Chapter-1

Introduction
1.1 General

Nature has bestowed Kerala with abundant rainfall. The average annual rainfall of the State, situated in the southwestern corner of the Indian peninsula is about 300 cm, which is about three times the average for the whole of India. Kerala is one of the smallest states of India and has an area only a little more than 1% of the country as a whole. The adjoining state of Tamil Nadu to the east is three times the size of Kerala, while Karnataka to the north is nearly 5 times bigger. However, Kerala receives annual rainfall, which is three times greater than that of Tamil Nadu and twice greater than that of Karnataka. Despite its small size, Kerala supports about 4% of the population of India (31.82 million as per 2001 census) and has the highest population density among the Indian states.

The annual rainfall pattern of the state displays large north-south and east-west gradients. There are two pockets of large rainfall exceeding 400cm in the high lands. The Western Ghats act like a long wall up to a height of 1-2 km obstructing the low-level monsoon current. The southwest monsoon current, which brings in moisture for rainfall, gets a forced ascent at the Ghats and the windward slopes experiences heavy rainfall. The northern pocket of large rainfall is to the north-east of Kozhikode where the hill station Vaithiri gets annual rainfall of over 450cm and the southern pocket is to the east of Kottayam with Peermade getting more than 400cm of annual rainfall. However, rainfall is not uniformly distributed on the windward slopes and there are regions of very large rainfall and relatively less rainfall.

The peculiar geographic orientation of Kerala with Arabian Sea as the western boundary makes the weather pattern very unique in this part of the Indian subcontinent. Along the coast of Kerala, rainfall increases from about 150cm in the extreme south to more than 350cm in the extreme north. Rainfall decreases to the west with the Lakshadweep islands receiving only 150cm of annual rainfall. The Arabian Sea becomes the center of the oceanic warm pool in May with Sea Surface temperature (SST) reaching 30 to 31 degrees Celsius.
Soon after the monsoon onset over Kerala, the SST of the Arabian Sea cools rapidly. The southwest monsoon current as it approaches west coast of India, turns clockwise and becomes northwesterly. The northerly alongshore component of the surface wind produces upwelling in the coastal waters of Kerala and it has important consequences in relation to the meteorology of the region.

Even though the state does not suffer large interannual variations in annual or seasonal rainfall, there is large spatial variation in the rainfall distribution. It will be of great socio-economic importance if we learn to use our rainfall bounty to our greatest advantage and learn to cope with the year-to-year and decade-to-decade rainfall fluctuations, which are not large percentages of the mean annual rainfall. A thorough investigation on the rainfall characteristics both on the spatial and temporal scales with emphasis on the influence of orography is needed. The results of such a study will help engineers and hydrologists to manage our rainfall resource in a proper manner.

1.2 Objectives of the study

This study focuses on the aspects of southwest monsoon rainfall over Kerala and its variability both on the spatial and temporal scales. The objectives of this work are to study: (i) the Intra Seasonal Variability during south-west monsoon season (ii) the interannual, long-term and decadal variabilities in monsoon rainfall (iii) the relationship between antecedent global circulation parameters with Kerala rainfall. An attempt has been made to develop a statistical model for long-range forecast for south-west monsoon rainfall (iv) the diurnal variability using data of a large number of stations in Kerala and (v) the spatial distribution of rainfall under two large scale synoptic settings and the strong influence of the orography of Western Ghats.

1.3 Physiographic Features of Kerala

Kerala is a small-elongated coastal state in the south-west tip of peninsular India with Western Ghats to the east and Arabian Sea to the west.
Located within latitudes 8° 15’ N and 12° 50’ N and longitudes 74° 50’E and 77° 30’ E, it has an area of 38863 sq. m (1.18 % of the area of India) with length (north-south) 590 km, a coast line of nearly 500km and an average width (east-west) of 66 km (varies from 35 to 120 km).

Fig. 1.1: Political map of Kerala

Kerala is surrounded by Dakshin Kanad (South Kanara), Mercara and Mysore districts of Karnataka state in the north. Nilgiri, Coimbatore, Madurai, Ramanadhapuram, Thirunveli and Kanyakumari districts of Tamilnadu in the east, Arabian Sea to the west and North Indian Ocean to the south.
For administrative purposes the State is divided into fourteen districts (fig.1.1). The State capital is Thiruvanthapuram. These districts and their respective areas are given in Table 1.1.

Table 1.1: Districts of Kerala and their respective area in sq. km

<table>
<thead>
<tr>
<th>District</th>
<th>Area km²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thiruvananthapuram</td>
<td>2,197</td>
</tr>
<tr>
<td>Kollam</td>
<td>2,579</td>
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<tr>
<td>Alappuzha</td>
<td>1,414</td>
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<tr>
<td>Idukki</td>
<td>5,019</td>
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<td>Pathanamthitta</td>
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<td>Kottayam</td>
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<td>Thrissur</td>
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<tr>
<td>Palakkad</td>
<td>4,480</td>
</tr>
<tr>
<td>Malappuram</td>
<td>3,550</td>
</tr>
<tr>
<td>Kozhikode</td>
<td>2,206</td>
</tr>
<tr>
<td>Wayanad</td>
<td>2,132</td>
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<td>Kannur</td>
<td>2,997</td>
</tr>
<tr>
<td>Kasargod</td>
<td>1,961</td>
</tr>
</tbody>
</table>

The terrain of Kerala as derived by satellite data is given in fig.1.2. The land may be broadly divided into 3 natural divisions:

1. Lowlands
2. Midlands
3. Highlands.
Fig. 1.2: Terrain of Kerala as taken from satellite data
Orographic features profoundly influence the meteorology of Kerala. The Western Ghats comprise the mountain range that runs along the western coast of India, from Vindhya-Satpura ranges in north to the southern tip of India. This mountain range, which forms a natural wall separating Kerala from adjoining states has an average elevation of about 1 km with peaks rising over 2 km. The highest peak is Anamudi (2695km) at the crest of Anamalai (elephant hill) in Idukki district. A southern off shoot from Anamalai is the Cardamom Hills of south Kerala on which is located the hill station Peermade. Eastwards from Anamalai, run the Palani Hills (in Madurai district of Tamil Nadu) on which is located the famous hill station of Kodaikanal (2506m). To the north of Anamalai are the Nilgiris whose highest peak is Doda Betta (2640m) in the Ootacamund area. The Nilgiris merge with the Coorg Mountains, which divide the northern parts of Kerala from Karnataka. The Anamalai and the Nilgiris are the tallest mountains in the Western Ghats. A remarkable feature is the Palakkad Gap of about 25km width between Anamalai and the Nilgiris, which is the only marked break in the Ghat mountain wall. These descriptions are taken from Ananthakrishnan et al (1979b).

