Impact of Western Ghats Orography on the Weather and Climate Over Southern Peninsular India - A Mesoscale Modelling Study

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CERTIFICATE

This is to certify that the research work presented in this thesis ***Impact of Western Ghats Orography on the Weather and Climate Over Southern Peninsular India - A Mesoscale Modelling Study*** is the original work done by Mr. Venu G. Nair under my guidance and has not been submitted for the award of any degree or diploma by any other University or Institution.

Certified that Mr. Venu G. Nair has passed the Ph.D qualifying examination conducted by the Cochin University of Science and Technology in April, 2004.

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PREFACE

Mountain Meteorology is a fascinating subject in which a lot of studies and classical theories have been evolved during the middle of twentieth century in the sub-tropical latitudes. The tropical mountains have not been studied with an integrated approach especially its influence on the climate over the near by region. The impact of the Western Ghats orography on the weather and climate of the southern peninsular India is frontier topic and very limited studies have been done in this area. The availability of the data and the complex terrain of the study region makes the study more difficult. The only solution to this problem is the use of a meso-scale model like MM5 to study the mountain environment of the region. A detailed study on the topic has been carried out with an integrated approach to the problem. The results of these studies are presented in this thesis.The thesis carries of six chapters.

In Chapter 1, a general introduction about the topic and the deatiled Liturature Survey which include the studies in India and abroad are given. The data used and the methodology adopted in the study is also given in detail in this chapter. Before finalising the modelling part different schemes are tested with variety of combinations and a number of runs have been made to find the suitable combination for this study. Averaging of 17 years of output data with 3 hours interval for 48 hours in every month is done with precision and made the data set with normal and modifed orography. The resolution of the output of the modelled data is 10 kms for normal and removed orographic cases and 15 kms for filled Palghat Gap runs in the horizontal. The vertical resolution is 50 hPa and reaching upto 200 hPa level at the top. The study area extends from 8°N to 14°N and 75°E to 80°E which can be called as the Southern Peninsular India. The analysis is primarily based on the four major season described in Climatology as Winter, Spring, Summer and Autumn for this region.

In Chapter 2, the spatial and temporal variation of the surface meteorological parameters are dealt in detail.The north-south, east-west and the altitudinal variations of the parameters with stations are analysed. The vertical profile, the diurnal variation and the cross section along the latitude belts are also included in the results. The cross sections have been taken in such a way that it represents the different terrain of the study region. Even the cross section along the Palghat Gap, which is a major geological dicscontinuity of the mountain in the study area, is studied with special interest.

Chapter 3 deals with the complex circulation pattern exisiting over the mountain region. The general pattern of the winds over the region in different seasons and the generation and movements of the thermally and dynamically originated local wind systems of the Western Ghats region has been studied. The modification of the prevailing winds over the region by the Palghat Gap and its effect on the mouth regions of the gap is analysed in great depth. Since capture of the lee waves with this resolution is very difficult, a theoretical approach to calculate the wavelength of possible Lee waves in the lee side of the Western Ghats mountain has been successfully made with the modelled data.

Chapter 4 deals with the study of climatic elements of the mountain region such as energy budgets, rainfall studies, evaporation and condensation and the variation in the heat fluxes over the region. The causes of the rainfall vaiability over the region and the terrain induced changes in the rainfall pattern are also included in the study. Unusal variations of the observed temeprature pattern over the gap regions of Palghat and Aryankavu are analysed on the basis of the heat flux exchanges between the earth's surface and the atmosphere and tried to find out the reasons for this typical changes.

In Chapter 5 the impact of the orography is studied in a different approach. The Western ghats orography has removed and the changes in the surface meteorological parameters have observed from the normal case. This helps us to know the impact of the mounatin more precisely than any other attempt. Also the Palghat Gap is closed and the similar impact study has been made in an around the mouth of the gap on both sides. This type of hypothetical study gives more insight into the control of mountain on the distribution of meteorological parameters over the study region and helps to quantify the impact of the mountain in varying the weather climate of the region.

Chapter 6 includes the summary of all the four working chapters, discussed the major results and listed the over all conclusions. It also discussed the future out look of the study. Reference used in this study is given in the alphabetical order in the last section of the thesis.

CHAPTER 1

Introduction and Literature Survey

1.1 Introduction

The mountain environment has always been regarded with wonder and beauty. Mountains are quite important in controlling and modifying the atmosphere in meso-scale and even in synoptic scale. Despite their significance in such respect, and the fact that mountain ranges account for 20 per cent of the earth's land surface, the meteorology of most mountain areas is little known. Climatic studies in mountain areas have frequently been carried out by biologists concerned with particular ecological problems, or by hydrologists interested in snow runoff, rather than meteorologists. The complex relief features of mountainous areas as well as the high variability of mountain meteorological elements and the difficulties of its measurement and the limitations even attached to the analysis of mean values based on records from official meteorological observatories can be overcome upto a certain extent only through the downscaling of the atmospheric parameter with the help of a numerical models.

Mountain environment is so complex to study that even now lot of problems are remaining to be studied about the mountain climate and its variabilities. Climatological features of mountains, especially their associated cloud forms, are represented in many names and local expressions. On seeing the distant ranges of New Zealand, the ancestral Maoris named the land Aotearoa, 'the long white cloud'. Table mountain, South Africa, is well known for the 'table cloth' cloud which frequently caps it. Wind systems associated with mountains has also given rise to special names now widely applied, such as Fohn, Chinook and Bora, and others still used only locally. Today the majestic scenery of mountain regions makes them prime recreation and wilderness of the country. Such areas provide major gathering grounds for water supplies for consumption and for hydro electric power generation, they are often major forest reserves, as well as some times containing valuable mineral resources. Mountain weather is often severe, even in summer, presenting risks to the unwary visitor and, in high mountains, altitude effect can cause serious physiological conditions.

Mountains have three types of effects on weather in their vicinity. First there is substantial modification of synoptic weather systems or airflows, by dynamic and thermodynamic processes, through a considerable depth of atmosphere. Second there is the recurrent generation of distinctive regional weather conditions, involving dynamically and thermally induced wind systems, cloudiness and precipitation regimes and so on. Both these major effects require that mountain ranges should have extensive width and height and uninterrupted by deep transverse valleys and passes in their long dimension. The third type of mountain effect is the result of slope and aspect variations. It operates primarily at the local scale of tens to hundreds of meters to form a mosaic of topoclimates. *Ekhart* (1936) suggests that the atmosphere in the mountain can be separated into the slope atmosphere (a few hundred meters thick), a valley atmosphere dominated by thermally induced circulations and in extensive mountain ranges an enveloping mountain atmosphere where the air flow and weather systems are subject to major modification (fig.1.1).

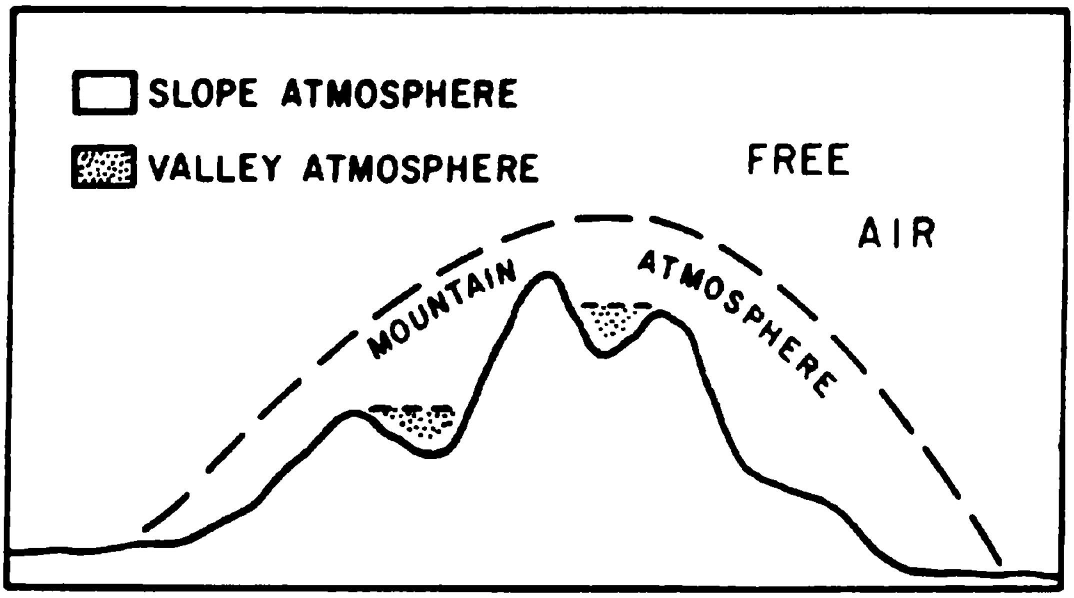


Figure 1.1: The mountain atmosphere. (after*Ekhart*)

1.2 Characteristics of Mountain Area

Mountain ares are defined arbitrarily and no quantitative or qualitative distinction is made between mountains and hills. The global coverage of mountain areas and the high plateau over the earth's surface is given in the table (1.1). In North America 600 meters or more of local relief distinguishes mountains from hills (*Thompson*, 1964) and 1800 m as the 'Sierran type' (*Finch and Trewartha*, 1949). Troll delimits high mountains by reference to particular landscape features. The most significant once are the upper timberline, the snowline during the Pleistocene epoch and the lower limit of periglacial processes. It is

HEIGHT (m)	**MOUNTAINS (No.)**	**PLATEAU (10^6 km^2**	**MOUNTAINS / LAND SURFACE (%)**
3000 m & above	6		4.0
2000-3000	4	6	2.7
1000-2000	5	19	3.4
0-1000	15	92	10.1
Total	30	117	20.2

(After *Louis* (1975))

The total land surface is 149 million km ^{2}

Table 1.1: The global area of mountains and high plateau

clear that each of these features is related to the effects of past or present climate and to micro-climate conditions at or near ground level (*Troll*, 1973). On the basis of Troll's criteria, the lower limit of the high mountain belt occurs at elevations of a few hundred meters above sea level in northern Scandinavia, 1600-1700 m in central Europe, about 3300 m in the Rocky mountains at 40°N and 4500 m in the equatorial cordillera of South America. In arid central Asia, where trees are absent and the snow line rises to above 5500 m, the only feasible criterion remaining is that of relief. In the mountains, however, we are dealing with at least three types of situation - summit, slope and valley bottom - apart from considerations of slope orientation, slope angle, topographic screening and irregularities of small scale relief. The most latitudinally extensive mountain chains are the cordilleras of Western, North and South America. The most extensive east-west ranges are the Himalaya and adjoining ranges of central Asia. Reference should also be made to the vast high land plateau exceeding 3000 m in Tibet and even larger ice plateau of Greenland and Antarctica. All of these regions have major significance for weather and climate at scales upto that of the general circulation of the atmosphere. In contrast, major, but isolated, volcanic peaks which occur in east Africa and elsewhere, have their own distinctive effects on local weather and climate.

1.3 Earlier Studies of Mountain Meteorology

1.3.1 Major Studies conducted in Abroad

The major studies of the mountain meteorology got momentum in the second half of the twentieth century. The relation between the latitude and the mountain climate system has been studied by various group especially *Hedberg* (1964), *Hnatiuk et al.*, *Barry* (1973), *Lauscher* (1966) and *Lauscher* (1976). After the initial enthusiasm for the mountain weather data in the United States, several problems led to a decline in interest in maintaining mountain observatories (*Stone*, 1934). The value of observatories in connection with upper air studies was raised again in the 1930's when the modern aerological networks were first being established (*Bjerknes*, 1934).

The variation of pressure with altitude has been studied by *Prohaska* (1970). he connected this variation with the virtual temperature. Variation of vapour pressure in the altitude in the mountains of Fuji in Japan has studied by *Yoshino* and *Fujimara*. *Storr* (1970) linked this vapour pressure variation with the transmission of infra red radiation. Some of the most extensive studies of altitudinal effects on solar radiation have been made in the European Alps by *Steinhauser* (1939).

Measurements made by *Sauberer and I.Dirmhirn* (1958) at the Jungfraujoch, Sonnblick and Zugspitze observatories of Europe have provided a wealth of material for analysis. They found a relationship between the global radiation, cloud amount and the altitude. *Reiter et al.* show that cloud cover has less effect on UV totals at higher elevations. The albedo gradient and the net radiation are connected well and its variation with height is studied by *Voloshina*. Infact based on observations from many high mountain stations, the increase is broadly exponential due to the concentration of water vapour in the lower troposphere. The altitudinal dependence of the ratio of diffuse to global solar radiation has been estimated for cloudless skies by *Klein* (1948). For a solar elevation of 65°, the ratio is around 0.16 near sea level and 0.08 at 4400 m. The ratio increases at lower solar altitudes. In the middle latitudes there exists a decrease in diffuse radiation with increased atmospheric transparency; the minimum of global radiation at 1.0-1.5 km represents the effect of water vapour absorption (*Flach*, 1966). The effects of decreasing air density are not constant with wavelength and there is a wide range of estimates of the magnitude of the effects at short wavelengths. Free air data indicate that the increase in ultra-violet radiation between sea level and 4 km altitude for Θ=90°decreases with increasing wavelength.

Gates and R.Janke (1966) estimated that alpine areas (3650m) at 40°N receive 1.5 times more total ultra violet radiation than at sea level. *Caldwell* (1968) measured increases from sea level to 3650 m in Colorado that were only 4% and 50% for m = 1.05 and m= 2 respectively. He also reported an absolute decrease in sky ultraviolet radiation for these wavelengths with increasing elevation above 1500 m due to reduced atmospheric scattering. This corresponds with earlier findings in the Alps (*Eckel*, 1936). While the effect of reduced atmospheric density with altitude is important for solar radiation, the maximum absorptance by an atmospheric column under clear skies is only about 15% of the incoming extra-terrestrial solar radiation. Infra-red radiation fluxes are significantly affected by the increased atmospheric transparancy at high elevation and by the lower air temperatures.

Some of the most extensive studies of altitudinal effects on solar radiation have been made in the European Alps. Steinhauser(1939) analyzed the direct radiation, on a surface normal to the beam, and showed that, as a percentage of extra-terrestrial radiation, there is a rapid increase up to about 2000 m, after which the rate of increase declines (table 1.2). The effect of cloud cover on solar radiation as a function of altitude is complex and

Altitude (m)					
	200	1000	2000	3000	Extra-terrestrial total Wm^-2
15 December	37	48	58	61%	488
15 June	51	58	67	72%	865

Table 1.2: Direct radiation on a perpendicular surface at 47°N, as a percentage of the extraterrestrial total

the most detailed results are available from the Alps (*Sauberer and I.Dirmhirn*, 1958); (*Thams*, 1961a) & (*Thams*, 1961b). In June and December there is a linear relationship between global solar radiation and cloud amount in the mountains at 3000 m, whereas lower elevations thicker clouds cause a sharper decline for conditions of overcast. The diffuse radiation increases upto a limiting value of cloud amount that varies according to altitude. This limit is about 6/10 cover over the lowlands, but increases to 9/10 at about 2000 m. This effect represents the predominance of thinner cloud layers at the higher stations (*Thams* (1961b) & *Berner* (1963)). *Reiter et al.* (1980) showed that cloud cover has less effect on UV totals at higher elevations.

For example, the mean UV for all weather conditions, 1964-1971, is 66% of that on cloudless day at the Zugspitze compared with reductions to 55% at 1780 m and to 53% at 740 m (Garmisch) of the respective cloudless sky values. Maximum UV intensities are recorded just below the upper boundary of startiform cloud layers, rather than in cloudless conditions, as a result of the scattering effect. In general, both the infra-red radiation emitted from the surface and the atmospheric back radiation decreases with altitude. This arises due to the lower effective temperature and, in the case of the atmospheric emittance, as a result of the smaller vapour content in the overlying air column. De Saussure, working in the Mont Blanc massif, was one of the first physical scientists to approach a realistic explanation of the cause of cold in mountains (*Barry*, 1978).

In Japan *Yoshino* (1966) made a study of altitudinal variation of temperature with airmass. The analysis of temperature with stablity of the atmosphere is studied by Harding in Norway and central France (*Harding* (1978) & *Harding* (1979)). Altitudinal gradient of soil temperature in Great Britain is studied by *Gloyne* (1971), *Green and R.J.Harding* (1979), *Green and R.J.Harding* (1980) and *Harrison* (1975). Soil temperature lapse rate in the upland and the evaporation in an area is connected by *Oliver* (1962). Numerous comparisons of mountain temperatures and comparable data from air craft or baloon soundings have been made by many scientists like *Ferguson* (1934) & *Samson* (1965). *Eide* (1948) correlated the summit winds and the summit-free air temperature difference in the Norway mountains.

Flohn (1974) first proposed that elevated plateau surfaces are warmer in summer than the adjacent free air as a result of the altitudinal increase in solar radiation and the relative constancy of the effective infra-red radiation with height. The estmation of advective transport of heat and the radiative cooling in the mountain region has been done by *Flohn* (1968), *Flohn* (1974) & *Kreuels et al.* (1975). A study in the British columbia by *Peterson* (1969) shows that the freequency of below freezing temperatures in winter can be estimated from 0400 hrs radiosonde soundings and *Cramer* (1972) shows that isentropes of surface air temperature generally parallel the terrain contours in the morning hours.

Lot of studies have been carried out with real time wind meassurements at the mountainous areas. *Eustis* (1942a) has studied about the winds over New Hampshire (1915m) of Mt.Washington. In New Guinea at 4250 m on Mt. Jaya, a mean value of only 2 ms^{-1} is reported during December and February (*Allison and Bennett*) and on El Misti, Peru (4760m) there is an estimated mean speed of about 5 ms^{-1} with a recorded maximum of 16 ms^{-1} is reported by *Bailey* (1908). The effect of mountains on the wind flow over them aroused early interest through the manned balloon flights of *Ficker* (1913) especially. *Georgii* (1922) , *Georgii* (1923) argued that wind speeds generally increase above mountain summits upto a level corresponding to about 30% of their absolute altitude, which he termed the 'influence height'. *Schell* (1936) attempted to explain contrasting observations with balloons on three summits in the Caucasus at about 1300 m. He concluded that in the case of an isolated peak, or an exposed ridge, the compressional effect outweighs frictional retardation, giving stronger winds upto about 50-100 m over the summit than in the overlying free air. The accelaration due to compression is attributeable to a 1-2 hPa pressure reduction as a result of the streamline curvature over the crest line, the so called 'Bernoulli's effect'(*Davidson et al.*).

Schumacher (1923) studied about the mountain wind for three Alpine stations. He found that for Santis, Sonnblick and Zugspitze, the mean annual wind speeds average about 0.8 times those in the free air. An extensive survey of wind observations on mountain summits and in the free air has been carried out by *Wahl* (1966). From data of European station he found that, in general, speeds on summits average approximately half of the corresponding free air values. *Eustis* (1942b) reported summit to free-air ratios of 1.4 in summer and 1.8 in winter for Mt.Washington.

