

Kerala has had a dense network of raingauge stations over a long period. In the present study, area-averaged daily rainfall series for south and north Kerala have
been constructed and utilised to derive semi-objective criteria for fixing the dates of monsoon onset, characterised by sharp and sustained increase in rainfall. The dates of onset determined from the rainfall time series are compared with the corresponding dates as per the IMD records for the period 1901-1990 and comments are offered where large discrepancies are noticed. From the present study the mean onset dates for south and north Kerala are found to be 30 May and 1 June respectively with standard deviation of 8.5 days. The earliest onset date was 7 May in 1918 and the latest 22 June in 1972.

The time series of the onset dates do not show any long-term trend, but there are epochs when the onset dates were significantly different from the long-term mean dates. The duration and the mean daily rainfall associated with the rain spell that heralds the onset of the monsoon have large interannual variations with statistically significant decreasing trend in recent decades. The sharp and sudden increase of rainfall during the monsoon onset which distinguishes it from the pre-monsoon thunderstorm rain is strikingly brought out by the superposed epoch analysis of the daily area-averaged rainfall of south and north Kerala.

The synoptic features during the monsoon onset over Kerala in individual years have broad similarities as well as interannual variations. In Chapter III an attempt has been made to highlight the similarities by making a composite study of the rainfall, wind, relative humidity, vertically integrated moisture transport and outgoing long wave radiation (OLR) utilising relevant data for a period of 15 years. The study covers a period of 20 days before and 20 days after, centered on the onset date over Kerala for the individual years.

The rainfall composites show sharp increase at stations along the west coast progressing from south to north. The composite wind analysis brings out the manner in
which the upper tropospheric sub-tropical westerlies over north India weaken and shift northward while the tropical upper tropospheric easterlies strengthen and spread towards north with the onset of the monsoon. The low level westerlies over the peninsula strengthen and deepen to about 400 hPa rapidly with the onset. The onset vortex which takes the monsoon northward along the west coast in many years is noticed as a trough between 600 and 400 hPa levels in the composite streamline charts.

The vertical distribution of relative humidity at individual stations shows deepening of the moist layer a few days before the monsoon onset at the respective stations which indicates large scale increase in the moisture content of the atmosphere over the country prior to the strengthening of the monsoon flow. Over peninsular India, the composite vertically integrated transport of moisture shows rapid increase with the onset. The OLR data composites show that the main convective area before the onset of monsoon over Kerala is over northeast Indian Ocean. About 5 days before the onset, a deep convective zone develops close to the equator near 70° E. The onset of monsoon over Kerala occurs with the intensification and northward movement of this convective zone.

The daily rainfall data of individual stations are utilised for deriving monthly, seasonal and annual rainfall and various studies based on them. It is well known that a small number of days with heavy rain contribute the bulk of the total rainfall, particularly at tropical stations. The association between cumulated percentage rain amount (x) and the cumulated percentage number of rain days (y) when the daily rainfall time series are arranged in increasing order of rain amount has been examined for 15 Indian stations with widely different rainfall regimes. The results of the study are presented in Chapter IV. This investigation was prompted by the conflicting results of earlier studies in the literature.
Both $x$ and $y$ are normalised non-dimensional parameters which vary from 0 to 100; the graphical association between $x$ and $y$ is designated here as the normalised rainfall curve (NRC). Some of the earlier workers had claimed that the NRC is a universal curve for all rainfall regimes; subsequent studies have disputed this claim. The present study has been able to explain this contradiction by showing that the NRC is uniquely determined by the coefficient of variation (CV) of the rainfall series. As such, there is no universal NRC, but widely different rainfall regimes with the same value of CV can be represented by the same NRC. Illustrative examples are presented. It is shown that the NRC can be represented by the analytical equation $x = y \exp\left[-b(100-y)^c\right]$ where $b$ and $c$ are empirical constants that depend on the CV of the rainfall series.

Various aspects of the NRC as represented by the analytical equation are discussed. In particular, the equation is able to account for the occurrence of high values of daily rainfall at stations with large values of CV. It is also shown that days of significant rainfall defined as days with rain amounts not less than the mean daily rainfall, account for about 75% of the total rainfall in about 30% of the rain days.

Much of the information about the rainfall climatology of India is based on monthly, seasonal and annual rainfall. Chapter V presents different aspects of the rainfall climatology of India based on the daily summer monsoon rainfall of 365 stations for a period of 80 years.

Spatially, the mean daily rainfall per rain day varies from about 10 mm/day to a little over 30 mm/day. The lowest values occur over the rain shadow regions of the peninsula and the highest values along the west coast and over some parts of northeast India. The CV of the daily rain amounts, which is an important parameter of the daily
rainfall distribution, varies from 100% to 230% at individual stations with nearly half the number of stations being in the interval 130-150 per cent. The maximum values of the CV are found over Gujarat and northern parts of the west coast, where very heavy rainfall of more than 500 mm/day have been recorded. The average number of rain days over different parts of the country varies from about 10 days to more than 100 days out of the 122 days of southwest monsoon season. The coefficient of variation of the number rain days varies from 10 to 60%, the higher values being associated with smaller mean number of rain days.