The western slopes of Western Ghats receive copious rainfall during the south-west monsoon months June to September and form the watershed for a number of rivers. There are 41 west-flowing rivers in the state in addition to three east flowing ones, which are the tributaries of the Kaveri. The 41 west flowing rivers along with their tributaries cut across the state to join the Arabian Sea or one of the numerous backwaters. The longest river in Kerala is the Periyar with a length of 229 Km. The rich traditions of the state are associated with these rivers. Kaladi on the banks of Periyar was the birthplace of the great philosopher Sri. Sankaracharaya. Mamamkam, a festival of great pomp and fervour used to be held once in 12 years at Tirunavai on the banks of Bharatapuzha under the patronage of the Zamorin of Calicut till the latter half of the 18th century. Today many rivers have been harnessed for irrigation and power and are making great contributions to the economic progress of the state.
In addition Kerala has a continuous chain of lagoons and backwaters. The backwaters, rivers and the canal system form a navigable inland waterway of about 1960 kms, which is more than one fifth of the total length of India’s inland waterways.

The midlands lying between the mountains and the lowlands are made up of undulating hills. This is an area of intensive cultivation where coconuts, arecanuts, tapioca, banana, rice, ginger, pepper, sugarcane and a large variety of vegetables are grown. The lowlands or the coastal area, which is made up of the river deltas, backwaters and the shore of the Arabian Sea, is essentially a land of dense coconut palms and verdant rice fields. Fisheries and coir making are major industries in this area. Backwaters form an especially attractive and economically valuable feature of Kerala. They include lakes and ocean inlets, which stretch irregularly along the coast. The biggest backwater is the Vembanad Lake, which is around 200 sq. km in area, and opens out into the Arabian Sea at the Cochin Port. Six Major rivers – the Periyar, Pamba, Manimala, Achenkovil, Meenachil and Muvattupuzha discharge into this lake.

The legend of the sea giving birth to the state - thanks to Parasurama - is widely accepted and the oceans have helped in moulding the history of Kerala. There was peaceful interaction with far-flung lands through trade and commerce for more than two millennia before the incursions from modern Europe with the landing of Vasco Da Gama at Calicut in 1498. It changed the temper of the contact., loaded it with conflicts and created a turbulent phase of history which ended only with India’s independence in 1947.

There is a great variety of vegetation all along the Ghats: scrub jungles, grassland along the lower altitudes, dry and moist deciduous forests, and semi-evergreen and evergreen forests. There are two main centres of bio-diversity, the Agasthyamalai and the Silent Valley. The complex topography and the heavy rainfall have made certain areas inaccessible and have helped the region retain its diversity. Richness of soil, heavy rainfall and damp climate has given rise to a
flora and fauna of great variety. A few of the indigenous and exotic tree and plant species in the Western Ghats are the teak, jamun, cashew, hog plum, coral tree, jasmine, and crossandra. There is an equal diversity of animal and bird life. Elephants, black leopards, tigers, sloth bears, giant squirrels, bison, a variety of deer, the charming little honey sucker, the golden beaked wood pecker and the Malabar whistling thrush are seen in the forests of Western Ghats. The famous Periyar national park in Kerala is home to a large number of elephants, gaur, sambhar, and lion-tailed macaque and a variety of birds.

The distinctive characteristic of the agricultural sector in Kerala deserves special emphasis. The high pressure of population on land has rendered a large part of the rural population traditionally dependent on agriculture. In Kerala only about 56% of the total area of the state is available for cultivation, the rest being forests and uncultivable lands. The cultivation of cash crops is better organized in Kerala than anywhere else in the country. In the country as a whole about 70% of the cropped area is under food grains, but in Kerala only about 30% is under food grains. On the other hand more than 50% of the cultivable area is under commercial crops like tea, rubber, coconut, cardamom etc. This cropping pattern has its own advantages and disadvantages. It earns valuable foreign exchange for the country by the export of commercial crops but at the same it also creates a huge deficit in food grains that sustains the population. Only about 55% of Kerala’s rice requirements are produced within the state. For the balance, the state has to depend on supplies from outside.

1.4 Climatology of Kerala

The climate of India and that of Kerala in particular is dominated by the monsoon circulation. During one half of the year the wind blows from the oceans to the south of the Asian land mass, while during the other half there is a seasonal wind blowing from the Asian landmass to the oceans to the south. There is a spectacular reversal of pressure and wind patterns between these two six-month periods. The gradual rise in temperature through spring to summer
does not happen, due to the onset of the south-west monsoon. Temperatures drop sharply in June. The usual classification into spring, summer, autumn and winter is therefore not adopted in the state. January and February is winter season, March to May is the pre-monsoon season, June to September is the south-west monsoon season and October to November is the post-monsoon season.

### 1.4.1 Seasonal Variation of Pressure

There is an annual variation of atmospheric pressure over the state with maximum pressure during January and minimum during May, with an annual range of only 3-3.5 hPa. The monthly variation of sea-level pressure for selected stations in Kerala is given in fig.1.3. The pressure gradient over the state generally remains weak except during late summer and in the monsoon season. The diurnal range of pressure increases from the coast to inland regions and this is also within about 5 hPa (Kumar, 1994). The maximum range in the diurnal cycle is observed during February when clouding is almost minimum. However, during June and July the range in the observed diurnal pressure variation is large in the state. This is also the period of maximum clouding and precipitation. In all seasons pressure gradient over the state is in the east-west direction. The pressure decreases from west to east except during the period from about middle of October to the beginning of March when the reverse gradient prevails.