The effect of orographic barrier on air motion has been studied by *Smith* (1979a). From an energy stand point the air arriving at a barrier must have sufficient kinetic energy inorder to rise over it against gravity (*Stringer*). *Wilson* (1974b) also studied about the roll of kinetic energy to overcome the orographic barriers. *Giles* (1976) suggests that the winds observed to the east of the Carpathian mountains and Transylvanian Alps in Roumania appear to reflect the principle of Coanda effect since they are deflected southwestward towards the adjacent convex surface of the range. Detailed accounts of orographic effects on airflow are given in *Alaka*, *Nicholls*, *Smith* (1979b), *Smith* (1979c), *Beer* (1976). *Kasahara* and *Kasahara et al.* (1973) studied about the effect of orography on the planetary waves and found that the distribution of land and sea, through their thermal difference contribute to the wave pattern in winter. The effect of divergence and vorticity in large scale circulations around orography is studied in detail by *Queney* (1948), *Colson* (1949) and *Bolin* (1950). *Reiter* found that there is a critical value for the flow pattern which will be deciding the lift of the air over a mountain and he proposed the theory of diffluence of air motion over the mountains. Upper wind profile of winter supports the difflunce of Reiter and it is established over the Rocky mountain and Tibetan plateau by the study of *Chaudhury* (1950).

It is found that the frontal cyclones crossing a mountain range undergo structural modifications and in the lee of the mountain cyclogenesis is enhanced. There are several dynamic and thermodynamic mechanisms involved in the orographic modification of frontal characteristics such as 'masking' refered by *Godske et al.*. *Taylor-Barge* found that the effect of mountain on the frontal system is depending on the intensity and the speed with which the system moves. Cold fronts with a typical 1:20 slope also tend to be slowed down by mountain barriers, since the wind component normal to the front is slowed first, and to a greater degree at lower levels. This tend to lift the frontal surface through the accumulation of the cold air near the ground level (*Radinovic*, 1965).

The barrier effect of mountain ranges are studied by *Church and Stephens* (1970) for Canada and the Pacific coast of the state of Washington. The evidence of the typical Fohn nose evident on the daily pressure maps was illustrated by *Brinkmann* (1970a). Malberg also points out the problem of over estimating mean sea level pressure in mountain area due to freequent inversion conditions with cold air ponded in mountain valleys and basins (*Walker*, 1967). *Cruette* (1976) noted that the intensified pressure gradient due to corner effect causes a local wind maximum such as observed in the east of the Massif central in France. In high latitudes, mountain barriers exert substantial influence on shallow stable air streams ((*Dickey*, 1961) & (*Schwerdtfeger*, 1961)).

Lee cyclogenesis is of major importance in many areas of the world. It occurs not only downwind of major barriers to the mid-latitude westerlies, such as the Western Cordillera of North and South America and the Tibetan Plateau. The effect of the Rocky mountains in the cause of cyclogenesis, especially in eastern Alberta and Colorado is well known (*Hess* (1948), *McClain* (1960), *Hage* (1961) & *Chung et al.* (1976)). The process involved in the case of the Alps are some what different and more complex. *Speranza* (1975) notes that true lee cyclogenesis occurs in perhaps fewer than five cases per year. The following description, based primarily on a case study by *Buzzi and Tibaldi* (1978), illustrates the interaction between the topography and a cold front advancing from the northwest, operating in conjuction with an intensifying upper level baroclinic field over northern Italy. Below 2 km, where the Alps form a 450 km barrier to westerly air flow (*Egger*, 1972) , interaction between the barrier and the airflow initiates a low level pressure perturbation with anticyclonic vorticity, produced by the vortex tube compression over the mountains and the cyclonic vorticity set up in the lee.

According to the vertical profile of wind speed *Forchgott* (1949) distinquished three basic type of flow for the modification of local air flow. He classifed this three type of flow as the laminar streaming, standing eddies and the lee waves formation. The generation of rotor motion forming individual vortices in the air flow is the concern of *Scorer* (1955a). Some times these vortices may attain mountain-sized dimensions as iluustrated for Mt. Fuji, Japan by *Soma* (1969) and by *Forchgott* (1969) for Little Carpathian Ridge, Czechoslovakia. *Corby and Wallington* (1956) studied about the formation of small wavelength large amplitude waves by facilitating the restoring action of the force of gravity on the air motion.

Scorer (1949) has formulated a stability factor known a Scorer parameter (denoted by 'l') in connection with the Brunt-Vaisala freequency and the trapped lee waves. Typical values of $'l'^2$ (x 10^6) may range in the vertical from 1 to < 0.05 km^{-1}. A scale for determine the values of 'l' from a tephigram plot of an appropriate upper-air soundings has been developed by *Scorer* (1953) and *Wallington* (1949) while *Casswell* (1966) gives graph for computing wave dimensions and velocities from 'l'. Computations of wave development by *Sawyer* (1960) for surroundings from various actual airstreams show general agreement with observations made at the time.

A useful approximate relationship for the wavelength (λ, in km) of lee waves in the lower troposphere is, $\lambda = 0.5\overline{U}$, where $\overline{U}$=mean tropospheric wind speed (ms^{-1}), assuming an average temperature lapse rate of 5°CKm^{-1} (*Corby*, 1954). An obstacle located one-half wave length downstream can eliminate the lee waves set up by an upstream ridge. For this reason, air may sometimes descend while crossing some sections of a broad mountain range. *Wallington* (1970) has observed this during aircraft profiles across the Welsh mountains. *Starr and Browning* (1972) suggested that radar observations may be the most feasible means of providing short term aviation forecast to avoid the lee wave development area.

The general classes of flow for an ideal fluid encountering an obstacle can be described with reference to the Froude number (F) which is the ratio of internal viscous forces to gravitational forces. According to *Wilson* (1974a) the barrier effect is detectable for F=0.25, neglecting the friction, and increases as $F \rightarrow 1$. *Long* (1970) studied the relationship of the hydraulic jump in the atmosphere when the air flow across a ridge is partially blocked. *Houghton and Issacson* (1970) show that hydraulic jumps may occur with high mountain ranges and a low upstream Froude number. For multi layer fluids , an internal Froude number (Fi) is defined by *Long* (1954). *Klemp and Lilly* (1975) argue that the hydraulic jump mechanism is too restrictive in its assumption to account for many observed aspects of strong wave amplification and downslope windstorms.

Recently, numerical solutions of the equations of motion have been used to examine non-linear flow behaviour over mountains. *Peltier and Clark* (1979) showed that, for homogeneous stable flows over a two dimensional barrier, non-linearities are related to the aspect ratio of the barrier. For inhomogeneous flows, Peltier and Clark find resonant lee waves and trapping and amplification of internal wave disturbances by reflection from a region of wave breaking and turbulance in the lower stratosphere. *Klemp and Lilly* (1978) incorporated an upper dissipative boundary region to remove upward propogating wave energy before reflection. The occurrence of rotors is one of the most important aspects of mountain waves. The idea that they are related to hydraulic jumps has been proposed by *Kuettnerr* (1958).

When a barrier has steep slopes or bluffs, especially on the lee side, the flow may become highly turbulent. *Smith* (1977) shows analytically that the steep lee slope accentuates the forward steepening of mountain waves, causing earlier breakdown of the waves and increased downslope wind velocity. Gust speeds during the downslope windstorms on the lee slopes of the Rocky mountains appear to be intensified by this factor at locations such as Boulder, Colorado (*Lilly and Zipser* (1972) & *Brinkmann* (1974)). For stratified flow over low to moderate slopes (<45°), the boundary low regime is determined primarily by the ratio of the wavelength of the lee waves ($2\pi U/N$) to the total width of the barrier (W), not by its height (*Hunt and Snyder*, 1980).

Gerbier and Berenger (1961) made so many observations on French Alps and analysed the mountain effects on airflow. Satellite photography often illustrates lee wave clouds behind the mountain ranges or peaks, and *Gjevik and Marthinsen* (1978), reported trapped waves during inversion conditions in the lee of JanMayen, Bear Island and Hopen. Another meso-scale circulation which may occur in lee side is the vortex street. This is common in the lee of islands in the trade wind zone and other areas with low level inversions. By analogy with von Karman's vortex street theory, air flow drag over such high, steep-sided islands leads to eddies being shed alternately on each side with a period of of about 5-10 hours (*Chopra*, 1973).

Flow seperation when the vortices are shed give rise to pressure fluctuations of about 1 hpa (*Zimmerman*, 1969), although it is not entirely clear how divergence and vertical motion due to such effects generates the observed cloudiness. Experimental analysis of strongly stratified flow past a bluff obstacle by *Brington* (1978) supports the idea of the key role of a strong low level inversion in vortex shedding. In this context, it is intresting to note that small vertical vortices have occassionaly been reported at Boulder during windstorms, as well as more moderate westerly flow conditions (*Bergen*, 1976). Similar vortices, made visible as 'cloud spotuts' extending 300 m below cloud base, have been observed in the lee of Mount Washington, New Hampshire (*Brooks*, 1949). A detailed classification of orographic cloud was proposed by *Abe* (1941) from his laboratory model. He notes that cumuli form cloud, stratocumulus and turbulent fracto-forms may all occur over or near mountains.

The winds blowing in the lee slopes due to the effect of topography is termed as fall winds and fohn winds comes under this category. Fohn winds are found to be important for vegetation and soil moisture extending upto 50 kms from the foot hills of the Rocky mountains in Colorado (*Ives* (1950) & *Riehl* (1974)). The generic term fohn derives from the Alps, although the term chinook is used along the high plains east of the Rocky mountains and there are many other local names throghout the world (*Brinkmann*, 1971). The relation between the fohn winds and the potential temperature in the region is widely studied by *Topil* (1952) & *Lockwood* (1962). Two mechanisms producing the fohn type of temperature fluctuations have been identified on the east slope of the Rocky mountains by *Beran* (1967).

To formulate some criteria to identify the fohn wind based on the temperature pattern is derived by *Brinkmann* (1970b) and *Longley* (1967). Commonly three criteria are used at lee stations to identify the fohn winds and they are surface winds blowing in the direction of the mountain, abrupt temperature change and simulataneous drop in relative humidity (*Osmond*, 1941). Synoptic conditions exisiting for Santa Ana winds, which is a fohn type wind in southern California, south and west of San Bernadino Mountains have examined by *Sommers* (1978). A small scale three dimensional numerical model has been used by *Vergeiner* (1978) to analyse the fohn winds in the vicinity of Innsbruck, Austria.

Bora is another type of fall winds, which is a cold dry and gusty winds that blow in winter over the Dalmatian mountains of Yugoslavia towards the Adriatic sea. On a hemispheric scale, Januaries with frequent Bora days on the Adriatic coast also have frequent Oroshi winds in the Kanto Plain of Japan (*Tamiya*, 1975). In Bora winds adiabatic warming through descent and disruption of surface inversions may cause other complexities. As noted by *Suzuki and Yakubi* (1956) temperature characteristics on the lower slopes may be masked by local heating or cooling effects.

Reports of extream wind conditions have been reported due to fall wind conditions in many places. In the coastal stations it is found that the large scale topography inland determines the strength and persistence of these winds (*Mather and Miller*, 1967). *Streten* (1963) distinqushes a normal Katabatic regime when synoptic control is weak. The onset and cessation of strong coastal winds tends to be very abrupt at Cape Dennison and *Ball* (1957) interprets this as a standing jump phenomenon due to the gravity flow. In a wholly different environment, jump features are reported by *Lopez and Howell* (1967) from the Cauca valley in equatorial Colombia.

There is a distinction between the Katabatic winds and the small scale drainage of air which causes cold air pockets. While both arrises from radiative cooling and density differences, a minimum slope of about 1:150 to 1:100 seems to be necessary for Katabatic air flow (*Lawrence*, 1954), whereas small scale air drainage does not setup any significant compensating currents. Small closed basins can cause some dramatical local temperature inversions which are investigated by W.Schmidt and recorded even minimum temperature of the order -40°C (see *Geiger*, pp. 398-401). *Manins and Sawford* (1979a) explains about three theoretical approaches to the analysis of the Katabatic flows. The first approach has been followed subsequently by *Fleagle* (1950) and by *Petkovsek and Hocevar* (1971). Vertical structure of the flow is ignored but time variations are considered in this method. In the second approach, *Prandtl*, *Defant* and *Holmgren* analyse the vertical structure of the tempearture and wind velocity above the slope by regarding the flow as steady and invariant down the slope. The third approach allows inclusion of advection through numerical solution of primitive equations of motion (*Thyer*, 1966).

Petkovsek and Hocevar developed a model to find out the wind speed of the downslope wind and this is tested by *Streten et al.* (1974) in McCall glacier, Alaska and found to be in general accordance with the observations. A field study by *Manins and Sawford* (1979b) in southern Australia confirms the inapplicability of the above one dimensional model. There observations shows that surface friction effects are restricted to only a few meter thick. Model calculations by *Orville* (1964) for a 1000 meter high mountain with 45°slope indicates that , in a neutral environment, convection bubbles move up and away from the slope.

Observations between 515 and 830 meter on the south-eastern slope of Mt.Bandai, Japan(37°36' N, 140°04' E), together with special soundings, allowed *Mano* (1956) to develop a model of such flows. The earlier theories of mountain valley wind systems are elaborated by many scientists based on the aerological studies in the Alps, and later modified more recently by *Buettner and Thyer* (1966) working in the vicinity of Mount Rainer, Washington.

Concurrent cloud observations for a long time is very difficult to get to evaluate the specific cloud radiation relationships but *Greenland* (1978) illustrates the magnitude of probable differences due to cloud cover by comparison of two synoptic regimes. At high elevation stations, 5000 m and above, cloud layers are freequently thin and have high transmissivities. This has been varified by *Marcus and Brazil* (1970) & *Marcus and Brazel* for Mt.Logan, Yukon. At 4750 m on Mt.Everest (28°N) the net radiation on 9 days in April

1963 represented 55% of the incoming short wave with a surface albedo of 0.16 (*Kraus*, 1971). One of the extensive series of the Alpine meassurements is that of *LeDrew* (1975) & *LeDrew and Weller* (1978). They found the large sensible heat flux due to the generally strong advection of cool westerly air streams. Similarly the estimate of turbulent fluxes on a monthly basis for Croatia is prepared by *Plesko and Sinik* (1978).

The temperature variation in a mountain region is a particular problem for climatic atlases, due to the sharp temprature gradients over short distances and their seasonal vaiability (*Steinhauser*, 1967a). *Pielke and Mehring* (1977) use linear regression analysis of mean monthly temperatures as a function of elevation in an attempt to improve the spatial representation of temperature for an area in north-western Virginia. Inversions at low levels in winter introduce greater variability and better estimates may be obtained by fitting polynomial functions or alternately by the use of potential temperatures (*Hennessy*, 1979). Numerous regression equations have been worked out in a similar fashion for the West Carpathian mountains (*Hess et al.*, 1975) inorder to produce the topoclimatic maps.

Furman (1978) shows that daily maximum temperatures in summer at stations on a forested ridge in Idaho can be described by a second order auto-regressive model. *Reiter and Sladkovic* (1970) compared the lapse rate detrmined from a the cable car with the exchange coefficent for eddy duffusivity based on radon meassurements at Zugspitze. Aerial surveys using a radiation thermometer (*Fujita et al.*, 1968) offer another means of determining apparant temperatures over mountain slopes, but such data are expensive to aquire and are not readily converted to absolute values. The first description of the thermal belt zone in the history is attributed to Silas McDowell, a farmer in the southern Appalachian mountains of North Carolina in 1861 (*Dunbar*, 1966). In this area the thermal belt is centered, on an average , about 350 m above the valley floors (*Cox*, 1923).

Cloud cover is more freequent and thicker over mountains than over the surrounding low lands. Mechanical uplift and the convective effect due to slope heating is the main reason for this clouding. When clouds already present, slowing down of the air by the mountain barrier also leads to an increase in cloud water content (*Pedgley*, 1971). The effect of diurnal heating on build-up of mountain cumulus in the Triol has been described by *Tucker* (1954). The predominent clouds in mid-latitude mountain region during summer is convective and the surface temperatures of the mountain region during summer after noon tend not to differ much from those in adjacent valleys since the change of net radiation with height is small (*Scorer* (1955b) & *MacCready* (1955)). The pattern of stronger convective motion on the high ground is confirmed by the observations of *Silverman* in the Santa Catalina mountains, Arizona, which rise 2000 m above the surrounding terrain. However the wind field determines the cloud locations with respect to the ridge line and , in most cases, it is difficult to seperate the effects on convection of barrier heating on the one hand and lifting on the other hand (*Hosler et al.* (1963), *Orville* (1965a), *Orville* (1965b), *Orville* (1968) & *Kuo and Orville* (1973)).

As recognised by *Salter* (1918) from the analysis from the British data, the effcet of altitude on the vertical distribution of precipitation in mountain areas is highly variable in different geographical locations. A convective pattern of vertical precipitation distribution is widely found in the tropics where the cloud base is typically about 500-700 m in coastal areas and 600-1000 m inland. Similar trends are found on the windward slopes of the coastal mounatins of Central America (*Hastenrath*, 1967). The large scale forced ascent of air over a mounatin barrier leads to a lifting condensation level and this ascent may intensifies the general vertical motion in a cyclonic system or it may release conditional instability and shower activity especially in the polar maritime air streams (*Smithson*, 1970).

The amount of orographic precipitation depends on three factors such as air mass characteristics, local vertical motion due to terrain and microphysical processes (*Sawyer*, 1956). *Poulter* (1936) noted that the orographic increase at warm fronts was about two-fold over windward slopes of similar inclination to the front. *Browning et al.* (1974) & *Browning et al.* (1975) shows that , over Britain, orographic effects are negligible at surface cold fronts, where precipitation is heavy in any case. Ahead of a front, orographic effects vary according to the existence, first, of a low level jet maintaining high liquid water contents in the low level feeder clouds and , second, of seeding particles which may derive from high level releaser clouds (*Storebo*, 1968).

Fulks (1935a) formulated an equation which comprising vertical velocity and saturation mixing ratio to find the condensation in a mountain region. An analysis (*Pedgley*, 1970) of six cases of heavy precipitation associated with strong south-westerly air flows over Snowdonia suggests that there would be insufficent time for raindrops to grow in the air stream across these mountains. It is found by *Henz* (1972) that Cumulus cloud generated by convection and valley wind effects over the Rocky mountain is typically carried eastward by the general air flow and may cause afternoon hours if continued convection in the adjacent high plains permitts Cumulonimbus to form in the lee of the mountains. For studying the emperical evidence of the altitudinal effects on precipitation, *Chuan and Lockwood* (1974) shows that for eastern Pennines mean elevation over an 8 km of radius from a gauge site appears to be a better predictor of annual precipiation than station height. Several studies demonstrate that the altitudinal increase is due to the combined effects of higher intensities and greater duration of precipitation (*Atkinson and Smithson*, 1976).

In mid-latitudes, the general tendency for increased precipiation with height is modified considerably by a leeward or windward slope location. The maximum precipiation in the Sierra Nevada is found to be on the western slope around 1600 m (*Armstrong and Stidd*, 1967). On the western slope of the central Colorado Rockies, winter precipitation at 3200 m is almost six times that at the base of the slope (*Hjermstad*). Accumulation of rainfall in Antartica and north Green land increases inland to about 1500-1600 m altitude and thereafter decreases (*Sugden*, 1977).