Heavy rainfall in 10 to 20% of the rain days contributes 50% of the seasonal rainfall at different stations. The threshold intensity in ordered rainfall series which contributes 50% to the seasonal total, varies from about 20 mm/day to 60 mm/day. The rain intensities which are likely to be exceeded once in 100 rain days and once in 1000 rain days are largest over Gujarat region and adjoining parts of west coast.

A day with rainfall $\geq$2.5 mm is considered as a rainy day in statistical records of the IMD. In the present study a day with any measurable amount of rainfall (0.1 mm or more) is defined as a rain day. The differences in rainfall statistics using these two definitions are examined and it is found that in some parts of the country, the difference between the number of rain days and rainy days is as high as 30 to 50%.

Since its discovery around the 1970's, the 30-60 day quasi-periodic oscillation in meteorological parameters over the global tropics has been extensively investigated. These oscillations are most pronounced over the Indo-Pacific region during the summer monsoon season. Over the Indian area, one of the reported features is the formation of zonally oriented convective cloud bands near the equator and their northward propagation towards the foot of the Hima-
layas in about 40 days. Trough/ridge systems in the zonal wind field also show similar behaviour. Chapter VI presents the results of the harmonic analysis of the daily area averaged rainfall series for a period of 80 years over three selected regions, two over the south of the peninsula and the third over the central parts of the country, to understand interannual behaviour of the 30-60 day mode and its northward propagation.

The normal daily rainfall data series for the 80 year period for all the three regions show little variance in the 30-60 day period range. Analysis of the actual data for the individual years shows that the percentage variance comprised in the 30-60 day mode varies from about 4 to 35% with a mean value around 15%. All the rainfall series were also analysed after removing the annual cycle in the usual way. The year to year values of the variance in the 30-60 day mode are now found to range from 5 to 50% with a mean value around 25%. Appreciable part of the variance is also contained in the oscillations with periods less than 30 days. Large interannual variations of the 30-60 day mode as well as its intra-seasonal variability has been brought out in the present study. It is also found that there are substantial year to year variations in the northward propagation features. This is brought out by examination of lag correlations between the data series for southern and central regions.

The interannual and intra-seasonal variations of 30-60 day oscillation have not been sufficiently emphasised in the literature although it is known that such variations exist. The results of the present study utilising rainfall series for a long period show that these variations can be substantial. As such, one has to exercise caution for rainfall prediction over the Indian area on the basis of this tropical oscillation mode.
The summer monsoon rainfall has large spatial and temporal variations. Over a given region, spells of good rainfall alternate with periods of little rain. Chapter VII presents results of a study of the association between contrasting rainfall situations and vertical distribution of thermodynamic parameters, utilising upper air and rainfall data at 23 aerological stations for the months of July and August for three years. The daily 00 UTC upper air data and the 24 hourly rainfall recorded at 03 UTC of the day have been utilised in the study.

The association between rainfall and the thermodynamic parameters has been examined in two complementary ways. In the first method the days were classified into three types (A,B,C) on the basis of 24 hourly rainfall, corresponding qualitatively to active, normal and weak monsoon conditions. The aerological data for the three categories were averaged to obtain mean profiles of observed and derived parameters along with the mean daily rain for each category. In the second method, the aerological data were sorted out into three categories (X,Y,Z) on the basis of vertical variation of dew point depression without prior reference to rainfall. The X category comprises of days with relative humidity (RH) of about 90% up to 500 hPa level while the Z category comprises of days with rapid decrease of RH above 700 hPa; Y category represents the remaining days. Mean daily rainfall and mean profiles of upper air parameters were evaluated for the three categories.

The results of the two methods of analysis are presented in the form of tables and diagrams and the similarities and differences discussed. One of the unexpected findings is that the mean daily rainfall associated with the X category of soundings with nearly 90% RH up to mid-tropospheric levels is appreciably less than for A-category for which the RH decreases more rapidly in the vertical. This shows the limitations of drawing conclusions about the preceding 24-hourly rainfall on the basis of the data of
routine aerological soundings. Much larger variations in the vertical distribution of moisture occur in the monsoon field than what is brought out by mean data of soundings associated with active, normal and weak monsoon conditions on the basis of 24-hourly rainfall.

Despite substantial variations in the vertical distribution of moisture, there are only marginal differences in the mean dry bulb temperature at isobaric levels for different categories of soundings. On the average the dry bulb temperature is lower by 1°C or less below 600 hPa level and warmer by about the same order in the upper troposphere for the more humid categories associated with larger preceding 24-hour rainfall.

The vertical distribution of pseudo-equivalent potential temperature ($\Theta_e$) shows a minimum between 500 and 700 hPa levels for all stations for all categories of soundings. Profiles of $\Theta_e$ are presented for some selected stations. The variations of static energy ($C_p T + gz + Lq$) for unit vertical column from 1000 to 100 hPa are presented as isopleth diagrams.

Chapter VIII presents a summary of the main results and conclusions. This is followed by References and a list of author's publications.