![Fig.1.3: Monthly variation of mean sea level pressure in Kerala](image-url)
1.4.2 Seasonal Variation of Temperature

The main factors, which affect the mean surface temperature of the air at any place, are latitude, elevation, distance from the sea, type of prevailing air mass, which in turn determines the pattern of cloudiness and weather. The annual changes in the thermal pattern would naturally show the highest temperature in summer and the lowest in winter. However, due to the onset of summer monsoon which gives rise to extensive cloudiness and rainfall temperature pattern is modified. Because of its low-latitude location the annual range of temperature over Kerala is small compared to other parts in north and central India. At coastal stations in the state, the highest maximum temperature of about 33° C occurs in April and the lowest minimum temperature of about 22° C occurs in August. However, in coastal stations in other parts of the country the maximum temperature is attained in April/May but the lowest minimum is in December/January (Ananthakrishnan, 1979a). At Palakkad, an interior station the maximum temperature during the hot weather season reaches up to about 37° C while the minimum temperature is more or less the same as at the coastal stations. Fig. 1.4 shows the monthly variation of mean temperature ((maximum + minimum/2)) at few stations in Kerala. The temperature at various pressure levels (1000hPa to 10hPa) for 3 selected stations in Kerala: Thiruvananthapuram, Kozhikode and Mangalore (representative station for north Kerala) for the month of July is given in fig. 1.5. During July (south-west monsoon) the surface temperature is around 25°c for all the stations and the tropopause is at around 100hPa with a temperature of around –77°c. The details are given in Table 1.2.
Fig. 1.4: Monthly variation of mean temperature in Kerala

Fig. 1.5: Temperature at various pressure levels in mb (marked on y-axis) for July for
(a) Thiruvananthapuram, (b) Kozhikode and (c) Mangalore
1.4.3 Seasonal Variation of Wind

The winds are predominantly from east during October to May in the state and become westerly during the southwest monsoon season of June to September. Fig. 1.6 gives the u-component of wind for the month of July for the three selected stations. As seen from the figure, the westerlies prevail from 1000hPa to 400hPa during the southwest monsoon season, with strength of the order of 25 knots at 850hPa. In the upper troposphere during July the easterlies are well established and the strengths are highest of the order of 68 knots at Thiruvananthapuram. The details are given in Table 1.2. The diurnal variation in winds show that in general surface winds are strong during afternoon when the thermal circulation is well-developed and weak during night (Kumar, 1994).

![Fig. 1.6: U-wind at various pressure levels for July for (a) Thiruvananthapuram, (b) Kozhikode and (c) Mangalore](image)

1.4.4 Humidity

Over the entire subcontinent the moisture content of the atmosphere is minimum during December to February and maximum during monsoon months.
Annual variations over Kerala are less than over north India. At the coastal stations of Kerala monthly mean relative humidity at the surface is of the order of 75% in the morning during winter months and increases to about 90% in the monsoon months. The relative humidity and hence the moisture content, decreases rapidly from coastal to highlands during December to February. During monsoon periods, spatial variation in the moisture content is less. During the period from January to March, afternoon humidities reduce varying from 35% in the interior to 71% in the coastal area. Diurnal variation in relative humidity during the period is maximum and ranges from 4 to 16% depending upon the proximity of the sea. Humidity in the monsoon period rises to about 90% for the state as a whole and diurnal variation in this period is minimum and ranges from 2 to 12%.

Table 1.2 Temperature, Dew point temperature, wind speed and direction for July for three selected stations.

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<th>975</th>
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<th>400</th>
<th>300</th>
<th>200</th>
<th>150</th>
<th>100</th>
<th>50</th>
<th>10</th>
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</tr>
<tr>
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<td>-15.3</td>
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<td>-13.3</td>
<td>-24.2</td>
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<td>224.0</td>
<td>153.7</td>
<td>99.4</td>
<td>85.2</td>
<td>85.7</td>
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<tr>
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<td>-61.3</td>
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<td>16.3</td>
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<td>18.0</td>
<td>41.7</td>
<td>63.8</td>
<td>64.2</td>
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</table>
1.5 Rainfall Climatology of Kerala – Temporal and spatial

The principal rain-giving seasons in Kerala are south-west monsoon (June-September) and post monsoon (October-November). The pre-monsoon months (March-May) account for the major thunderstorm activity in the state and the winter months (December-February) are characterized by minimum clouding and rainfall.

Kerala’s annual average rainfall (for the period 1901-2003) of 286 cm is received primarily during the southwest monsoon season of June to September (Table 1.3). Pattern of the spatial distribution of annual rainfall amount brings out the effect of orography on rainfall. Isohyets run more or less parallel to Western Ghats. However, orography does not have a direct relationship with rainfall (Anu Simon and Mohankumar, 2004). Rainfall increases eastwards from Arabian Sea islands as the coastline is reached. Air stream undergoes ascent and uplift progressively as it reaches the coast and then blows nearly perpendicular to the mountains. This forced ascent results in intense clouding and precipitation. Moving east from Arabian Sea there is increased rainfall on the windward slopes of Ghats and there is sharp decrease further eastwards. Steepest gradients of rainfall are seen in Idukky and Kozhikode districts. Rainfall is comparatively less in Palghat district where the presence of the Palghat gap reduces uplift.

Table 1.3: Distribution of Rainfall over Kerala

<table>
<thead>
<tr>
<th>Season</th>
<th>Rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amount (cm)</td>
</tr>
<tr>
<td>June to Sep</td>
<td>193.3</td>
</tr>
<tr>
<td>Oct &amp; Nov</td>
<td>46.3</td>
</tr>
<tr>
<td>Mar to May</td>
<td>39.5</td>
</tr>
<tr>
<td>Dec to Feb</td>
<td>7.2</td>
</tr>
<tr>
<td>Annual</td>
<td>286.2</td>
</tr>
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</table>
The annual rainfall distribution for the 14 districts in Kerala is given in fig. 1.7. District wise, annual rainfall increases from the minimum value of 181cm for Thiruvanthapuram in the south to 329cm for Ernakulam in central Kerala. There is a slight drop for Thrissur district followed by a steep decrease for Palghat where the annual rainfall is only 236cm. The rainfall again increases to the north in Malappuram district followed by a maximum of 376 cm for Kozhikode and 343 cm over Kannur district. The districts on the high ranges also receive good rainfall.