Strom types and synoptic flow patterns can also introduce major differences in orographic effects (*Peck*, 1972). For Rocky mountains in Albertia, *Reinelt* (1970) uses a statistical approach to calculate the precipitation. A specific case study of orographic effects over the Cascade mountains, Washington, has been made during the passage of an occluded front by *Hobbs* (1975a). He found that a decrease of cloud amount and precipitation ahead of the front during its passage across the mountains, apparently due to the blocking effect of the barrier on a low level southerly flow of moist air. Statistical analysis of total precipitation in mountain areas have used regression techniques incorporating topographic parameters (*Spreen* (1947), *Linsley* (1958) & *Pech and Brown* (1962)).

The use of modern multiple regression techniques allows spatial patterns of residuals from the regression to be analysed and this may enable additional parameters to be incorporated in the equations in order to improve the statistical explanations (*Hutchinson* (1968) & *Bleeasdale and Chan* (1972)). This type of procedure has been used to construct precipitation freequency maps for mountain areas of the United States by *Miller* (1972) and to analyse elevation, orientation and inland distance effects on precipitation in West Africa (*Gregory*, 1968) and in the great basin of the Western United States (*Houghton*, 1979). A similar approach have applied by *Rhea and Grant* to estimate snow depth at Colorado and Utah. Formerly precipitation maps for mounatin areas are obtained from the extrapolation from existing station data, emperical altitude-precipitation relationship, and adjustments for windward or leeward locations (*Steinhauser*, 1967b).

Several studies shows that, at low land stations in middle latitudes, a threshold temperature can be used to discriminate the type of precipitation on a statistical basis. For low land Britain, there is an equal probability of precipitation occuring as rain or snow when the screen temperature is 1.5°C, implying a freezing level about 250 m above the surface (*Murray* (1952) & *Lamb* (1955)). *Jackson* (1978) re-evaluated the British data to make an empirical relationship between the snow cover and the snowfall on the basis of median rather than mean duration. *Manley* (1971) also made the study of relationship of snow cover and snowfall in Scottish high land. *Caine* (1975) found an elevational influence in the relative variability of maximum snowpack as well as on the accumulation.

Theoretical analysis of precipitation rates over mountains has a long history. *Pockels* (1901) used the hydrodynamic equations to calculate the precipitation rates. Another similar theoretical analysis to that of Pockels was carried out by *Ono* (1925) and tested with Japanese data. *Marwitz* (1974) studied the ratio of the precipitation to condensation in winter cyclone over Colorado mountain. In some other models, such as those of *Young* (1974) and *Nickerson et al.*, cloud micro physics is also incorporated. For simple barriers, several models use a calculation of the vertical transport of water vapour due to the mean terrain slope. The horizontal wind may be adjusted directly to the mean flow perpendicular to the barrier (*Elliot and Shaffer* (1962) & *Myers* (1962)) or for actual topography the vertical wind component reltive to the slopes can be determined and *Danard* (1971) used this for the model.

Illustrative maps of terrain induced vertical motion have been prepared for the Aplachian mounatins (*Jarvis and Leonard*). The theoretical decrease with height of terrain induced vertical motion has an approximately parabolic profile (*Berkovsky*, 1964). *Rhea* has developed an operational model for winter precipitation in the Rocky mountains of Colorado. The linerised equations for the perturbation of vertical velocity were originally developed by *Holomboe and Klieforth*. Later *Wilson* also modified the model. In the earlier models, the precipitation amounts are calculated from the esimated condensation rate for saturated air flow crossing an idealised mountain range (*Fulks*, 1935b). Studies of westerly air stream crossing the Cascade mountains in California indicates that solid precipitation can be transported upto 50-70 km downwind (*Hobbs*, 1975b). A different meso-scale boundary layer model has been used to study the effect of arctic outbreaks over the foothills of the Rocky mountains in Alberta (*Raddatz and Khandekar*, 1977).

Barros (1994) tried to incorporate radar and sattelite observations in the data assmilation of the model to improve the prediction of orographic precipitation. The mechanism of the intense Alpine rainfall was studied by *Rotunno and Ferretti* (2000) with the help of MM5 model and they tried to incorporate idealised orography instead of real orography and found that it provides a clear picture of the model's mechanisms of orographically induced rainfall. The changes in the ambient condition and the sensitivity in the orographic precipitation has been dealt in detail by *Colle* (2003). He found that precipitation distribution is highly dependent on how the terrain induced gravity wave modifies the circulation aloft. The long range influence of orography on precipitation is studied by *Ahijevych et al.* (2004) in the central and western United States.

In mountainous area, gauge catch is strongly affected by local and micro-scale wind effects (*Rodda*, 1967). Two different type of errors have studied by *Reid* (1973) and *Hovkind* (1965) . Former used two grids, each of six gauges, across the 12-15 °slopes in the windward and later in the lee side. *Sevruk* (1972a) used an evaporation suppresant such as a film of 5 mm thick of glycol for his study. *Alter* (1937) invented an altering type shield for the gauge which was not found much use. Further research on this subject have been done by *Rechard* (1972). Studies in Switzerland has led *Fohn* to state that the only reliable approach for snowfall meassurement is to use snow boards, which are reset on the snow surface daily.

In North America, at sites below timber line, considerable use has been made of snow courses to determine net accumulation from depth-density surveys on a monthly basis (*Warnick and Penton*, 1971). In steeply slopping terrain the gauge orifice is sometimes constructed to be parallal to the ground and presumably the air flow. *Sevruk* (1972b) & *Sevruk* (1974) argues from long term experiments in Switzerland that they give more representative meassurements on steep, open slopes exposed to rain-bearing winds. However Soviet research shows that in moderately sheltered locations the catch of the snow exceeds that in open terrain by considerable amounts particularly at moderate wind speed (*Struzer et al.*, 1965). Comparison of winter precipitation and water equvalent of the snow pack of four to six seasons at 30 sites above 2400 m in Utah by *Brown and Peck* (1962).

An expression for sheltering of individual gauge sites has been developed by *Catterall* (1972). In view of the many problems facing by the gauge catch in mountainous terrain the use of radar in the precipitation meassurements have been used by *Harrold* (1966). *Andrel et al.* (1976) found that the results were good for two small basins near Hohenpeissenberg in Bavaria. *Collier and Larke* (1978) showed that even for snowfall the accuracy similar to that for aerial rainfall is feasible. A more practical approach in remote mountains is to estimate a hydrological budget for entire drainage basins (*Flohn*, 1970). Also in mapping mountain precipitation, estimates of seasonal altitude relationships using data from storage gauges or snow courses can usefully suppliment the regular gauge network (*Peck and Brown*, 1962).

Some of the latest modelling studies reveals the mechanism of up valley winds in mountain terrain (*Rampanelli*, 2004). A three-dimensional topography is used in this study and is composed of 2 two-dimensional topographies: one a slope connecting a plain with a palteau and other a valley with a horizontal floor. The three-dimensional structure of lee waves is investigated using a combination of linear analysis and numerical simulation (*Sharman and Wurtele*, 2004). They considered the flow over mountain is actually a superposition of three-dimensional lee wave structures produced by each obstacle, the actual lee wave structure depending on the particular individual obstacle geometry and the nature of the local upstream flow.

Teixeira and Miranda (2004) developed an analytical model to predict the surface drag exerted by internal gravity waves on an isolated assymetric mountain over which there is a stratified flow with a velocity profile that varies relatively slowly with height. Later this model is modified by *Teixeira et al.* (2004) to calculate the gravity wave drag exerted by a strtified flow over a 2-D mountain ridge. Impact of the mountain torque has been studied by *Lott et al.* (2004a). Spectral analysis of the atmospheric angular momentum budget shows that the dominent variations of mountain torque have periodicities near 30 days and shorter while the dominent variations occur in the 40-60 day band. In the 20-30 day band, relationships are found between the Rockies torque and the dominent patterns of Low freeqency variability over the Pacific (*Lott et al.*, 2004b). These results are consistent with the Himalayas.

1.3.2 Orographic Studies in India

The Indian mountains are first covered by the survey parties and they collected mountain weather data systematically for their studies such as those in Himalayas (*Hill*, 1881). The development of meteorological observations in the Nilgiri area generally corresponds to that of India as a whole. According to *Eliot* and *Roy* (1954) three phases may be distinguished. First one is the Period of isolated local observations (before 1865), the second one is the period of provincial systems of meteorological observations (1865-1875) and the third one is the period of the India meteorological department (after 1875). There was no organized meteorological service before 1865. Some of the english people who came here for trading and agriculture activity in tea had made some studies about the Nilgiri's during that period. From the scientific point of view many observations during this period lacked the precision of documentation and instrumental standards required in modern climatological research; there was only one notable exception: the Dodabeta observatory.

In the beginning, observations on Dodabetta were made twice daily (09.40 and 15.40 IST) with hourly observations on one day of each month from September 1849. But from December 1855 hourly observations were recorded on three days of each month. Under the impression of two extremely destructive cyclonic storms that struck the coastal areas adjacent to the head of the Bay of Bengal in October and November 1864, an organizational setup for meteorological observation services for a cyclone warning system started by India Meteorological Department. As a result, various provincial meteorological organizations were formed, that of Madras commencing in 1866 (*Roy*, 1954). Regular collection of rainfall data from stations such as Calicut, Palghat, Coimbatore and Ootacamund started and later two meteorological observatories were established at Wellington cantonment and Coimbatore. Later officially India Meteorological Department started functioning on September 27, 1875 and published the monthly and annual normals of rainfall and rainy days for rain-gauges in different states (*Department*, 1962).

The orographic studies conducted in India is very limited. *Rai* (1958) made a note on the excessive rainfall of Cherrapunji. He calculated the rate of rainfall production by assuming that the ascent of the surface air upto 5000 feet. Comparing with the actual rainfall, he concluded that some extra rain falls owing to instability. *Banerji* (1930) conducted a study about the effects of Indian mountain ranges on the air motion during the monsoon periods. He regarded the monsoon trough as a dynamical development rather than thermodynamical. Extensive studies have been done about the circulation existing over the Himalayan region during these periods. *Rai* (1958) suggested that when the wind speed in the lowest 2 or 3 km decreased with height, air flowing across Western ghats would be subject to considerable turbulence, as distinguished from lee waves, and this would be more favourable for rainfall at Poona.

The profiles of normal rainfall at stations along West coast is given by *Ramakrishnan and Rao* (1958). They show a maximum at 14°N and a secondary maximum at 18°N. *George* (1962) finds the average rainfall in one degree squares in the coastal belt has a maximum in all months between 13°N and 14°N. The secondary peak at 18°N reported by Ramakrishnan and Gopinath is due to the inclusion of Dapoli which has been omitted by George, as it is not very close to coast. *Raghavan* (1964) found the relationship between coastal rainfall and distance of 150 m contour from the place giving a correlation of 0.6. He made an extensive study on the influence of Western Ghats on the coastal monsoon rainfall of the Peninsular India. He concluded that variations of rainfall are intimately related to variations of the gradient of up-slope practically all along the coast. He found that there is a strong tendency for the rainfall to be relatively high or low over the same area in each month. Such a recurring feature of rainfall is characteristics of orographic influence.

An integrated study of the Western Ghats mountain by numerical models have been done by *Sarker* (1966) & *Sarker* (1967). He investigated theoretically mountain waves over Western ghats with the help of a two dimensional model with a smooth profile of orography starting from sea level about 60 km ahead of the crest height of the mountain peak which was at about 1 km above MSL. The modelling results correctly positions the maximum fall near the crest line on days of strong monsoon flow, and on average the model accounts for about 65 percent of the coastal precipitation. It also suggest that 'spill over' on the leeward slope, due to the winds, extends 10-15 km beyond the crest. *George* (1962) extended the analytical work of Sarker by introducing friction in the analytical treatment of monsoon flow across the Western Ghats.

Gadgil and Sikka & *Gadgil* (1977) have attempted to simulate analytically the flow pattern on the lee side of the Ghats. They used quasi-geostropic model with f-plane and β-plane approximations. The weather and climate of Nilgiri hills have studied in detail by *Lengerke*. In this work he made extensive collection of the observed surface meteorological data from various government agencies and done an elaborative study on the basis of these observational data. In the monsoon monograph prepared by *Rao*, the orographic effect on the Indian region has described very well. He analyzed the rainfall pattern of the mountain region spatially and made a review of the whole work in this regard.

The wind structure of the Palghat gap is studied in an expedition during 1966. Some of the results of these expeditions are given by *Ramachandran et al.* (1980). The distribution of the rainfall of summer monsoon near the mountain region of Maharashtra state has been analyzed by *Patwardhan and Asnani* (2000). He took two cases of strong and weak monsoon conditions. He found that in the region rainfall increases rapidly from the Arabian sea coast close to the line of maximum height of the Western ghats. Also there are two rainfall maxima corresponding to the two mountain peaks parallel to the coastal line. In the valley, rainfall increases from the coast upto the line of maximum height of the Ghats, and then decreases eastwards towards the plateau.

1.4 Western Ghats and its Geographical Specialties

Western ghats is a range of mountains about 1000 miles (1600 km) in length, forming the western boundary of the Deccan and the watershed between the rivers of peninsular India (fig.1.2). The range stretches from the Tapty valley of Maharashtra in the north to Cape

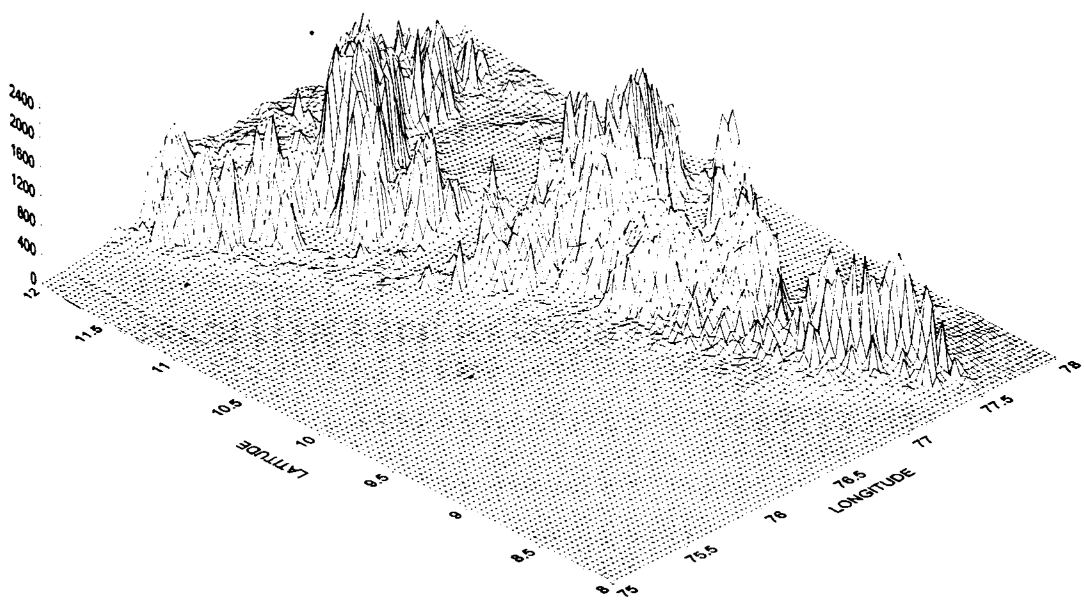


Figure 1.2: 3-dimensional view of Western Ghats orography across the southern peninsular India (source: ETOPO 30 sec. data)

Comorin of the Tamilnadu at the south. The sanskrit name is Sahyadri. The mountain runs southward with an average elevation which seldom exceed 4000 feet (1330 m) , in a line roughly parallel with the coast, from which its distance varies from 20 to 65 miles (30 to 110 km). In the old Madras presidency, the Western ghats continue in the same general direction, running south-wards at a distance of from 50 to 100 miles (80 to 160 km) from the sea until they terminate at Cape Comorin.

Soon after emerging from the Coorg they are joined by the range of Eastern ghats, which sweeps down from the other side of the peninsula and at the point of junction they rise up into the high plateau of the Nilgiri, on which stand the hill station Ootacamund (7000 feet or 2120 m) and whose loftiest peaks are Dodabetta (8760 feet or 2654 m) and Makruti (over 8000 feet or 2425 m). Immediately south of this plateau the range, which now runs between the districts of Malabar and Coimbatore, is interrupted by the remarkable Palghat gap, the only break in the whole of its length. This is about 16 miles wide and is scarcely more than 1000 feet (300m) above the level of sea. South of this gap the ghats rise abruptly again to even more than their former height.

At this point they are known as Anamalai and the mountain ranges here throw off to the west and the east are called respectively the Nelliampathi and Palani hills. North of the Nilgiri plateau the eastern flank of the range merges some what gradually into the high plateau of Mysore, but its western slopes rise suddenly and boldly from the low coast. South of the Palghat gap both the eastern and western slopes are steep and rugged. In elevation it varies from 3000 to 8000 feet (900 to 2424 m) above the sea and the Anamudi peak (8837 feet or 2677 m) in Kerala is the highest point in the range and in southern India. Thus the northern part of the Western ghats having a narrow space of low land bordering the sea below (from 20 to 50 miles wide) known as Konkan coast and the southern coast as the low-lying plains of Malabar coast. The south-eastern part comprises of the rain-shadow region of Tamilnadu and the northeastern section is the high land merging with the Eastern ghats and it is the southern tip of the Deccan plateau extending from 12°to 21°north latitude rising about 600 m mean elevation above msl (*Gunnell and Radhakrishna*).

1.5 Data and Methodology

Data used for the study

The NCEP - NCAR reanalysis data (NNRP-global) compatible for MM5 is used for running the model. This data set is available from 1984 to 2000 for the months May to October. The resolution of the data set is 2.5°X 2.5°with 17 levels from surface to 100 hPa with an interval of 6 hours everyday. The sea surface temperature data used for the boundary condition in the model is also from NNRP for the above mentioned 17 years. Final Analysis data (FNL) of NNRP with a resolution of 1°X 1°is also used for the model run for the month January to April and November to December. The climatological mean of surface meteorological parameters from 1931-1960 published by India Meteorological Department has been used to check the ground truth of the modelled data.

Model Description

The model used for the study is the fifth generation NCAR/Penn state university mesoscale model MM5. A schematic diagram (fig.1.3) is provided showing a flow chart of the complete modelling system. It uses the non hydrostatic dynamics with multiple nesting and four dimensional data assimilation facilities. Terrestrial and isobaric meteorological data are horizontally interpolated from a latitude-longitude mesh to a variable high resolution domain on a Mercator projection. Then the pressure coordinates are converted into sigma coordinate system. The model output data are then converted into GrADS format and plotted.