![Graph showing district-wise annual rainfall distribution](image)

**Fig.1.7: District-wise distribution of Annual Rainfall**

The normal pentad rainfall reveals finer details of rainfall variations in space and time of individual stations, which may be regarded as spectra of rainfall under high dispersion compared to low dispersion spectra of monthly rainfall (Ananthakrishnan et al. 1971). Fig. 1.8(a-i) gives the pentad rainfall of some selected stations as given in Ananthakrishnan et al. (1971). It can be seen that for Trivandrum (Thiruvanthapuram)(fig. 1.8a), there is a rainfall maximum
around pentad 32 (in the month of June) and a secondary increase near pentad 58, in October. The annual rainfall for the station is 1812 mm. Similarly, Allepey (Alappuzha) (fig. 1.8b) has one maximum around pentad 32 and a small secondary maximum during pentads 54-55. The monthly rainfall distribution of this station shows that the station receives maximum rainfall in June during the south-west monsoon season (June to September) and there is an increase in rainfall during the month of October (north-east monsoon). The station also receives good rainfall during the pre-monsoon month of May. For Cochin (Kochi), shown in fig. 1.8c the pentad rainfall distribution shows a steady increase from pentad 24 (end of April), attaining a maximum at the 32nd pentad and then decreases steadily. There is a secondary maximum in pentad rainfall at pentad 58. The monthly distribution of rainfall for this station shows that the station receives maximum rainfall in June during the south-west monsoon season and in October during the north-east monsoon. Fig. 1.8d gives the pentad rainfall pattern of Palghat. It can be seen that there are two rainfall maxima (around pentad 37 and 58), although the second maximum is not very well pronounced. It should be noted that this station, which lies in the gap of the Western Ghats, receives 2040mm of annual rainfall. The pentad rainfall analysis for Kozhikode (fig.1.8e), a station in north Kerala shows that the pentad rainfall is maximum around pentad 38 (2nd week of July). The secondary maximum seen in Trivandrum, Alleppey and Cochin is not very pronounced in Kozhikode. In Manglore (fig.1.8f) a representative station just north Kerala there is one broad maximum near 34-40th pentad and then rainfall decreases gradually having no peak in October. The pentad rainfall analysis for Mercara a high altitude station east of Kozhikode is given in fig.1.8g. The station receives maximum rainfall in the month of July, as evident in the pentad and monthly rainfall pattern. For both the island stations Amini and Minicoy, (fig. 1.8h&i) the rainfall increases in the pentad near 32 and then falls steadily.
TRIVANDRUM
08° 29'N, 76° 57'E
Altitude: 64m
Annual Rainfall: 1812 mm

Fig. 1.8a: Pentad Rainfall for Trivandrum as given in Ananthakrishnan et al. (1971)

ALLEPPEY
09° 33'N, 76° 20'E
Altitude: 2m
Annual Rainfall: 3252 mm

Fig. 1.8b: Pentad Rainfall for Allepey as given in Ananthakrishnan et al. (1971)

COCHIN
09° 56'N, 76° 14'E
Altitude: 3m
Annual Rainfall: 3407 mm

Fig. 1.8c: Pentad Rainfall for Cochin as given in Ananthakrishnan et al. (1971)
Fig. 1.8d: Pentad Rainfall for Palghat as given in Ananthakrishnan et al. (1971)

Fig. 1.8e: Pentad Rainfall for Kozhikode as given in Ananthakrishnan et al. (1971)

Fig. 1.8f: Pentad Rainfall for Mangalore as given in Ananthakrishnan et al. (1971)
MERCARA
120 25'N, 75 44'E
Altitude : 1152m
Annual Rainfall : 3265 mm

Fig. 1.8g: Pentad Rainfall for Mercara as given in Ananthakrishnan et al. (1971)

AMINIDIVI
11 07'N, 72 44'0E
Altitude : 4m
Annual Rainfall : 1504 mm

Fig. 1.8h: Pentad Rainfall for Aminidivi as given in Ananthakrishnan et al. (1971)

MINICOY
08° 18'N, 73°00'E
Altitude : 2m
Annual Rainfall : 1640 mm

Fig. 1.8i: Pentad Rainfall for Minicoy as given in Ananthakrishnan et al. (1971)
1.5.1 South-west Monsoon (June-September)

The climate of India and that of Kerala in particular is dominated by the south-west (SW) monsoon known as Kalavarsham. The winds are south-westerly (meaning from the south-west) to westerly during six months (mid-April to mid-October) of the year and north-easterly to easterly during the remaining six months. An east-west band of tall rain-bearing cumulo-nimbus clouds form over the north Indian ocean (Arabian sea and Bay of Bengal) and further east, towards the end of May or early June. The latent heat released by the conversion of water vapour into water in these raining clouds heats the atmosphere and lowers the atmospheric pressure below the cloud band and pulls across the equator a deep current of air which accompanies the onset of monsoon. Kerala is the gateway of SW monsoon to India. After SW monsoon sets in over Kerala, the monsoon current and the monsoon rains move northwards to cover the whole of India. The four-month period 01 June to 30 September is designated as the SW monsoon season. In Kerala it is also called Edavapathy (since it commences in the middle of the Malayalam month Edavam).

The spatial distribution pattern of rainfall during this season is similar to annual pattern. Coastal rainfall of Kerala increases northwards from 70 cm in the extreme south to 290 cm in the extreme north. The increase, however, is not uniform. Rainfall increases from west to east to the ranges, the sharpest rise occurring over the high ranges, concentrated over certain areas. In the southern half of the state there are two high rain pockets. One is centered around Peermade (377 cm) in Idukki district and the other in Neriamangalam (383 cm) in the adjoining Ernakulam district. There is another high rain pocket in the north in Kozhikode district with peak rainfall at Vythiri (353 cm) and Kutttiyadi (336 cm). This pocket extends northwards into the adjoining Karnataka region with highest rainfall of 516 cm at Bhagamandla. Palghat gap area and portion of Malapuram district extending to the west from the gap between the two high rain areas of the south and north get comparatively less rainfall. The isohyets
generally run north-south. Concentration of the isolines near the heavy rain pockets may be seen from fig. 12(c) in Ananthakrishnan et al (1979). Isohyets to the east of the Western Ghats show a steep gradient indicating rapid and sharp decrease of rainfall towards the leeward side in Tamilnadu. Rainfall in this rainshadow region is less than 50 cm during this period. (Spatial distribution of rainfall during a typical monsoon month of July is given in figure 7.5a)

Kerala's average rainfall during this season is 192 cm. South Kerala (stations south of about 10N) receive around 176 cm and north Kerala (stations north of about 10N) receives 224 cm during this period. An examination of the monthly pattern shows that rainfall is highest in June in south Kerala while north Kerala experiences the highest rainfall in July (fig.1.9). With each surge in the monsoon current, amount of rainfall is more in north-Kerala than in south and the frequency of surges is higher in July than in June. Rainfall decreases in August and September in the state.

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The date of onset of south-west monsoon over Kerala has varied from as early as 11 May (in 1918) to as late as 18 June (in 1972). The long-term mean date of monsoon onset over Kerala is close to 01 June. Fig.1.10 gives the dates of monsoon onset over Kerala as declared by the India Meteorological Department over the last more than hundred years from 1901 to 2004. The date
of monsoon onset has large inter-annual variability and also prominent decadal scale variability. On the inter-annual scale, delays in monsoon onset over Kerala are associated with El Nino (Joseph et al, 1994). In the early decades of the twentieth century monsoon onset over Kerala was mostly in the first or second week of June. During the decades 1950s and 1960s monsoon onset occurred early, many times in the second and third week of May.

![Dates of Monsoon Onset over Kerala and the 7-year moving average](image)

**Fig.1.10 : Dates of Monsoon Onset over Kerala and the 7-year moving average**

**1.5.2 Retreating Monsoon (October-November)**

Rainfall abates considerably in September but spurts again in October and decreases further in November. This spurt takes place in association with the retreat of south-west monsoon from north India and the consequent southward movement of ITCZ across Kerala. This period comprising October and November is the phase constituting the withdrawal of the southwest monsoon. Kerala gets ~ 50 cm of rainfall during this season. During this period rainfall decreases from south to north. Eastern side of the Ghats receives its main rainfall during this period. During the earlier part of October rainfall is confined to the interior, mostly in the afternoon, evening or early night. As season advances, rainfall incidence shifts to south and the coastal region. Time
of occurrence also shifts in the later part of the season to the early morning hours. During this season heavy falls and long spells are experienced under the influence of cyclones and depressions. In such cases rain persists throughout the day and there is no preferred time of incidence. Mostly precipitation in this season is from convective clouds (thunder cloud). Thunderstorms of the season are violent, particularly over and near the hills.

1.5.3 Pre-Monsoon (March-May)

Precipitation during pre-monsoon is mainly from thundershowers and there is an increased thunderstorm activity in the southern tip of Kerala state from March onwards increasing progressively with the advance of the season. During pre-monsoon the thunderstorm activity progresses from March to May but in the post-monsoon season thunderstorm activity decreases from October to December. South Kerala experiences more number of thunderstorms during both pre and post-monsoon seasons than north Kerala.

![Fig.1.11a:- Monthly rainfall distribution for south Kerala](image)

The monthly distribution shows that the rainfall for the state is bimodal with two maxima corresponding to the advancing and retreat of the Inter
Tropical Convergence Zone (ITCZ). The highest rainfall peak for all the districts is associated with the northward advance of ITCZ accompanying the onset of the southwest monsoon. This occurs in the month of June for most of the stations south of $10^6$N (south Kerala) and in July for stations north of $10^6$N.

The second rainfall peak occurs during the receding phase of the ITCZ associated with the retreat of the south-west monsoon, which occurs in the month of October in almost all districts of Kerala. It is also interesting to note that the southern districts of the state receive 25-30% of the annual rainfall during the pre-monsoon and north-east monsoon season and only 50% during the southwest monsoon, whereas the northern districts receive almost 65-75% of the annual rainfall during the southwest monsoon season.

Fig.1.11b: Monthly rainfall distribution for north Kerala

(north Kerala) (fig.1.11a&b).
1.5.4 Interannual variability of monsoon rainfall over Kerala

Monsoon rainfall of India has strong interannual variability. This interannual variability affects not only local processes like agriculture but also influences the global climate. The monsoon rainfall is considered to be normal if it is within 1 standard deviation of the long-term mean and WET/DRY if it is above/below 1 standard deviation of the long-term mean.

An investigation of rainfall for 96 years (1901-1996) show that the mean monsoon rainfall for south Kerala is 176.2cm with a standard deviation of 36.1 cm and 223.6cm for north Kerala with a standard deviation of 44.8cm. The mean monsoon rainfall for the state as a whole is 192cm with a standard deviation of 40 cm. A comparative study of the monsoon rainfall over Kerala and the Indian summer monsoon rainfall (ISMR) show that while ISMR was normal in 69 years, Kerala experienced normal rainfall in 72 years. ISMR was above normal (WET) during 11 years and the subcontinent had 20 DRY years during the study period. However, Kerala experienced drought only during 17 years.

1.6 Rain Causing Mechanisms

1.6.1 Southwest monsoon

Seasonal variation of the atmospheric circulation and precipitation is the most distinguishing feature of the monsoonal regions of the world. Since Halley (1686), monsoon has been viewed as a gigantic land–sea breeze and the land-sea temperature contrast is considered to be one of the most important factors in generating monsoon circulation. The term ‘monsoon’ is traced to an Arabic word meaning ‘season’. Ramage (1971) formulated four criteria to delineate a monsoon area:

1. the prevailing wind direction shifts by at least 120° between January and July;
2. the average frequency of prevailing wind directions in January and July exceeds 40%.
3. The mean resultant winds in at least one of the months exceed 3 ms\(^{-1}\).

4. Fewer than one cyclone-anticyclone-alternation occurs every two years in either month in a 5\(^0\) latitude-longitude rectangle. This monsoon region which includes parts of the African continent, South Asia, and North Australia is shown in Fig. 1.12.

![Areas with monsoon circulation according to Ramage, 1971](image)

**Fig. 1.12: Areas with monsoon circulation according to Ramage, 1971**

The planetary scale monsoon can be viewed as a manifestation of the seasonal migration of the equatorial trough, the near equatorial trough or the Inter Tropical Convergence Zone (ITCZ) and the associated seasonal reversal of winds. In the transitional months between southern and northern hemisphere summers, Inter Tropical Convergence Zone (ITCZ) is located in the equatorial regions making it the maximum heat zone. As sun moves northward through March to June the land is heated more intensely producing stronger vertical motion. The moisture content of the troposphere over the land slowly increases, as the surface wind turns onshore. At this time, organised precipitation zones associated with the ITCZ have moved well north of the equator, signaling the onset of the summer monsoon. Seasonal contrasts in land surface temperature produces atmospheric pressure changes, which produce seasonal
reversal of pressure gradients. As a result there are major seasonal wind reversals (fig. 1.13a and fig. 1.13b).