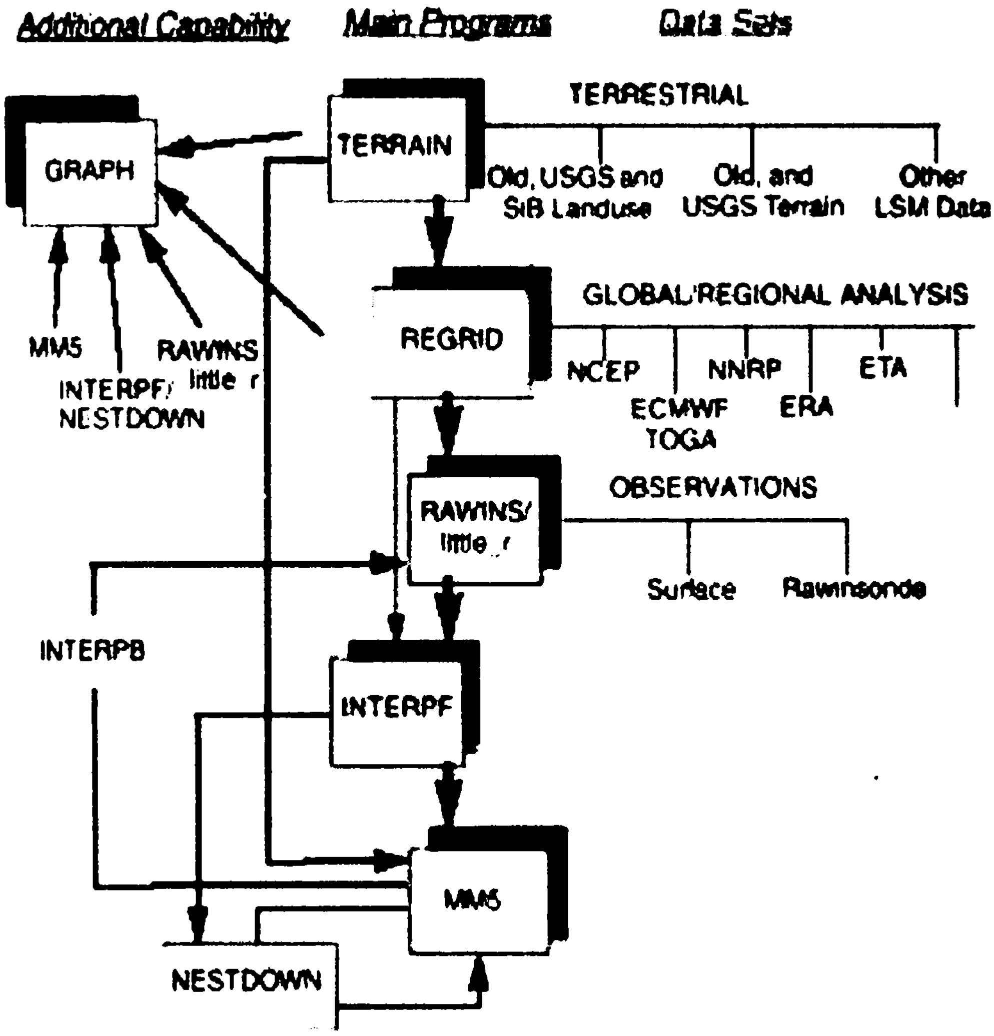


Figure 1.3: The MM5 modeling system flow chart

MM5 contains a capability of multiple nesting with upto nine domains running at the same time and completely interacting. The nesting ratio is always 3:1 for two way interaction. To run any NWP model requires lateral boundary conditions. In MM5 all four boundaries have specified horizontal winds, temperature, pressure and moisture fields and can have specified micro-physical fields. The boundary values come from analysis at the future times or a previous coarser-mesh simulation or from another model's forecast. The model generated boundary conditions can have a frequency of 6 hourly or even 1 hourly. Model uses these discrete time analysis by linearly interpolating them in time to the model time.

Historically the Penn state/NCAR mesoscale model has been hydrostatic because typical horizontal grid sizes in mesoscale models are comparable with or greater than the vertical depth of features of interest. However when the scale of resolved features in the model have aspect ratios nearer unity, or when the horizontal scale becomes shorter than the vertical scale, non-hydrostatic dynamics should not be neglected. The only additional term in non-hydrostatic dynamics is vertical acceleration that contributes to the vertical pressure gradient so that hydrostatic balance is no longer exact. Pressure perturbations from a reference state together with vertical momentum become extra three dimensional predicted variables that have to be initialized. The model has the option of three sets of land-use categorizations that are assigned along with elevation in the TERRAIN program from the archived data. These have 13, 16, or 24 categories (type of vegetation,desert,urban,water,ice,etc.). Each grid cell of the model is assigned one of the categories, and this determines surface properties such as albedo, roughness length, long-wave emissivity, heat capacity and moisture availability.

For the present study we have used two set of domains. One domain with 90-30-10 km (fig.1.4) resolution for normal and no-orographic runs and 45-15-5 km for a run

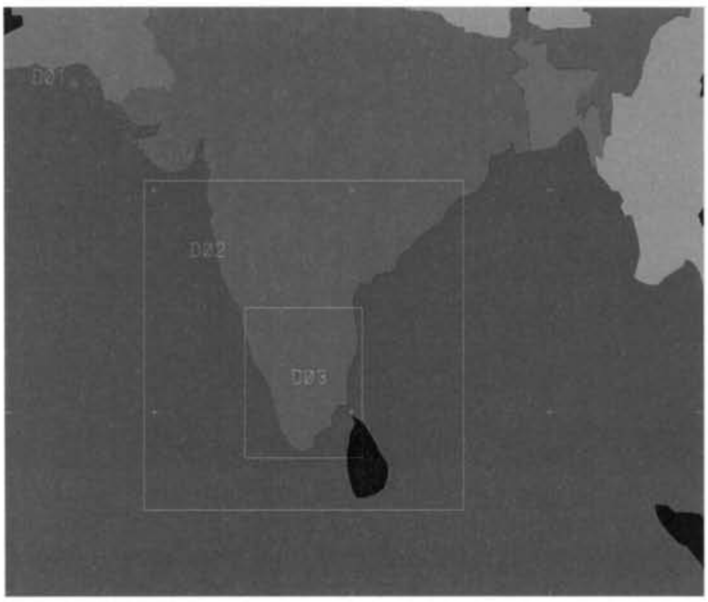


Figure 1.4: Model domain used for normal & no-orographic runs (resolution:90-30-10 Km)

with filled Palghat gap (fig.1.5). The model specifications used for the study are given in Table(1.3).

Methodology

The model has given a run for 48 hours in starting date of every month in a year. This has been repeated for seventeen years of data for the southwest monsoon season and these outputs are averaged to make the climatological mean. The other seasons, the number of years varies according to the availability of the data and then average is found out. The same way the the data has been made by removing the Western ghats orography and filling the Palghat gap. The filling of the Palghat gap has been done with an inner domain resolution of 5 km. The study area has been divided into 5 major cross sections (sections A to E) along

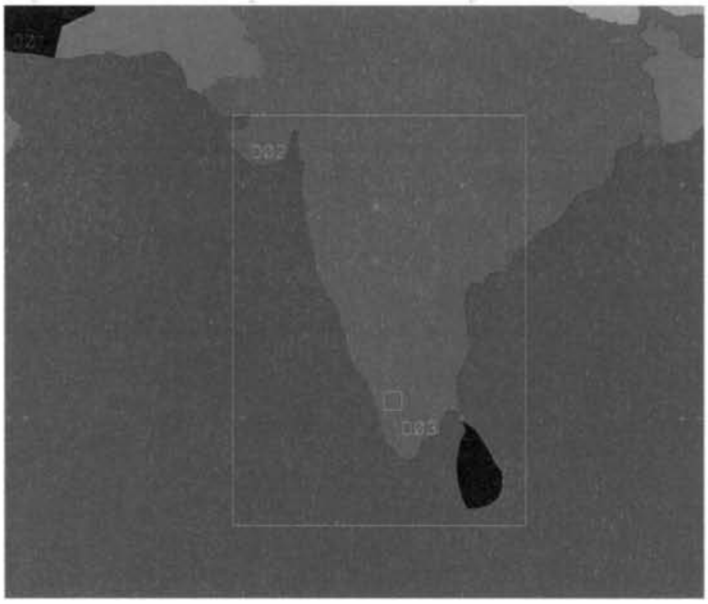


Figure 1.5: Model domain used for filled orographic runs (resolution:45-15-5 Km)

the latitudes and identifying 15 (A1 to E3) individual stations in the study area which will represents summit stations and plain stations both sides of the Western ghats in Kerala and Tamilnadu (fig.1.6).

First cross section 'A' passes through a small pass in the southern region that is Aryankavu pass. The other two cross sections 'B & E' passes through Anamalai and Nilgiri hills and the section 'C' passes through Palghat gap. The final section E cross through the extreme north end of the study area which is touching the southern tip of Deccan plateau.

Major seasons of the peninsular India has been classified as Summer, Autumn, Winter, Spring according to the classical theory of climatology and the representative months are taken as *June,July,August,September* for Summer, *October and November* for Autumn, *December, January, February* as Winter and *March, April, May* as Spring season. Most

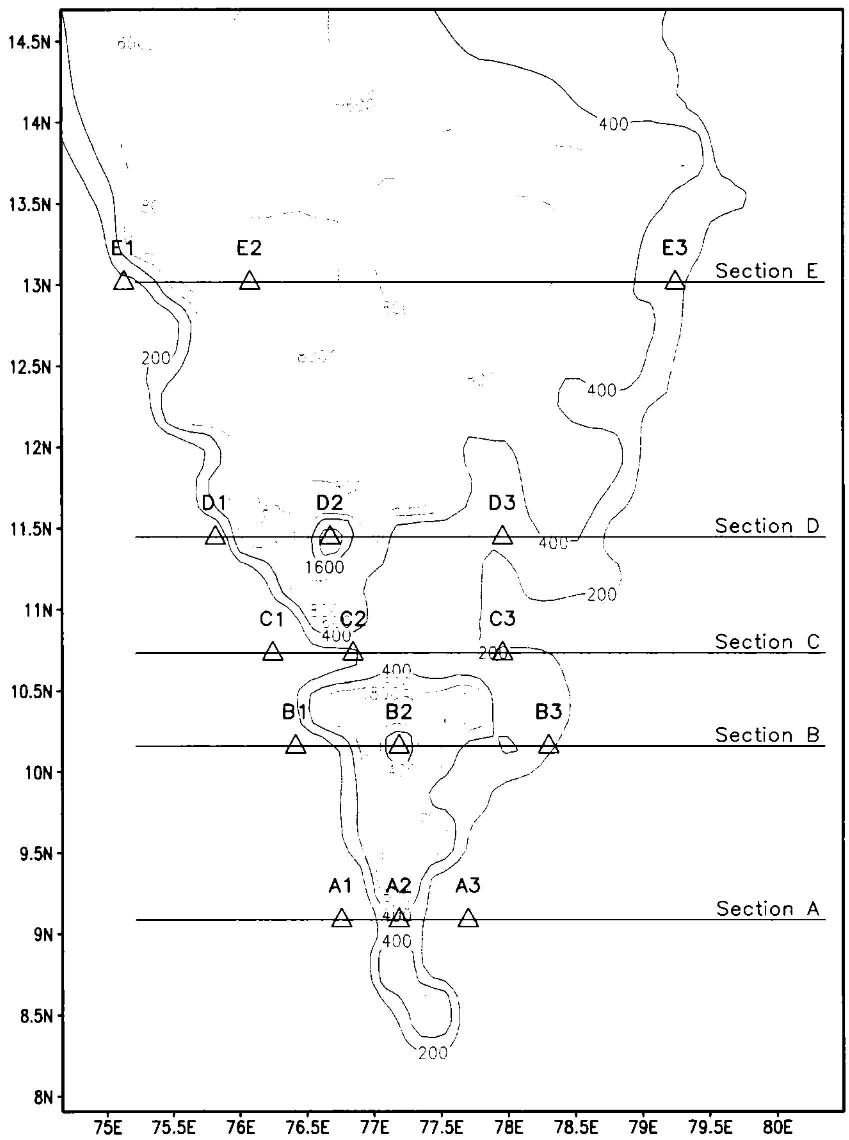


Figure 1.6: Location of fifteen stations and cross sections taken for analysis in the study area

PARAMETERS	SPECIFICATIONS
Domains used	90-30-10 and 45-15-5 Km
Input terrain data	USGS (10 min.)
Smoothing technique for terrain	Two pass smoother/de-smoother
Input meteorological data and SST	NCEP data compatible for MM5 (NNRP) & FNL data of NCEP
Resolution of Met.data	2.5°× 2.5°for NNRP and 1°for FNL
Processing interval of Met.data	6 hours
No. of sigma levels	24
Explicit moisture scheme	simple ice
Cumulus scheme	Betts-Miller
PBL scheme	Eta
Radiation	Cloud
ISOIL	1
ISHALLOW	0
Forecast length	48 hours
Frequency of output	3 hours
No of levels used in grads	20

Table 1.3: Model specifications used for the runs

of the figures have been plotted by taking a representative month from these season. Thus January has taken for winter, April for spring, July for summer and October for autumn season in most of the cases. Variations of some parameters have analyzed on a monthly basis where ever it is necessary. The climatological mean of actual observations of some selected stations of Kerala and Tamilnadu has taken from the data published by India Meteorological Department. Ground truth of the modeled values of temperature, pressure, wind and relative humidity on the basis of this data set has been checked and the model error is calculated from it.

CHAPTER 2

Geographical Control of Mountain Meteorological Elements in Western Ghats

2.1 Introduction

The Western Ghats mountain ranges extends from 8°N to 20°N and the present study limits the domain to 8°N to 13°N which is called the southern peninsular India. The mountain ranges is having a mean height of about 1 km in this region and positioned in the south-southeast to north-northwest direction. The southern stretch is called the Cardamom hills which is having a pass near Aryankavu called Aryankavu pass. The Anamudi (2677 m) and the Nilgiri (2654 m) peaks are the two highest peaks in the entire Western Ghats and a major Gap at Palghat cuts these two peaks and regulates the weather and climate of this region. The northern part of the study region is merging with the southern tip of the Deccan plateau which is about 600-1000 m above mean sea level and also to the Eastern Ghats. The study area is surrounded by the sea so that the presence of maritime air mass will be dominating with homogeneous characteristics over the region.

In the following sections the analysis is being carried out to understand the spatial and temporal variations of the meteorological parameters horizontally and vertically. This will give an insight into the variation of basic meteorological parameters at the eastern and western side of the Western Ghats as well as the summit and valley regions. As already mentioned in the previous chapter (fig 1.6) the fifteen stations and the five cross-sections have been identified according to the importance of their geographical position and which is representing the different terrains of the study area. For the seasonal study, the representative months have been considered and the analysis have been carried out for these months. They are January representing Winter, April for Spring , July for Summer and October for Autumn. The ground truth of the modeled data has checked with the available observations of IMD stations in both eastern and western side of the Western Ghats. The analysis of the variables are done primarily in two ways, the horizontal spatial variations and the altitudinal variations which includes the diurnal pattern also.

2.2 Horizontal Spatial Variation

2.2.1 Air Temperature

The climate of a mountainous area is modified by the latitude in different ways, primarily the variation in the incoming and outgoing solar radiation and the decrease in temperature with increasing latitude. The seasonal and diurnal climatic rhythm is very much depending on the latitude and is obtained from the seasonal trend in the daily sun path at different latitudes globally. Even though the seasonal changes of solar radiation, day length and temperature are small in low latitudes, the diurnal amplitude of temperature is relatively large . In the western and eastern side of the mountain the atmospheric temperature do not vary much latitudinally in an year (fig.2.1). Isotherms are generally parallel to the mountain, more widened towards north of the study region and follows the pattern of 400 m terrain to a great extent. In Winter the eastern coast will be cooler than the western coast. At the north end, the 24°C isotherm covers the plain land in the western side of the mountain due to the proximity of the mountain ranges. The summit stations shows the lowest temperature of all season by about 16°C. During the Spring season temperature at the summit stations is rising by 2-4°C than other season.

Through the eastern coast cooling is occurring towards the north and it reaches its minimum value of 20°C at the extreme north which is the southern tip of Deccan plateau. In Spring the eastern coast and the southern end of western coast shows similar pattern but it is 2°C cooler at the north end of Kerala coast. The warming up of the land area is visible even in the summit region. The Deccan plateau will be warmer by 26°C. The Summer season in which we are getting the southwest monsoon, the entire Kerala coast will be cooler than the Tamilnadu coast and the northern end of the eastern coast near Chennai is warmer by 28°C. Summit regions show similar pattern during April. Autumn again brings cooler air in both coasts and the Deccan plateau starts cooling by this time.

2.2.2 Mean Sea Level Pressure

Mean sea level pressure (mslp) shows minimum horizontal spatial variation in all season (fig.2.2). Similar pattern are observed in all season. The maximum value of surface pressure is seen in January. Northern part of Kerala coast shows higher mean sea level pressure (1014 hPa) in Winter months while the southern part shows 1-2 hPa reduction. The pressure increases to 1015 hPa northward along the Tamilnadu coast in Winter. A uniform pressure of 1015 hPa can be seen in a wider region of northern section of the study area including the Deccan plateau. In all other season, western coast shows high mean sea level pressure (1-2

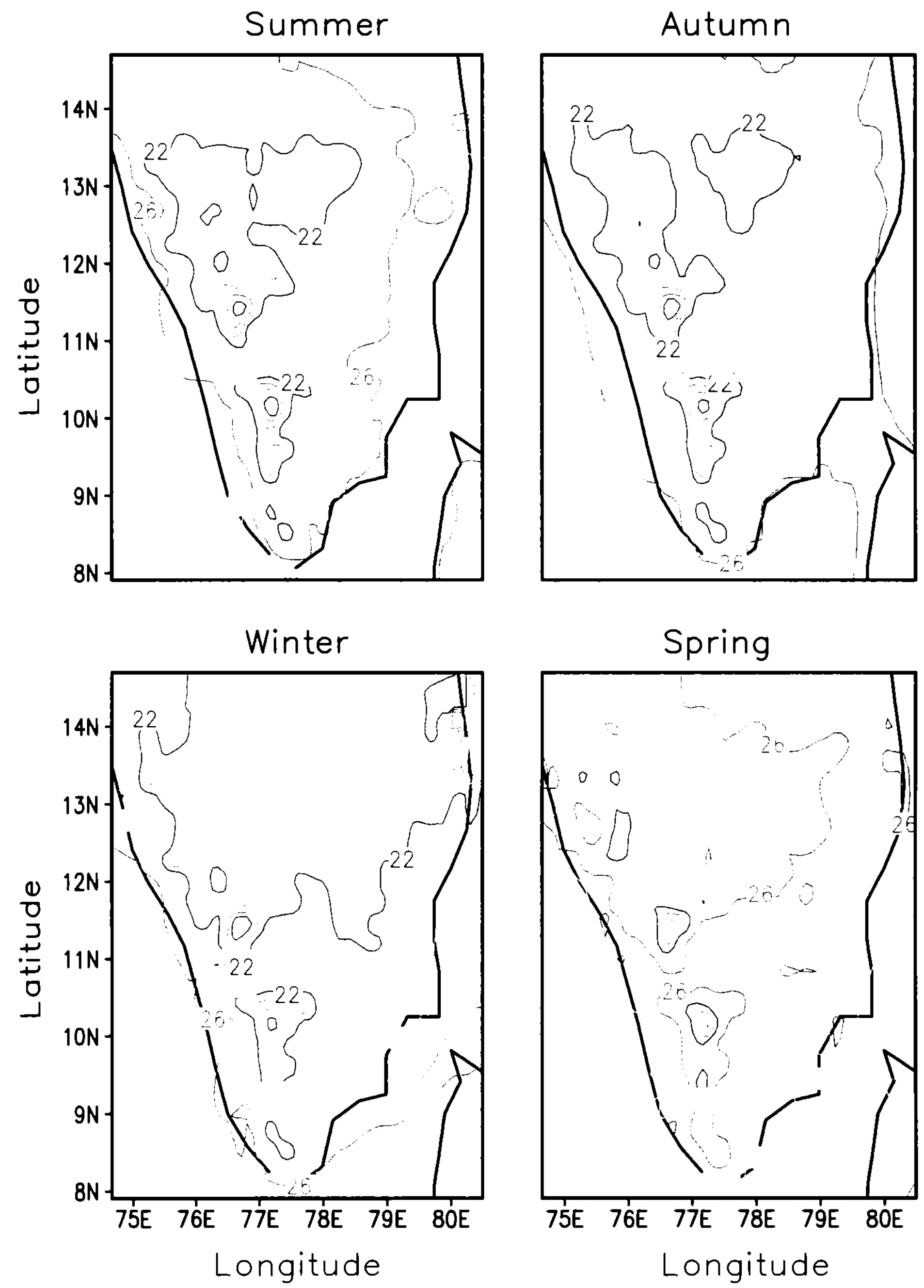


Figure 2.1: The horizontal distribution of atmospheric temperature (in °C) during different season in the study area (model output for 20.30 IST).