Fig. 1.13a: Surface winds during northern hemispheric winter monsoon (Webster, 1987)

Fig. 1.13b: Surface winds during northern hemispheric summer monsoon (Webster, 1987)

The basic trigger for the Asian monsoon is the contrast between the temperature of the Asian continent and that of the surrounding ocean (Randall, 2004). This thermal anomaly in the middle troposphere is enhanced by the elevated topography of the Tibetan plateau, which extends upward to about 500hPa. The Tibetan plateau is at about 3000m above the surrounding area and hence much of the surface heating actually occurs in the middle troposphere. After the non-permanent snow on the plateau has melted in late spring and early summer, the surface and the air above it are heated to a temperature higher than that of the surrounding atmosphere. Rising motion balances this heating and this forces convergence in the lower and middle troposphere and corresponding
divergence aloft. As the seasonal heating builds, a trough forms over southern India in late May and subsequently moves north. Cloudiness and precipitation begin to increase at the southern tip of India and by end of June the entire country receives more precipitation.

Studies of daily satellite imagery have shown that the prominent cloud band (maximum cloudiness zone) over the Indian region on a typical monsoon day bears a striking resemblance to that associated with the ITCZ over the other regions of the tropics. Sikka and Gadgil (1980) showed that over the Indian longitudes during the summer monsoon, the maximum cloudiness zone coincides with the trough zone at 700 hPa and is associated with large cyclonic vorticity above the boundary layer, strong low-level convergence and intense moist convection. The associated trough is seen from 850 hPa to 500 hPa. The temperature and specific humidity profiles over the eastern part of the trough is similar to that for the ITCZ. Thus the trough has the dynamical and thermodynamical properties of the ITCZ. Over the Indian longitudes, during summer, the belt of the low OLR extends over about 30-40° latitude which is larger by a factor 3 to 4 than the latitudinal extent over the rest of the tropics in this season and in the northern hemispheric winter, suggesting that, the ITCZ over the Indian ocean changes its character drastically from winter to summer.

An intense continental ITCZ characterises active phase of monsoon. Large-scale monsoon rainfall over the Indian region during summer is associated with ITCZ over the heated Indian subcontinent. On the seasonal scale also, convergence zone is characterized by high transport of mass, moisture and energy. Thus the variations of monsoon rainfall are associated with intra-seasonal and inter-annual time scales and are related to space-time variations of the continental ITCZ.

In meridional plane, circulation comprises of the Hadley cell with continental ITCZ as its ascending limb. Planetary circulation, in the boreal summer, is dominated by wave number 1 and 2 with subtropical highs of upper
troposphere over Tibet and Mexico regions flanked by the mid-oceanic troughs over north Atlantic and Pacific. Air ascending over large-scale heat sources over the Asian and Central American longitudes flow in a zonal direction to the mid-oceanic troughs constituting the east-west walker circulation.

The parameters of broad scale monsoon (*Krishnamurti and Balme, 1976*) are schematically shown in fig. 1.14. The main components of the monsoon circulation are the following:

![Schematic diagram of the elements of the monsoon system](image)

Fig.1.14: Schematic diagram of the elements of the monsoon system (*Krishnamurti and Balme, 1976*)
Fig 1.15: Mean sea-level pressure for July (Krishnamurti and Bhalme, 1976)

1. *Heat Low*

The progressive development of a heat low over the sub-continent and its location over the central parts of Pakistan in July is the most important causative factor of the monsoon. This heat low is part of the low-pressure belt extending from Africa to central Asia through Arabia, Iran, Afghanistan, Pakistan and the northwest India with offshoots of troughs in various directions. The centres of low are at different locations over land at various months. In April it is over East Madhya Pradesh – May over Punjab and June-July over Pakistan. The centers of low are located at places near to areas of maximum heating away from maritime air. The tapering shape of the Peninsula, the Himalayan mountain ranges and the Assam Hills in the north-east which make the maritime air mass pervade over most of India displace the center of the heat low to the extreme north-west of the country. Blocking of cold air incursion from the north by the Himalayas in the lower-troposphere make the Heat low of sub-continent more intense. Lowest pressure belt for the whole belt from Africa to Asia is over
Pakistan and its neighbourhood. This is not the place of highest temperatures. In fact the highest temperature is over Sahara. This heat low is only in the lowest 1.5km and is overlain by a well-marked ridge, which is part of the subtropical high-pressure-belt. There is frictional convergence below 1.5km and ascent of air while with ridge above this there is subsidence.

The intensity of heat low is correlated with the intensity of monsoon. Below normal pressures in Heat low and above normal pressure in peninsula will increase rainfall as the pressure gradient in peninsula will be more and is conducive for monsoon rains.

2. Monsoon Trough

This is a low-pressure trough at sea level that is part of global equatorial trough of the northern hemisphere seen during summer season (Fig 1.15). From the seasonal heat low over Pakistan and neighbourhood, a trough extends southeastwards to Gangetic West Bengal. The trough line runs at surface from Ganganagar to Calcutta through Allahabad, with west southwesterly winds to south and easterly wind to the north of trough line. This trough is seen in the upper air up to about 500hPa, the trough line sloping southwards with height. At 700hPa, it runs from Bombay to Sambalpur. In the western sector the trough rapidly shifts southwards with height in the lower troposphere but the slope becomes less marked in mid-troposphere. In the eastern sector, the southward slope is less in the lower troposphere and increase appreciably in mid-troposphere.

Monsoon trough is regarded as the equatorial trough of northern summer, in the Indian longitudes. In this season, a weaker trough persists within 5 degrees south of the equator. The latitudinal position of the monsoon trough line varies day to day and has a vital bearing on the monsoon rains. No other semi-permanent feature has such a control on monsoon activity. This is not so much due to the up glide along the slope of the trough or convergence in it, as due to the various synoptic systems that prevail with the different positions of the trough. Position of trough line close to the foothills of Himalayas is known as
‘Break monsoon’ with decrease in rains over the country and increase in rainfall over the mountain belt. Swing of the trough to the central parts is with monsoon depressions that form in the North Bay and move west to west-northwest across the country.

3. Mascarene High

This is a high-pressure area (sub-tropical anticyclone) south of the equator (fig.1.15) centered at around 30°S, 50°E, from which there is a large outflow of air. Variations in the location and strength of Mascarene high are important in relation to summer monsoon circulation and accompanying rainfall over India.

4. Low-level cross-equatorial Jet

The deep SW monsoon current has a high speed Low Level Jet Stream (LLJ) (Findlater, 1969) whose maximum wind speed is at an altitude of about 1.5 Km as may be seen from fig.1.16 taken from Joseph and Raman (1966). This jet has maximum winds near 1.5 km level and occasionally it has speeds of 100 kts, particularly where the LLJ crosses the equator. It is a very narrow jet (both horizontally and vertically). The Jet runs roughly parallel to the north-south oriented east-African coast which is favourable for cross-equatorial flow from south to north during the northern summer season particularly July-August. During April this current flows across the northern tip of Malagasy. It penetrates into eastern Africa during May and swings across the equator into southwest Arabian Sea and then to west coast of India during June. During July the current flows from the ocean near Mauritius, reaches the Kenya coast near 3°S and penetrates inland over the flat coastal strip of Kenya and low lands of Ethiopia and Somalia and emerges out into the Arabian sea near 9°N. Here it moves over the cold upwelling waters off the Somalia coast. In a way this jet causes the upwelling here and this upwelling determines the horizontal and vertical shear of the Jet. The axis of the LLJ over India on a monsoon day can be anywhere between latitudes 5°N and 25°N. The variation of wind speed and wind direction
in the vertical at a point along the axis (Vishakhapatnam) of the jet-stream is also shown in figure (1.16). Strength of westerly winds increase from sea level up to an altitude of about 1.5 kilometer (5000 feet) and decrease above that. In active monsoon conditions the depth of the monsoon westerlies become more than 6 Kms. Moisture bearing monsoon winds with such a vertical profile impinges on the slopes of Western Ghats during south-west monsoon season producing copious rainfall on its wind facing slopes.

South-west monsoon of India has an Active-Break cycle. During active monsoon spells that last three to five weeks the axis of the LLJ passes through peninsular India and a major portion of India including Kerala get heavy monsoon rains. During break monsoon spells typically lasting a week, the axis of LLJ bypasses India and flows eastwards south of India. During break monsoon, most parts of India receive very little rainfall. LLJ is the channel through which the water vapour evaporated over the vast expanses of the south Indian ocean and Arabian sea is taken to the raining monsoon areas over India and south-east Asia. The raining areas mapped by satellite (Outgoing Longwave Radiation-OLR- gives a measure of the rainfall, (lower OLR indicating higher rainfall) and
the axis of LLJ during monsoon onset over Kerala and in active and break monsoon spells as average of several cases taken from Joseph and Sijikumar (2004) are shown in fig.1.17 (a-c).

![Diagram](image-url)

**Fig. 1.17a:** Axis of Low-level Jet and the associated active areas of convection (OLR in Watts/m²) during onset as taken from Joseph and Sijikumar (2004). Wind is in ms⁻¹.
Fig. 1.17b: Axis of Low-level Jet and the associated active areas of convection (OLR in Watts/m²) during active spells of south-west monsoon as taken from Joseph and Sijikumar (2004). Wind is in ms⁻¹.
Fig. 1.17c: Axis of Low-level Jet and the associated active areas of convection (OLR in Watts/m$^2$) during break spells of south-west monsoon as taken from Joseph and Sijikumar (2004) Wind is in ms$^{-1}$.

During active monsoon conditions over India, Kerala also gets large amounts of rainfall, particularly on the wind-facing slopes of the Western Ghats, more particularly in the high ranges. On some of these days the low level westerly winds develop wave troughs and spatially small low pressure areas in them along and off the west coast of India including Kerala when the heavy
rainfall activity shifts from the high ranges to the coastal and just off-coast areas in the Arabian sea – Rao (1976).

5. Tropical Easterly Jet

It is seen that easterlies are well developed during northern summer over south-east Asia particularly over south India at 100hPa. Along meridian 70E – 85E, we have sea near the equator and High Himalayan plateau near 40°N. This creates intense temperature and pressure gradients between the sub-tropical and equatorial latitudes in this region, the sub-tropics having higher temperature and equatorial region having lower temperature throughout the troposphere. As a result, there is low-pressure area in the sub-tropical latitudes and high-pressure area in the near-equatorial latitudes in the lower troposphere and opposite pressure-gradient in the middle and upper troposphere. Due to the low values of Coriolis parameter in the near-equatorial latitudes, even a slight gradient of pressure can create zonal flow of considerable magnitude in these latitudes.

There is lack of observations in the tropical region and with the available data we can say that, an easterly Jet stream overlies south Asia and north Africa during northern summer (June-September.). Starting at the east coasts of southeast Asia the axis of the current accelerates and runs westwards, roughly along latitude 8°N-12°N attains maximum speed over south-east Arabian sea and decelerates over Africa, weakening and losing Jet intensity. Surface of maximum easterly wind is lowest (13.5km) near the equator, rising upwards towards north to a level of 16 km at 25°N. Maximum intensity of easterly wind is seen around 9°N (77kts) during this season.

6. Tibetan High

This is a large anticyclone that is known to have its largest amplitude near 200 hPa during the northern summer months. Upper air anticyclone first appears in April just to the north of Borneo. In May it is located over Indochina, by June it is found over northern part of Burma and thereafter it moves to Tibetan
highlands. This anticyclone moves south-south eastward in September and is found over Malaysia in November and then loses its identity. Summer heating of the Asian land mass is regarded as the principal cause of the onset of summer monsoon winds and rain. Flohn (1968) regarded the vast elevated Tibetan Plateau as the principal heat source in the mid-troposphere, which controls the monsoon circulation. Sensible heat flux from the elevated land surface is an important heat source in the monsoon system. Once the monsoon has set in very large amounts of latent heat over the monsoon region is released. Even though, the percentage contribution is not very clear, estimates say that contribution of latent heat is 80% and sensible heat is 20% for the maintenance of monsoon circulation.

1.6.2 Monsoon Depressions

Monsoon depression is one of the important synoptic scale (1000 km) tropical disturbances, which forms periodically on the quasi-stationary monsoon circulation. Prevailing over the Indian region during the south-west monsoon, its existence and pre-eminent position as a rain-producing system is well recognized. As per the current definition followed by IMD, low-pressure systems are referred to as depressions when surface winds in cyclonic circulation are between 17 to 33 kt. A depression in which the wind speed exceeds 33 kts is termed as a cyclonic storm. During active monsoon conditions these systems form in the Head Bay and move inland to Orissa and further west. These systems intensify the low level monsoon winds causing increased rainfall activity over India including in Kerala.