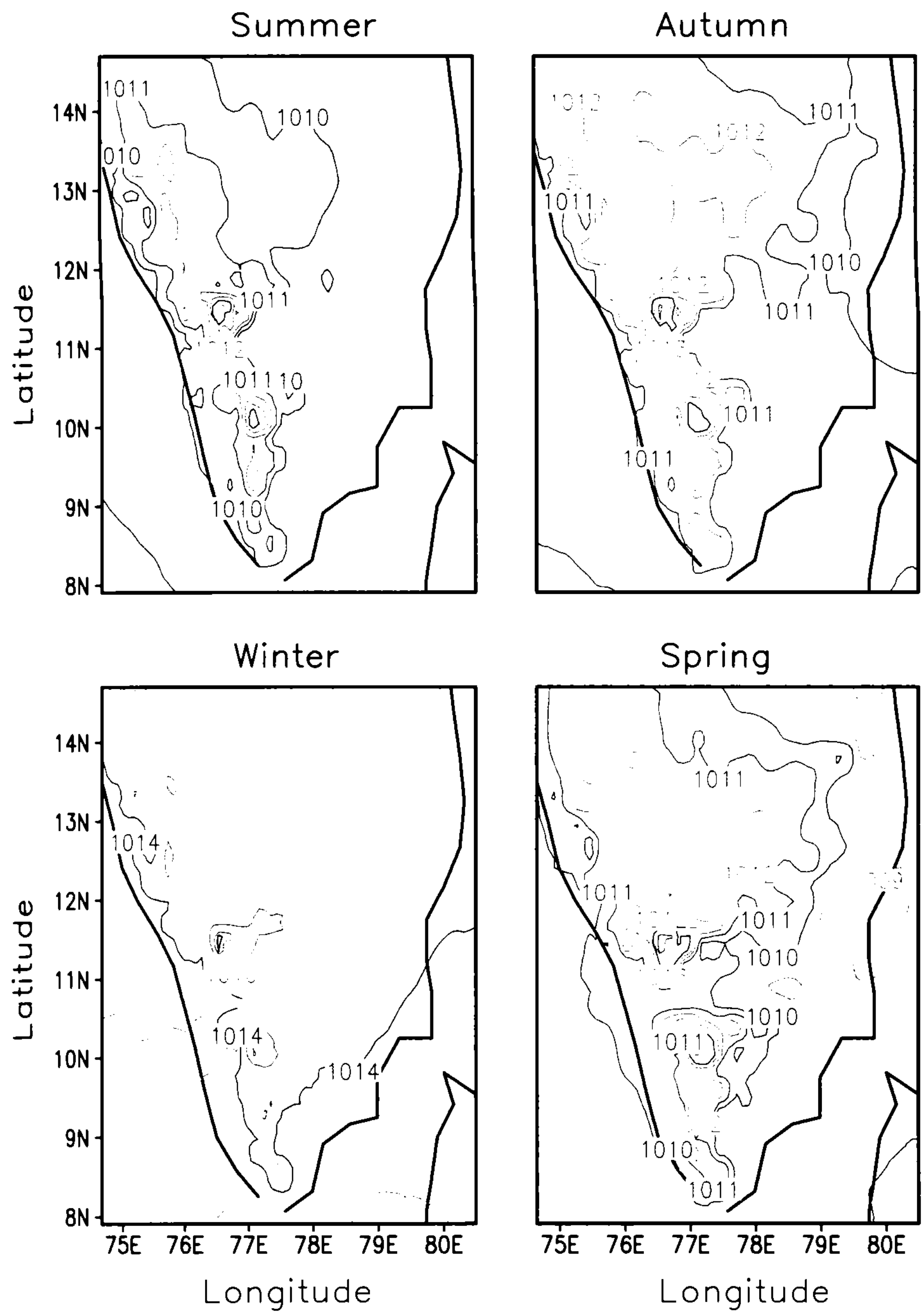


Figure 2.2: The horizontal distribution of mean sea level pressure (in hPa) during different season in the study area (model output for 20.30 IST).

hPa) than the eastern coast. The orientation of the isobars are parallel to the orography in the meridional direction. Thus, Kerala coast which is near to the mountain feels the effect of mountain more in controlling the surface pressure than the wide land area of Tamilnadu region. The maximum value of mean sea level pressure (1018 hPa) is seen in the Winter season at the summit region. The horizontal variation of surface pressure in the study area is therefore minimum in all season.

2.2.3 Wind

The wind speed at 10 m height shows abrupt changes in the horizontal direction in Winter and Spring months (see fig.2.3). The maximum wind speed in January at the eastern coast is 6 ms^{-1} and at the western coast is 2 ms^{-1}. Some pockets of the northern end of the study region (13.6°N, 76.3°E) also show an increased wind speed of the order of 7 ms^{-1}. During April the wind speed increases in the valley region of Tamilnadu, but remains shallow in the west coast of Kerala. With the onset of southwest monsoon the wind pattern become uniform in the study region with average surface wind reaching upto 4-5 ms^{-1} in Summer season. By this time, the wind speed is strengthened (9-10 ms^{-1}) over the off shore region of western coast, especially near to the central part of Kerala. During October the southern end of the eastern coast shows 4-5 ms^{-1} wind speed which is not seen over other part of the region. The analysis also shows that the horizontal variability is very less during Summer and Autumn season. The wind pattern shows more variability in the valley regions in Winter and Spring season than the Summer season.

2.2.4 Net Radiation

The latitudinal dependence of net radiation is very small in the study region (fig.2.4). The net radiation varies abruptly towards north, from 120 Wm^{-2} to 240 Wm^{-2} during the night time of the Winter season. The variability in the eastern coast is small compared to the

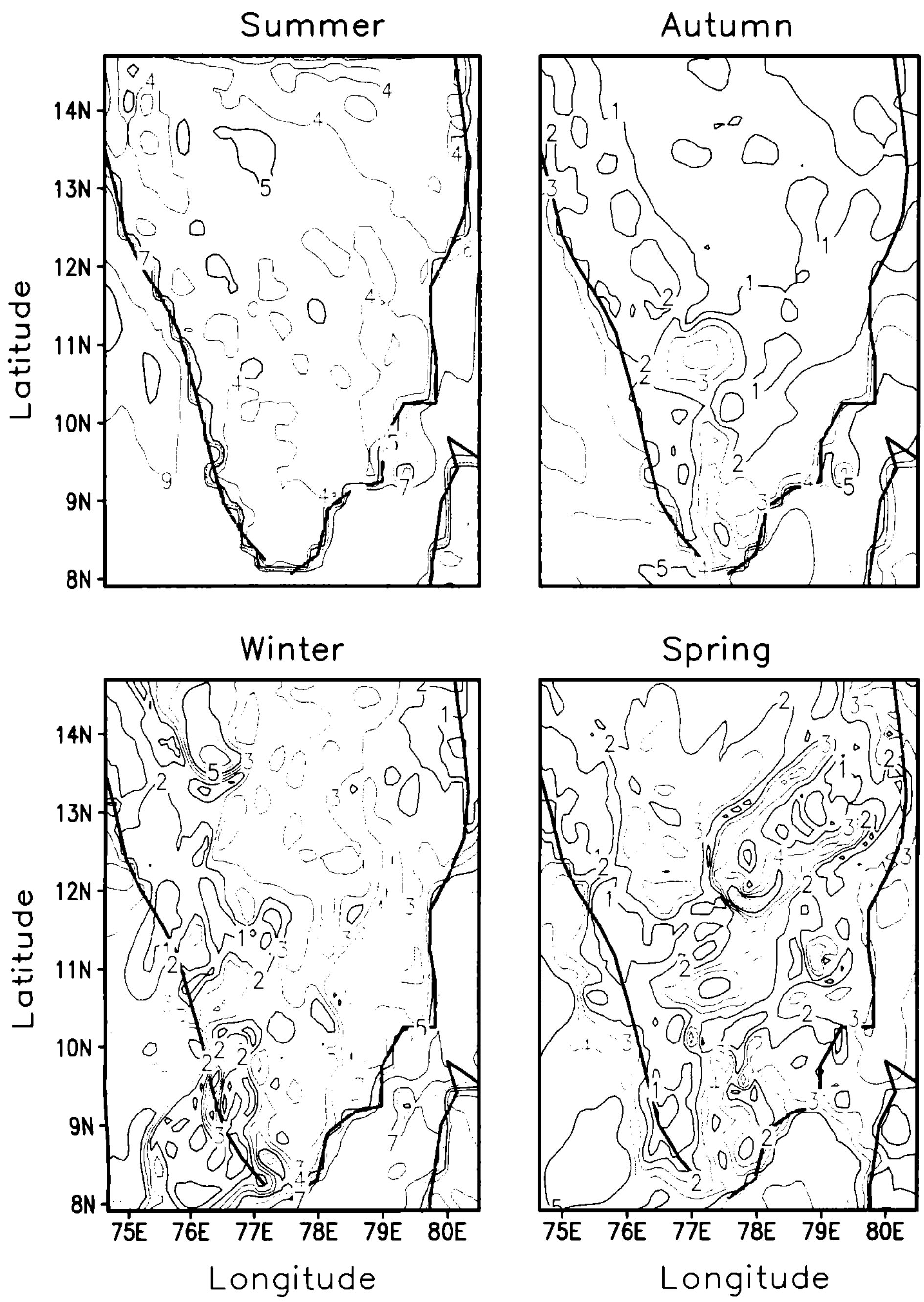


Figure 2.3: The horizontal distribution of wind speed (in ms^{-1}) at the surface during different season in the study area (model output for 20.30 IST).

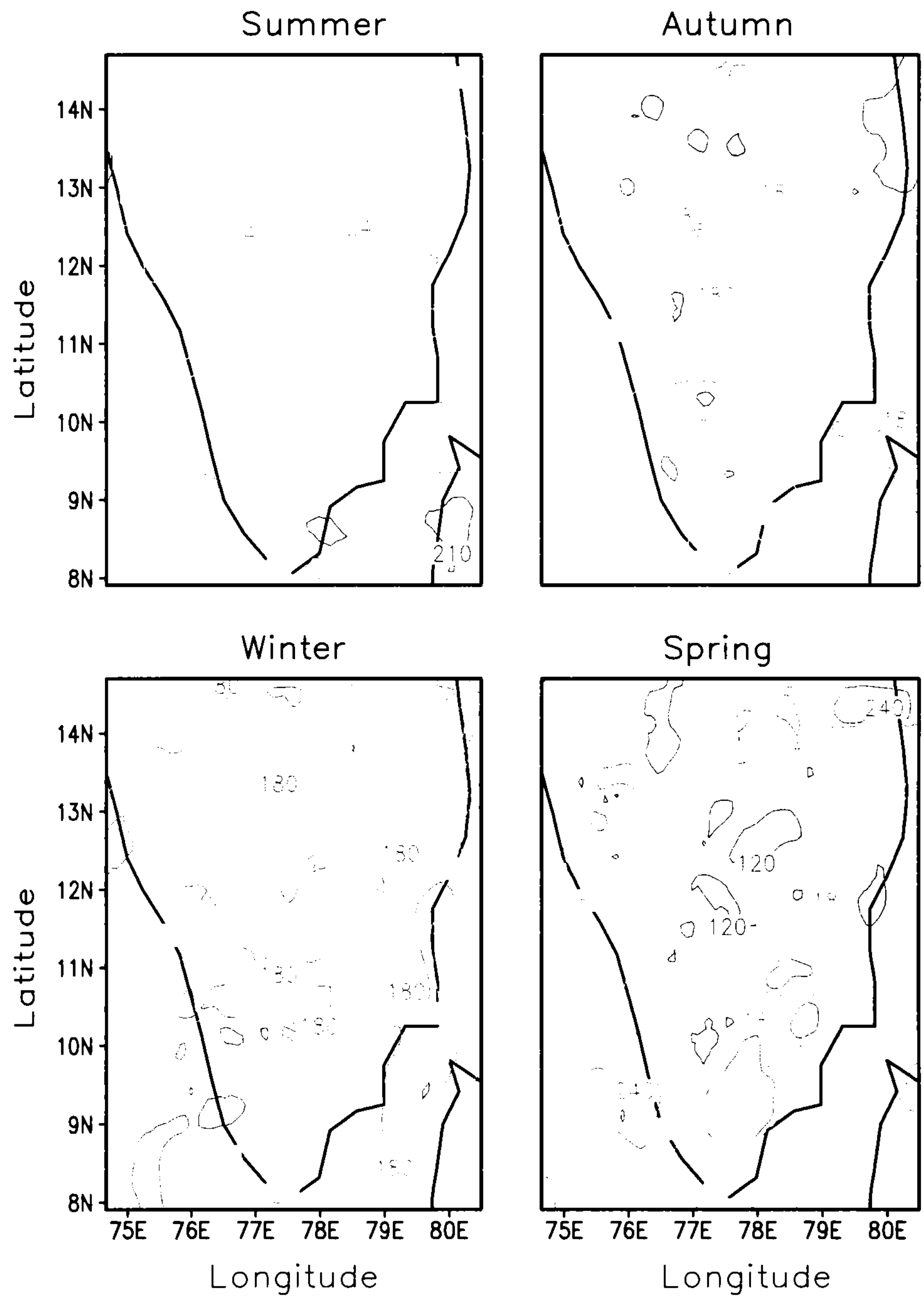


Figure 2.4: The horizontal distribution of net radiation (in Wm^{-2}) at the surface during different season in the study area (model output for 20.30 IST).

western coast over Kerala. In Spring, the trend is similar but the value of net radiation is as high as 300 Wm^{-2} in the night time at the southern tip of the peninsular India. The gradient of radiation also increases in the coastal and some pockets of valley regions. But in Summer a uniform pattern of net radiation (between 240 and 270 Wm^{-2} at night hours) is received in the wider area of the study region. The presence of increased clouding in the afternoon period during the monsoon may be responsible for this uniformity of net radiation over the study region. Only the southern tip of the Deccan plateau region shows minimum value. The pattern is more organized in Autumn and the value of the net radiation is between 180 and 210 Wm^{-2}. Thus south-west monsoon stabilizes the net radiative flux over the study region during Summer.

2.3 Altitudinal Variation

The altitude of the station drastically controls the climate of a region. The effect of altitude on climatic elements is of such primary importance that it is considered under several sub-headings. First, its general effects on the atmospheric state variables of pressure, density and vapour pressure are examined. Then, processes that determine the altitudinal variations of the radiation components, air temperature and wind velocity are dealt in detail. These parameters shows marked horizontal as well as altitudinal variations.

2.3.1 Air & Soil Temperature

The atmosphere is heated primarily through the absorption of terrestrial infra-red radiation and by turbulent heat transfer from the ground. The average lapse rate of the atmosphere (environmental lapse rate) is approximately 6.5°Ckm^{-1} in the free atmosphere. There is an upper limit to the absolute rate of temperature decrease with height, due to the hydrostatic stability of the atmosphere. When we look the seasonal variation of ground temperature (see fig. 2.1), during the Winter season both eastern and western coastal regions are warmer and the Deccan plateau is cooler compared to the surroundings. During Spring, the plateau starts slowly warming up. The cooling in the summit stations are less in the Spring and Summer season compared to that of Autumn and Winter. The temperature gradient in the valleys are also high in these two season (Winter & Autumn). During the Autumn (October) Deccan plateau starts cooling again and it persist upto the next Winter. The lapse rate shows uniform pattern irrespective of the station's geographical position (fig. 2.5). Lapse rate remains same in summit, valley or plain stations. It varies about $6°CKm^{-1}$ in all stations and the rate increases above 500 hPa level. Thus generally the temperature varies from 29°C at the surface level to -58°C to 200 hPa level in the study region.

The analysis of diurnal variation of temperature shows that maximum temperature occurs around 1430 hrs in all stations in all season (fig. 2.6). In Summer, the temperature is maximum by mid-noon itself in the western side of the mountain as well as the down wind region of the Palghat Gap at the eastern side of the Ghat. A warming of the atmosphere is clearly seen over the summit stations in the Summer season. The presence of abundant southwest monsoon clouds and the condensation processes going on at that level can be accounted for this increase in temperature in those high altitude regions. The diurnal amplitude is high along the Palghat Gap (about 5°C) and also at the stations in the eastern side of the Ghats. The diurnal amplitude in other parts of the study region is of the order of 2.5°C.

The zonal variation of temperature at 800 hPa level shows that there is not much variation ($\sim$ 1°C) between the eastern and western side (fig. 2.7). Even the mountain peak shows only a small dip in temperature than its surrounding free air (fig.2.7a). Another notable point is that the minimum temperature at the western coast is in Winter which is

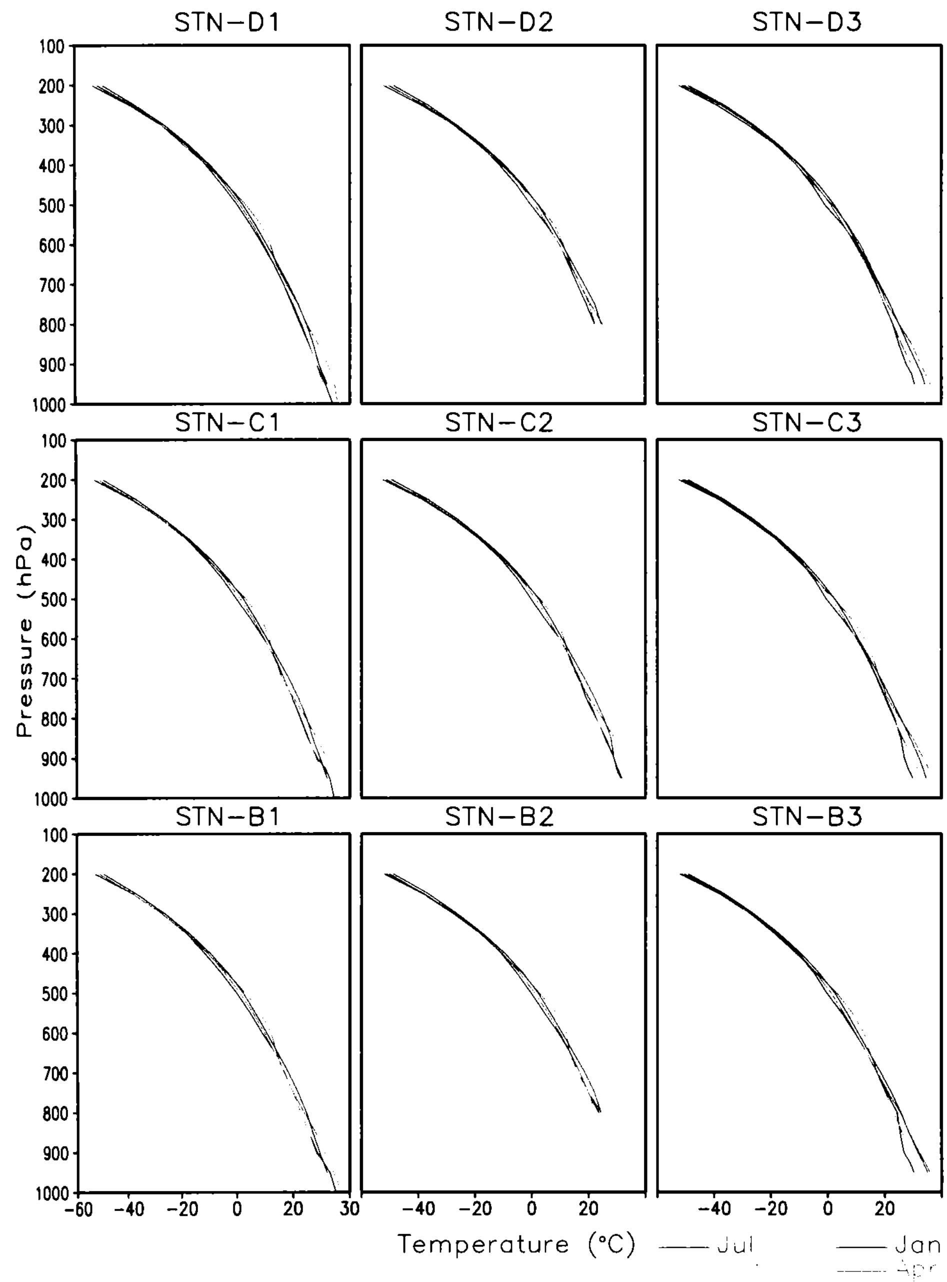


Figure 2.5: The vertical variation of temperature at different stations of southern peninsular India during various season (model output for 20.30 IST).

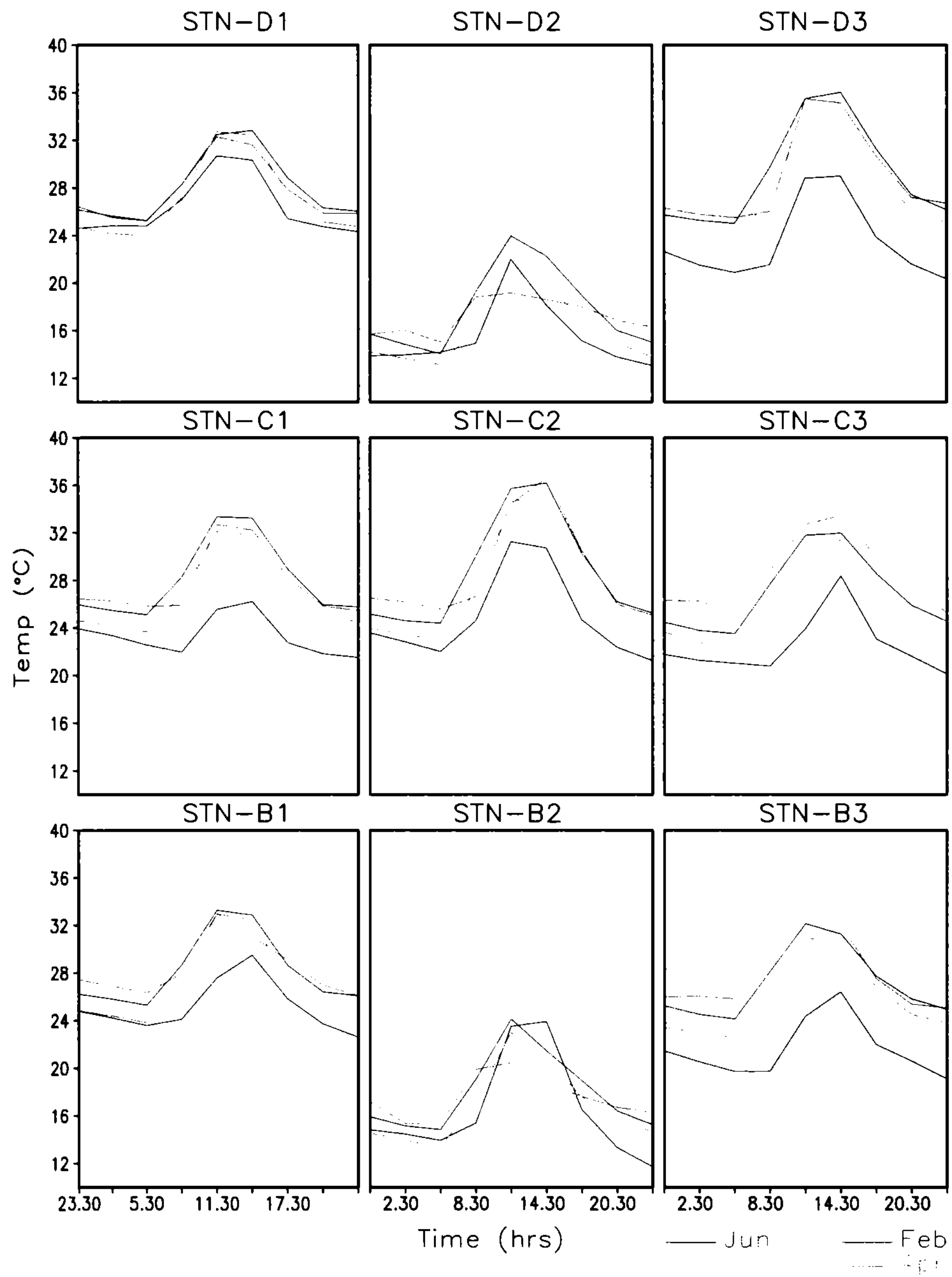


Figure 2.6: The diurnal variation of temperature at different stations of southern peninsular India during various season (model output).

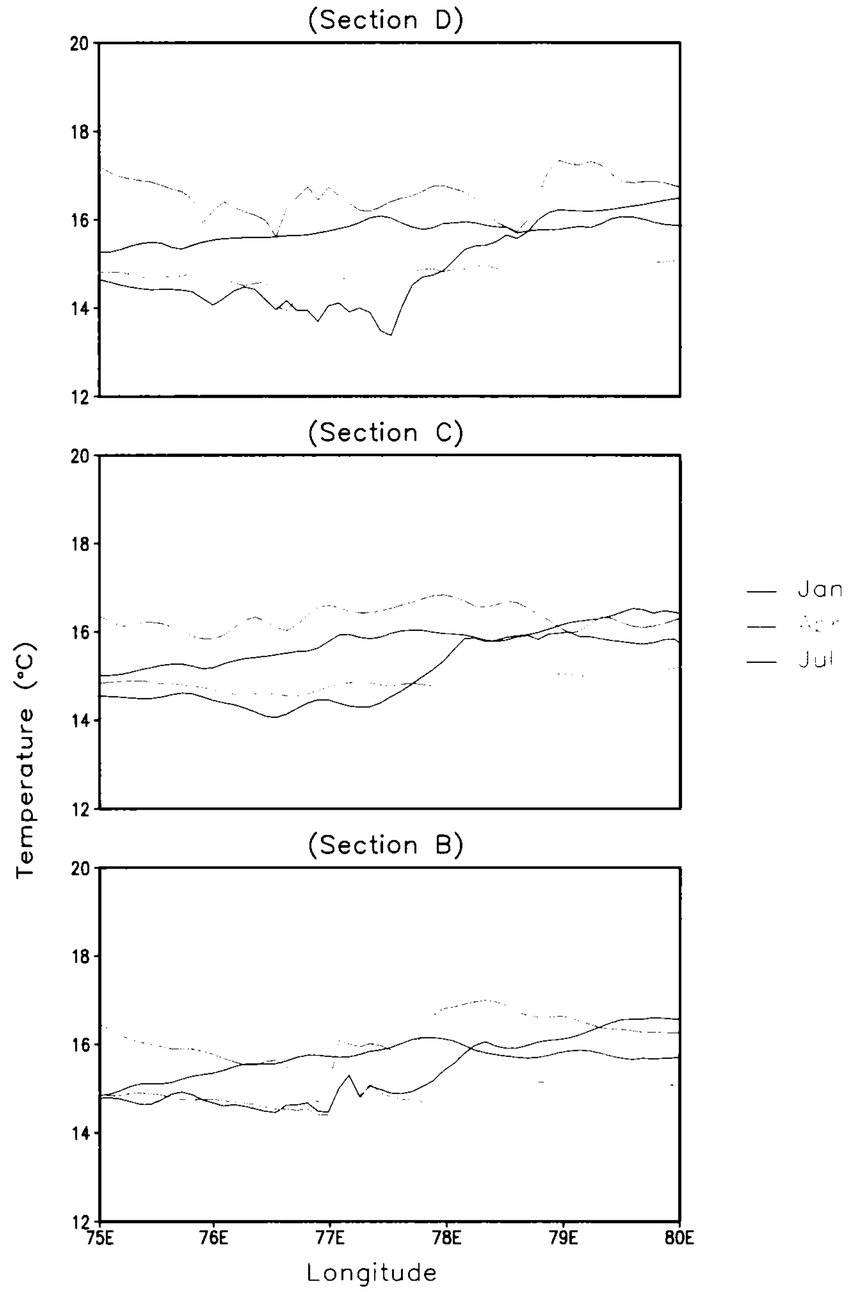


Figure 2.7: The latitudinal cross sections of air temperature for different sea
study area (model output for 20.30 IST).

2°C cooler than the eastern coast. This may be due to the modification of the dry air mass present in the eastern side of the mountain. The Winter air mass coming from the northern latitudes is modified by Bay of Bengal and its original temperature pattern is changing slowly. But in the western side of the mountain, a branch of cold continental air mass is arriving through the northwestern part of the Western Ghats. In Spring, the temperature is minimum in all latitude belt of the study area.

The effect of Western Ghats on the temperature pattern is evident in the analysis of the mean deviation of ground temperature along a latitude (fig. 2.8). The deviation is taken as the difference between the Summer and the Winter temperature from the annual mean temperature. It is seen that the temperature is modified by the orography in the eastern side of the Western Ghats drastically and the magnitude of the variation is increasing northward. Thus the temperature is increasing in Summer and decreasing in Winter drastically from the mean in the eastern side of the study region. The range of difference is -1 to 2°C in the western side of the mountain and -4 to 4°C in the eastern side. It is observed that the mountain peaks of more than 1200 m shows a marked reduction in the ground temperature unusually from the mean, both in Summer and Winter (fig.2.9). The figure shows the east west cross section of temperature at Nilgiri hills along Nilgiri peak and the temperature at the points of every 20 km distance downward on the hill in both Summer and Winter. The negative value indicates that the seasonal temperature goes below the annual mean value. The temperature over the terrain of 1200 m or above in Summer becomes negative, indicating the temperature goes down beyond the mean value. This variations is seen in the other mountain peaks also.

The annual variation of soil temperatures in different depths ie. 10, 40, 100 and 200 cm for a summit station and a plain station in Kerala and Tamilnadu are analyzed in

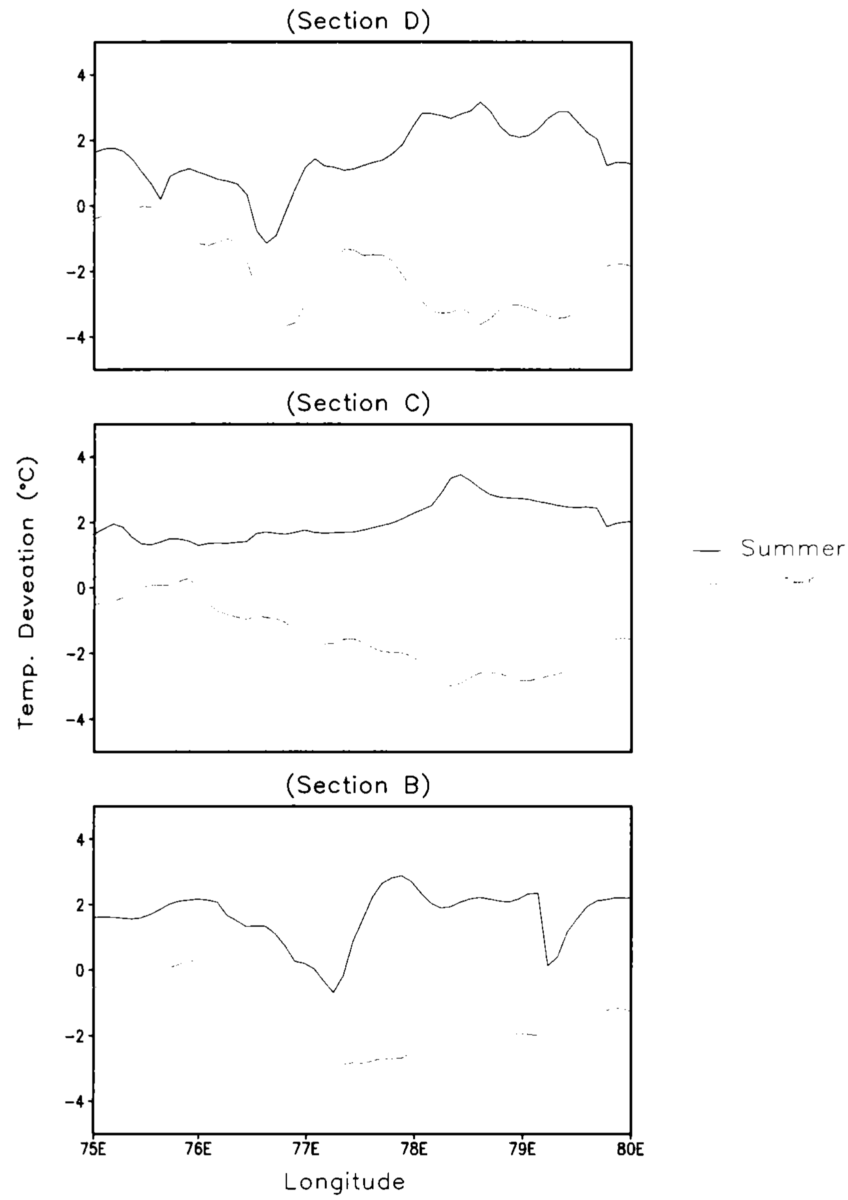


Figure 2.8: The latitudinal cross sections of mean deviation of air temperature during Summer and Winter (model output for 20.30 IST).

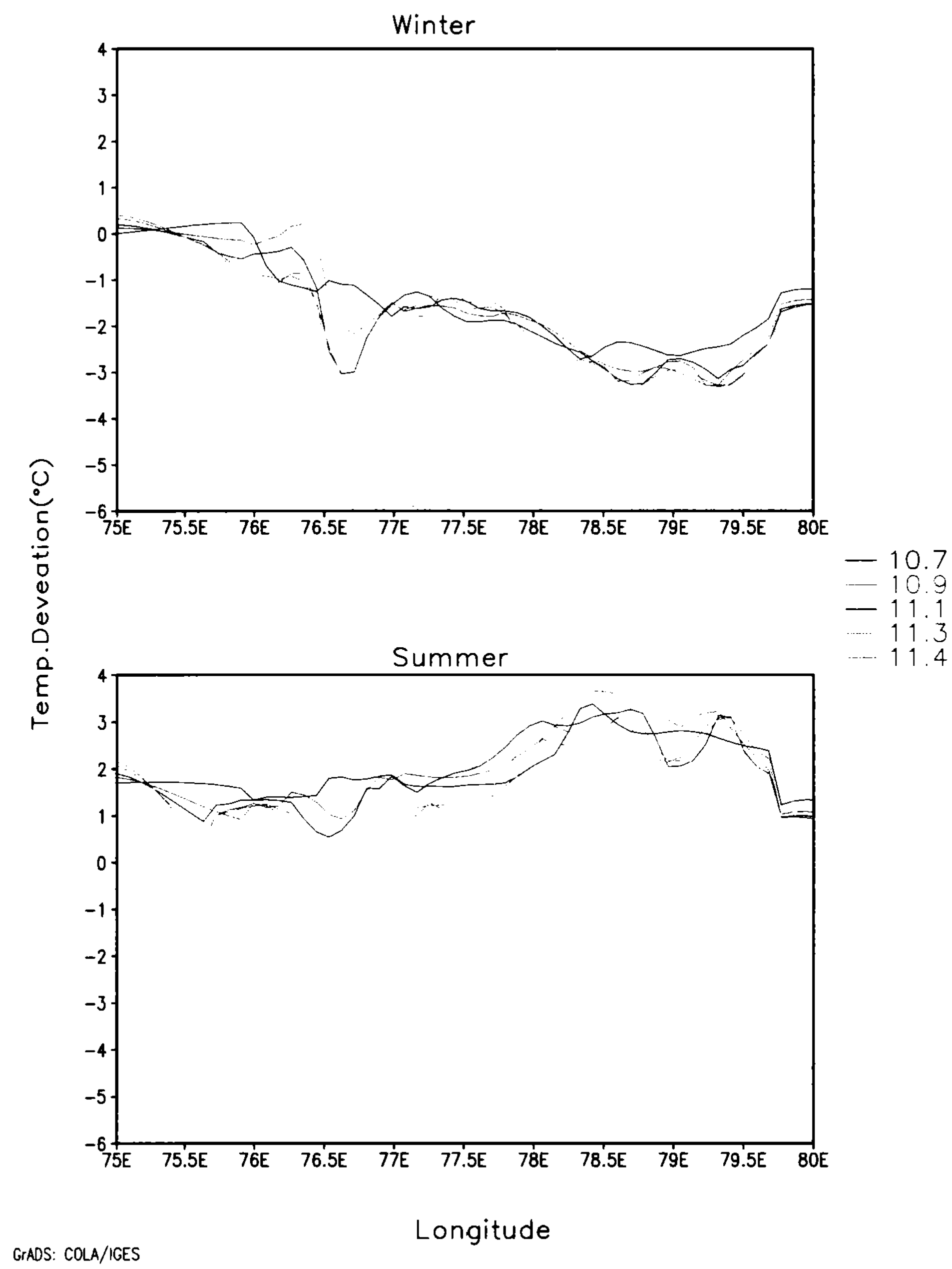


Figure 2.9: The latitudinal cross sections of mean deviation of air temperature in every 10 km of Nilgiri hills cross section (section E) for Winter and Summer season (model output for 20.30 IST)

the following section. The values have been plotted by taking the difference of soil temperature with the ground temperature at each level. So the negative value means the subsoil temperatures are lower than the ground temperatures. The analysis for Kerala is given in fig.2.10. The value of the soil temperature varies from 0 to 3°C in the entire