1.6.3 Thunderstorms

Assam and its neighbouring states and Kerala (particularly south Kerala) have the highest frequency of thunderstorms in India. In Kerala maximum frequency of thunderstorm days are in April, May and early June and in October and November. The world over one of the basic mechanisms causing rainfall,
particularly heavy rainfall is the thunderstorm. The cloud that causes a thunderstorm is the cumulonimbus. During the south-west monsoon season in Kerala, rainfall is also caused by tall cumulus clouds of height around 6 kms and by thick nimbostratus clouds. Fig. 1.18 gives the vertical structure of a typical thunderstorm (cumulonimbus) cloud growing up to altitudes of 12 to 18 kms. Strong vertical air currents (up-drafts and down-drafts) are a characteristic feature of these clouds. The down-draft air spreads on the ground causing surface wind squalls ahead of the arrival of the thunderstorm cloud overhead with its heavy showers. Kerala does not get the severe manifestations of the thunderstorm called supercell thunderstorms (frequently occurring in north India) that cause big hail and occasionally tornadoes and accompanied by surface squalls of 100 to 200 km per hour winds. However, the thunderstorms of Kerala produce heavy rain showers and strong electrical manifestations – lightning and thunder. For thunderstorms to form lower layers of the atmosphere should have large quantities of moisture and the atmosphere should be conditionally unstable. These conditions are generally available in Kerala. For severe thunderstorms to occur as in north India, the wind speed should have a large increase with height, particularly in the lowest five kilometers of the atmosphere. For triggering thunderstorms, the atmosphere should have vertical motion in the lower levels. These vertical motions are caused by atmospheric dynamics in the areas of low pressure and in areas of low-level wind speed variations (along and perpendicular to the wind direction). Stronger vertical motion is available in the high ranges when winds have a component perpendicular to the hill slopes. Heavy thunderstorm rains (cloud bursts) of a few hours duration in the high ranges can cause flash floods in our rivers and also land slides (urul pottal). The heavy rains associated with a thunderstorm cover areas only a few tens of kilometers wide.
1.6.4 Lows, Depressions and Cyclones

Tropical cyclones are large vortices in the atmosphere with powerful winds rotating in an anti-clockwise direction in the northern hemisphere. They develop a central eye, surrounded by an eye-wall called wall-cloud composed of thunderstorm clouds. An area extending radially up to about 100 kms from the cyclone centre causes destruction due to strong winds and heavy rain. The various stages in the intensification of a cyclone are low, depression, cyclone, severe cyclone and super cyclone depending on the speed of the low level winds in its circulation. A typical severe cyclone will have the eye, wall cloud and the spiral cloud bands of the cyclone, which occupy the inner region of the cyclone. Strong cyclonic winds without rain extend from the periphery of the spiral cloud bands up to 700 kms from the cyclone centre.

Cyclones of the Indian seas generally form between latitudes 5N and 18N during the pre-monsoon months of April, May and the early part of June and in the post monsoon period late September to December. During the south-west monsoon months only weaker systems called monsoon depressions form. The preferred motion of Indian cyclones is northward but in the month of November a high percentage of the cyclones formed in the Bay of Bengal move westwards, hit the Tamil Nadu coast and after weakening into depressions and lows move across Kerala giving plenty of rain in Kerala without causing much wind damage. Pre-monsoon cyclones of the Arabian Sea generally move northwards.
and do not affect Kerala. But in May 1932 and again in May 1941, cyclones that formed in the south-east Arabian sea moved eastwards and crossed into Kerala near Kozhikode in 1932 and near Thrissur in 1941 causing widespread and heavy rainfall and considerable property damages. We have now three cyclone detection radars one each at Cochin, Chennai and Karaikal and the Indian satellites in the INSAT series to keep constant watch on cyclones likely to affect Kerala.

1.7 Rainfall and Orography of the Western Ghats

Kerala gets average annual rainfall of about 300 cms. A good part of this rainfall is caused by the orography of the Western Ghat mountain ranges. Both convective (large cumulus and thunderstorm) and non-convective (nimbostratus) rain require vertical motion in the atmosphere and the slopes of the Western Ghats generate large vertical motion fields when winds impinge on them, particularly during the south-west monsoon season with strong westerly winds. Non-convective rain is caused purely by the vertical motion present in the atmosphere where the moist air is made to move up when the water vapour in the air condenses to form rain. In convective rain the strong vertical motion in the cloud that generates the rain is caused by the conditional instability present in the atmosphere, but vertical motion in the atmosphere in its lower levels is necessary to trigger the convective clouds and make them respond to the atmospheric instability.

Vertical motion in the atmosphere outside convective clouds is caused by the following main factors:

(a) Wind speed normal to the slope of the mountain terrain
(b) Slope of the mountain terrain
(c) Mountain (lee) wave generation
(d) Land-sea and land-land contrast in friction in the atmospheric boundary layer.
(e) Cyclonic Vorticity (anti-clockwise rotation about a vertical axis in the northern hemisphere) of the air in the frictional boundary layer of the atmosphere for generating upward motion. This rotation in the air can be due to low-pressure systems like lows, depressions and cyclones (vorticity due to curvature of the flow) or due to the wind speed variation normal to the wind (vorticity due to lateral shear of the wind). Clock-wise air rotation (anti-cyclonic vorticity) in the boundary layer causes downward movement of air and suppression of rainfall.

(f) Longitudinal variations (along the wind direction) in the wind (convergence or divergence)

(g) Large scale and weak vertical downward motion field is generated in the atmosphere (subsidence) by the convective heating of the atmosphere in distant areas as when El Ninos occur.

Factors (a) and (b) (orographic control) are very important for the monsoon rainfall of Kerala. In addition the shear vorticity in the SW monsoon wind also regulates monsoon rainfall (dynamic control). Factor (e) particularly the cyclonic vorticity caused by lows, depressions and cyclonic storms is an important factor (dynamic control) in NE monsoon rainfall of Kerala. Western Ghats orography also plays an important role in this season. In the pre-monsoon season, rain is mainly due to afternoon thunderstorms where conditional instability in the atmosphere is a very important factor. Orography provides trigger mechanism to initiate the thundercloud formation.