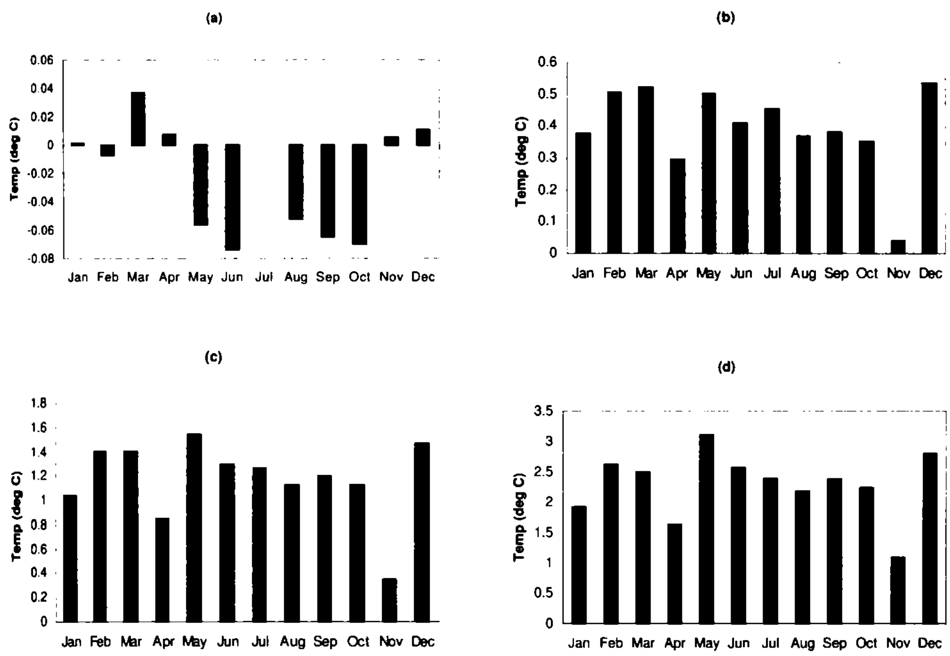


Figure 2.10: The monthly variation of soil temperature from the ground temperature in a plain station in Kerala (a) 10 cm (b) 40 cm (c) 100 cm (d) 200 cm soil temperatures (model output for 20.30 IST).

region. From May onwards the negative values prevails in the first 10 cm level. That clearly shows that in the southwest monsoon months the precipitation occurring at the surface is penetrating to the subsurface soil very quickly due to the impact of the rain spells. This is not seen in Tamilnadu even in northeast monsoon period (fig.2.11). In all other levels the minimum temperature gradient in Kerala occur during November whereas in Tamilnadu it is in January. The noteworthy point is that during the southwest monsoon period there is

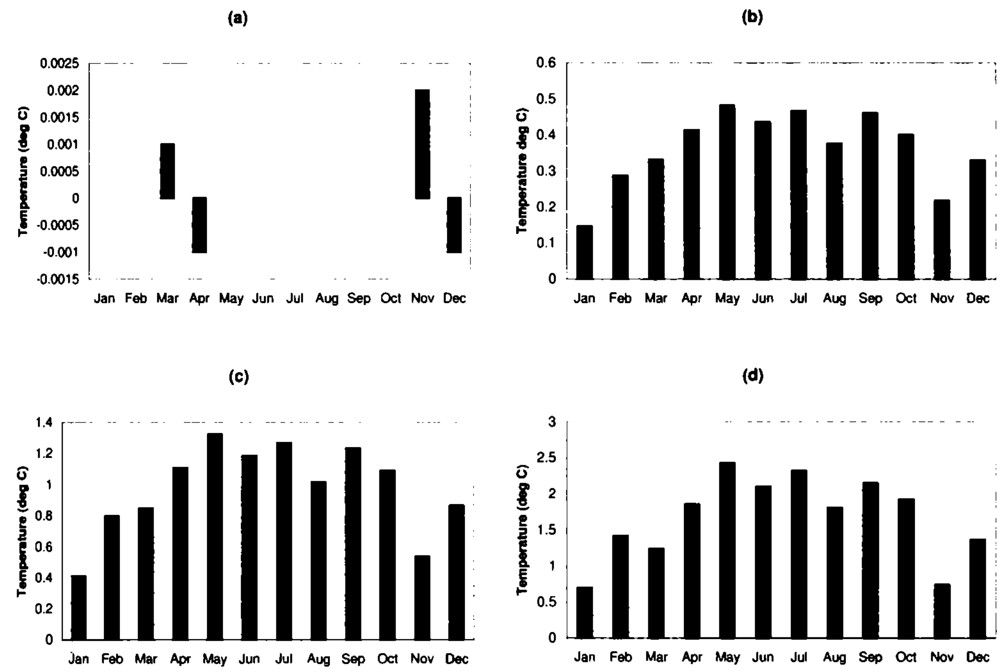


Figure 2.11: The monthly variation of soil temperature from the ground temperature in a plain station in Tamilnadu (a) 10 cm (b) 40 cm (c) 100 cm (d) 200 cm soil temperatures (model output for 20.30 IST).

no gradient existing in the top 10 cm soil in Tamilnadu station. The pattern is just opposite in these station than in Kerala. The maximum value of the soil temperature at 200 cm goes upto 2.5°C over Tamilnadu. The gradient of soil temperature is generally low in all subsurface levels in summit regions than that of the plain stations (fig.2.12). In the month

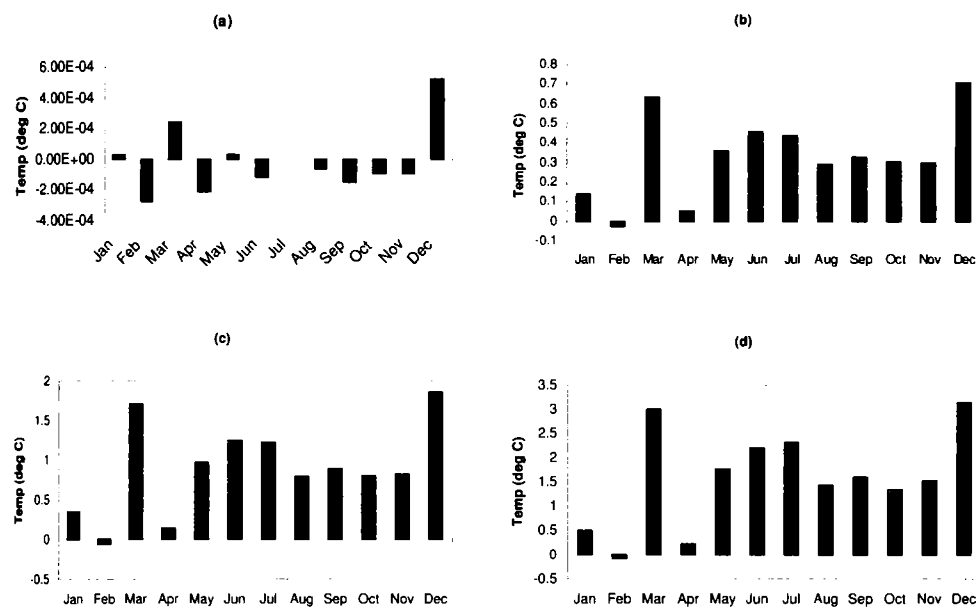


Figure 2.12: The monthly variation of soil temperature from the ground temperature in a summit station in Western Ghats.(a) 10 cm (b) 40 cm (c) 100 cm (d) 200 cm soil temperatures (model output for 20.30 IST).

of February, the soil at all levels is cooler than the ground, and April shows minimum positive gradient in all levels in summit stations.

2.3.2 Mean Sea Level Pressure

It is a well known fact that the atmospheric pressure decreases with increasing altitude. Normally to determine the altitudinal position we assume the linear vertical pressure change, but this is only an approximation partly due to the exponential character of the pressure altitude function.

A detailed analysis of the mean sea level pressure (mslp) along the horizontal direction and the diurnal change has been carried out in the following section. The analysis is being carried out along the latitude belts viz., 10.2°, 10.7°and 11.4°N (fig.2.13). The cross sections B & D is passing through the summit regions and the section C is passing through the Palghat Gap. The mountain effect on pressure is clear from the sudden rise of the mean sea level pressure contour at the longitude of the mountain. Winter gives more pressure and Summer gives minimum pressure in all stations, but the range is maximum at the eastern side of the mountain. The maximum difference of pressure between the summit and plain stations are occurring in the Spring season. The contours follow the same pattern in all the season.

It is believed that semi diurnal pressure wave can exert some influence on the weather pattern in the tropics, in particular on the cloud cover and precipitation. The analysis of station pressure for one day clearly shows the semi-diurnal wave in the pressure pattern in all the stations (fig.2.14). The maximum pressure is observed at 1130, 2330 hrs LT and minimum at 0530 and 1730 hrs LT. The afternoon oscillation is more prominent than the morning one in some stations especially at the eastern side of the Western Ghats. Palghat Gap do not show any change from the usual pattern. The mean amplitude of the diurnal wave is 1.0 hPa over the study region.

2.3.3 Wind

Contrary to atmospheric pressure, surface winds are immediate Geo-Ecological significance and, therefore, must be investigated in greater detail. Both wind velocity and direction are important climatic factors, particularly with respect to plant growth - whether

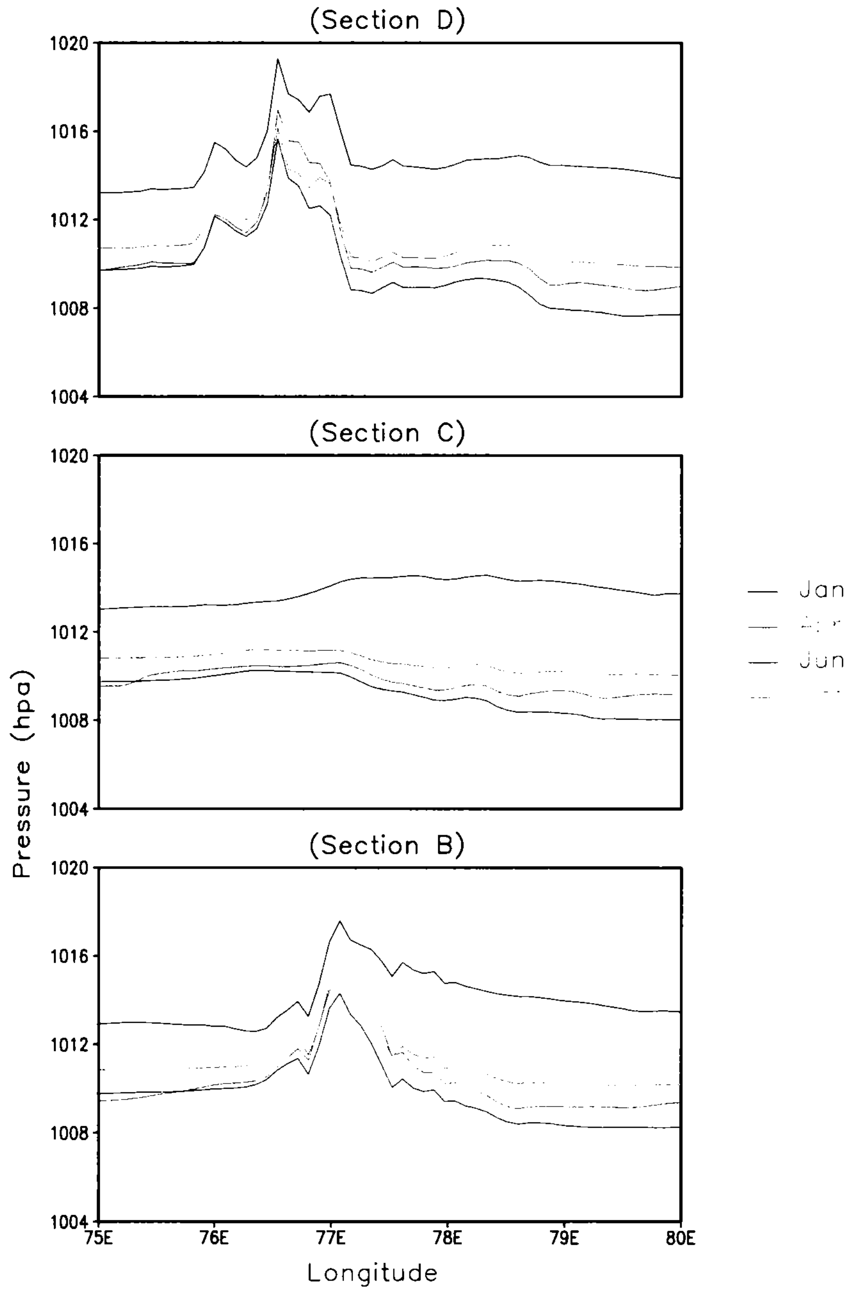


Figure 2.13: The latitudinal cross sections of mean sea level pressure for different season (model output for 20.30 IST).

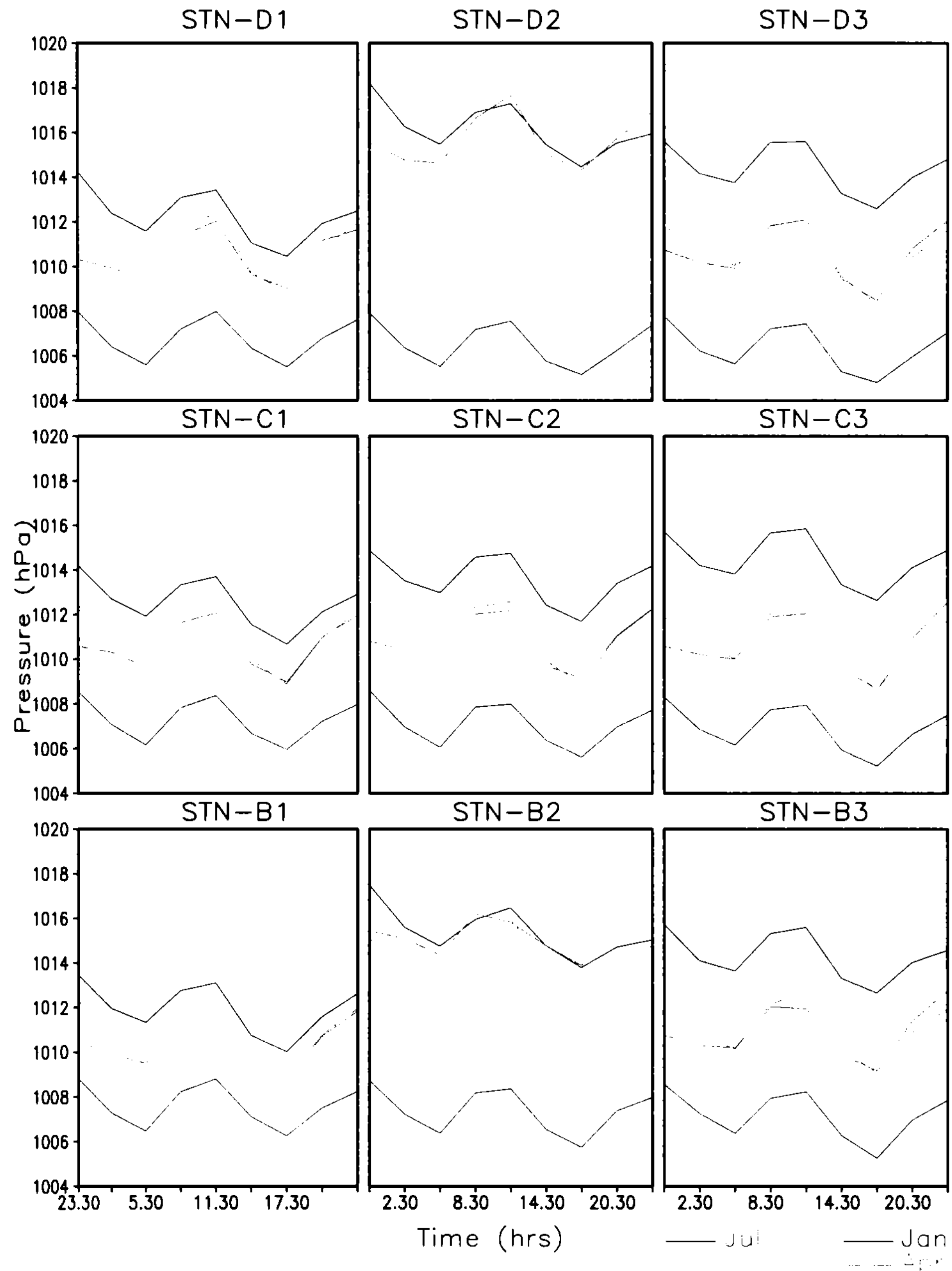


Figure 2.14: The diurnal variation of mean sea level pressure at different stations of southern peninsular India during various season.

natural vegetation, cultivated tree or field crops are concerned. The most important characteristics of wind velocity over mountains are related to their topographic, rather than their altitudinal, effects. Isolated peaks and exposed ridges experience high average and extreme speeds as a result of limited frictional effect of the terrain on the motion of the free air. The two basic factors which affects wind speeds on mountain summits operate in opposition to each other. The vertical compression of air flow over a mountain causes acceleration of the air, while frictional effects cause retardation. It is found that mountain effects must depend considerably on wind direction and wind speed as well as on lapse rate, but there are still few data on mountain and free air winds to determine the general nature of these relationships.

The surface wind analysis with 10 km resolution reveals the general pattern of wind over the southern peninsular India (fig.2.15). During the Winter season north-easterlies coming through Bay of Bengal will be covered throughout the Tamilnadu region and it tries to cross over the Western Ghat and touches the southern part of Kerala. Palghat Gap allows the easterlies to pass through it and reach the northern districts of Palghat and Malappuram. Northerlies coming through the Arabian sea is diverted to more southern latitudes by Western Ghats and it finally merges with the north-easterlies crossing the low altitude regions of south. These two type of air mass might be the cause for more thunder activity over southern region of Kerala during that season.

Northerlies will also be prevailing over the surface in Spring and channelized to more southern latitudes. In Summer season monsoon brings a heavy stream of westerlies to the windward side, which cross over to the leeward side and turns towards the northeastern latitude after passing through Bay of Bengal. Even in the month of October which is representing the Autumn season, we can see the westerly winds over the south Peninsular

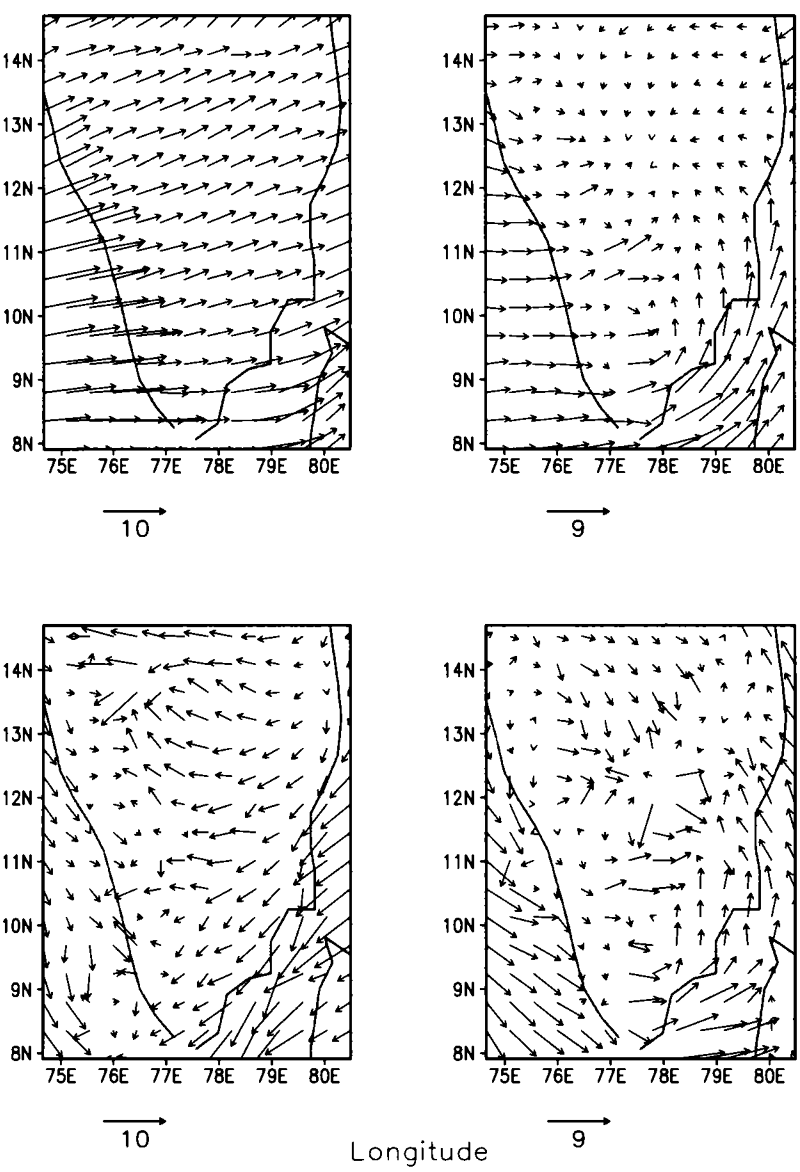


Figure 2.15: The average surface wind pattern over the southern peninsular India during different season in a year (model output for 20.30 IST).

India which is a part of the withdrawal phase of southwest monsoon. Northerlies start to invade the central and eastern part of India by this season.

The diurnal pattern of surface winds for different stations have been given in fig(2.16). It is clear that wind speed attains maximum value between 1130 and 1430 hours in all season and the maximum magnitude of about 6-8 ms^{-1} is noted during Summer. The amplitude of the feeble diurnal pattern is 1 ms^{-1}. The surface wind speed is minimum during Autumn in most of the stations. In Spring an increase in the wind speed is observed in the evening hours about 1730 hrs over Tamilnadu stations while it is around 1430 hrs in Kerala. In summit stations there is not much difference in the pattern observed in plain or valley stations. The amplitude of the diurnal pattern is weak in summit stations when compare with ground stations.

Analysis of the diurnal variation of U wind at the surface shows weaker wind component in Autumn and Spring (fig.2.17). In all the stations, the wind in the afternoon hours are stronger than the forenoon hours especially over Kerala. The diurnal variation is very clear in all season in the western side of the Ghats than the summit and the eastern side. An average of 1 ms^{-1} amplitude is seen for the diurnal wave of U wind in these region. The diurnal variation of V wind is less prominent than the zonal component (fig.2.18). An average of about 0.5 ms^{-1} amplitude is seen for the diurnal wave. The strength of the component is maximum (4 ms^{-1}) during the Winter season. The strength of the southerlies in summer season will be equal to the strength of the northerlies in winter season in all stations.

The monthly variation of surface wind is given in fig (2.19). In the figure, the station B2 is representing Anamudi and the C2 is the Palghat Gap. Generally, the wind speed

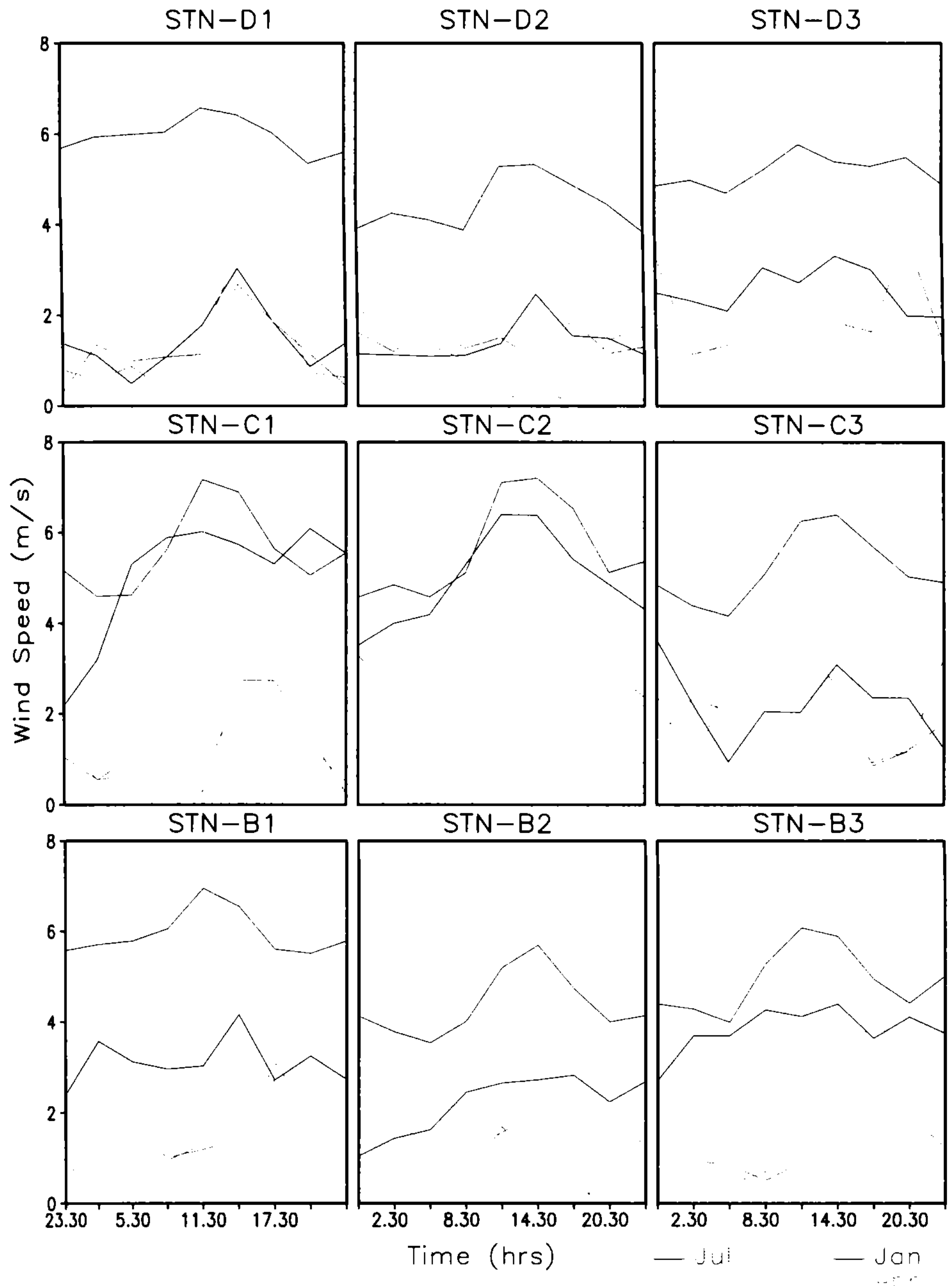


Figure 2.16: The diurnal variation of wind speed at different stations of southern peninsular India during various season.

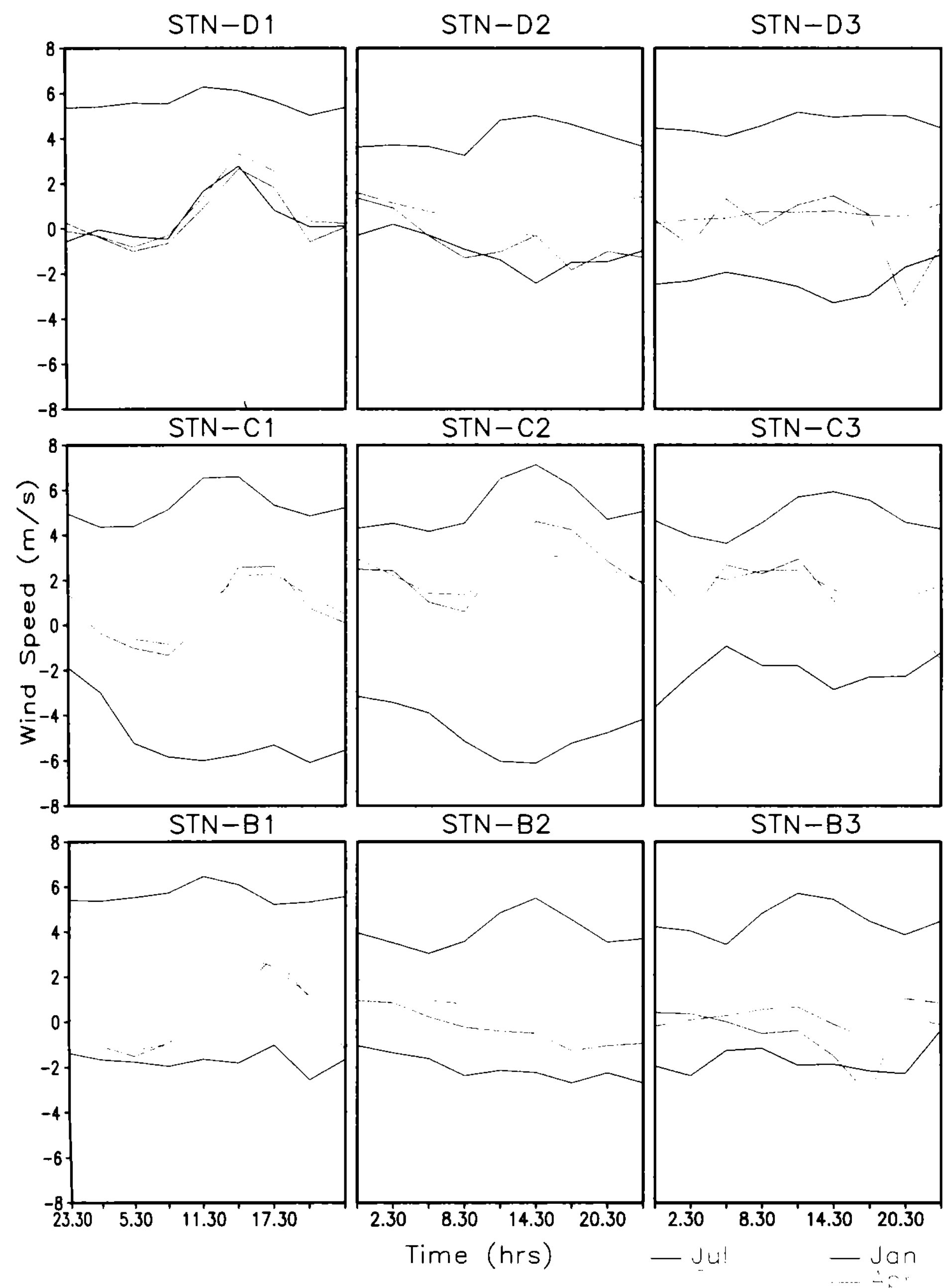


Figure 2.17: The diurnal variation of U-wind at different stations of southern peninsular India during various season.

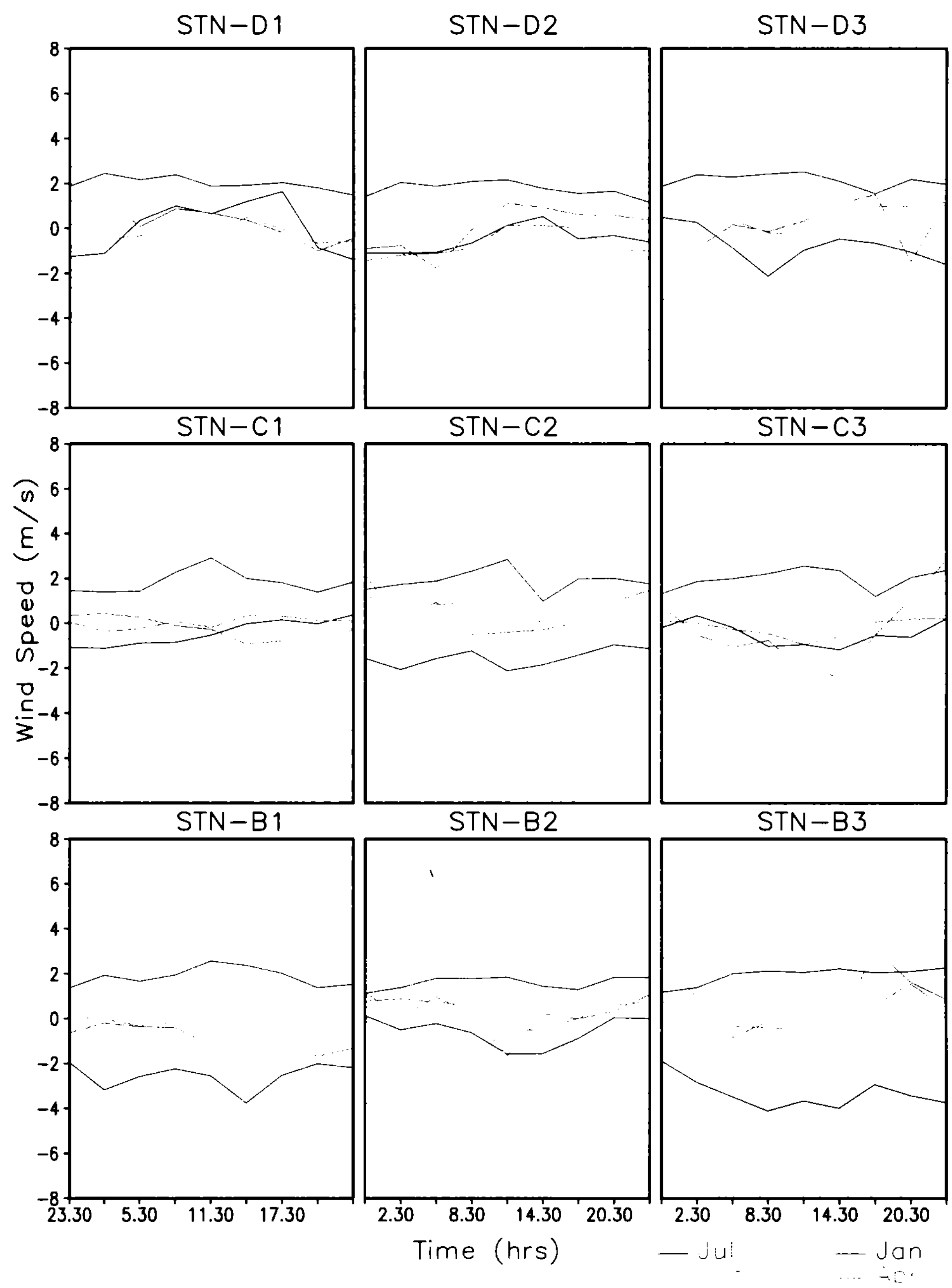


Figure 2.18: The diurnal variation of V-wind at different stations of southern peninsular India during various season.

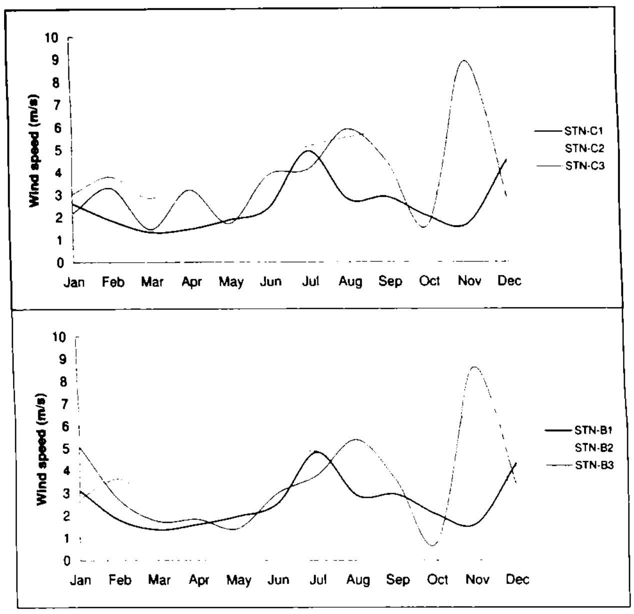


Figure 2.19: The monthly variation of surface wind in six selected stations of Peninsular India (model output for 20.30 IST).

increases from Winter season. High wind speed throughout the year are the characteristics of the summit regions, but it is oscillating in nature. A drastic reduction in wind speed is seen over Kerala and the summit stations in the Autumn season. A sudden increase of wind speed upto 9 ms^{-1} is found in the same season itself over Tamilnadu stations. Thus surface wind speeds are greater and more fluctuating in Tamilnadu than Kerala. A steady increase in wind speed is the characteristics of the Palghat Gap and which is more than 2 ms^{-1} than the surface winds over the other stations in Kerala in all months except in July. In July the higher wind speed prevails throughout the Kerala stations. There is a dramatic reduction of wind speed in all stations in the month of October. Thus the average annual wind speed over Kerala and the Palghat Gap region is 3 ms^{-1} while it is 4.8 ms^{-1}over Tamilnadu and 5 ms^{-1} over the summit stations.

The analysis of vertical variation of wind shows that the magnitude of wind is increasing in the lower troposphere upto 800 hPa in Summer monsoon season in all stations in Kerala and Tamilnadu as part of the low level jet present at that time but not seen over the summit stations (fig.2.20). The wind speed gradually decreases and then intensifies above 450 hPa level . The wind speed reaches upto 15 ms^{-1} in Kerala and summit stations while it is 10 ms^{-1} over Tamilnadu stations and 25 ms^{-1} at the level of 200 hPa above all stations in summer season. In Winter the winds strengthens above 500 hPa and during Spring it is more undulating in the vertical in all stations. Variation of U wind with height shows the change of westerlies to easterlies in the Autumn and the Summer season at about 450 hPa level (fig. 2.21). During other season the influence of easterly components are more predominant in all levels in all stations. The strength of the 15 ms^{-1} westerly component at the surface will be changing to 20 ms^{-1} easterlies at the 200 hPa level in summer season. Cross section of V wind with altitude shows that the strength of the V component is far less than the U component in all stations (fig.2.22). During Autumn season, northerly component is influencing more in south peninsular India than the southerly component in the upper levels. Generally the V-wind is varying between -5 to 5 ms^{-1} in the lower troposphere. The southerly component strengthens only below 900 hPa. Strength of the southerly component increases in Winter and reaches a maximum of about 12 ms^{-1} at 300 hPa level over summit and Tamilnadu stations and relatively weaker (about 8 ms^{-1}) in Kerala region. Mid-tropospheric levels shows strong northerly components in all stations during Spring season. Influence of meridional component will be minimum at all stations and at all levels in the Autumn season.

2.3.4 Atmospheric Moisture

Vapour Pressure

This is the partial pressure exerted by water vapour as one of the atmospheric gases. It is typically about one percent of the sea level pressure. The saturation value is determined

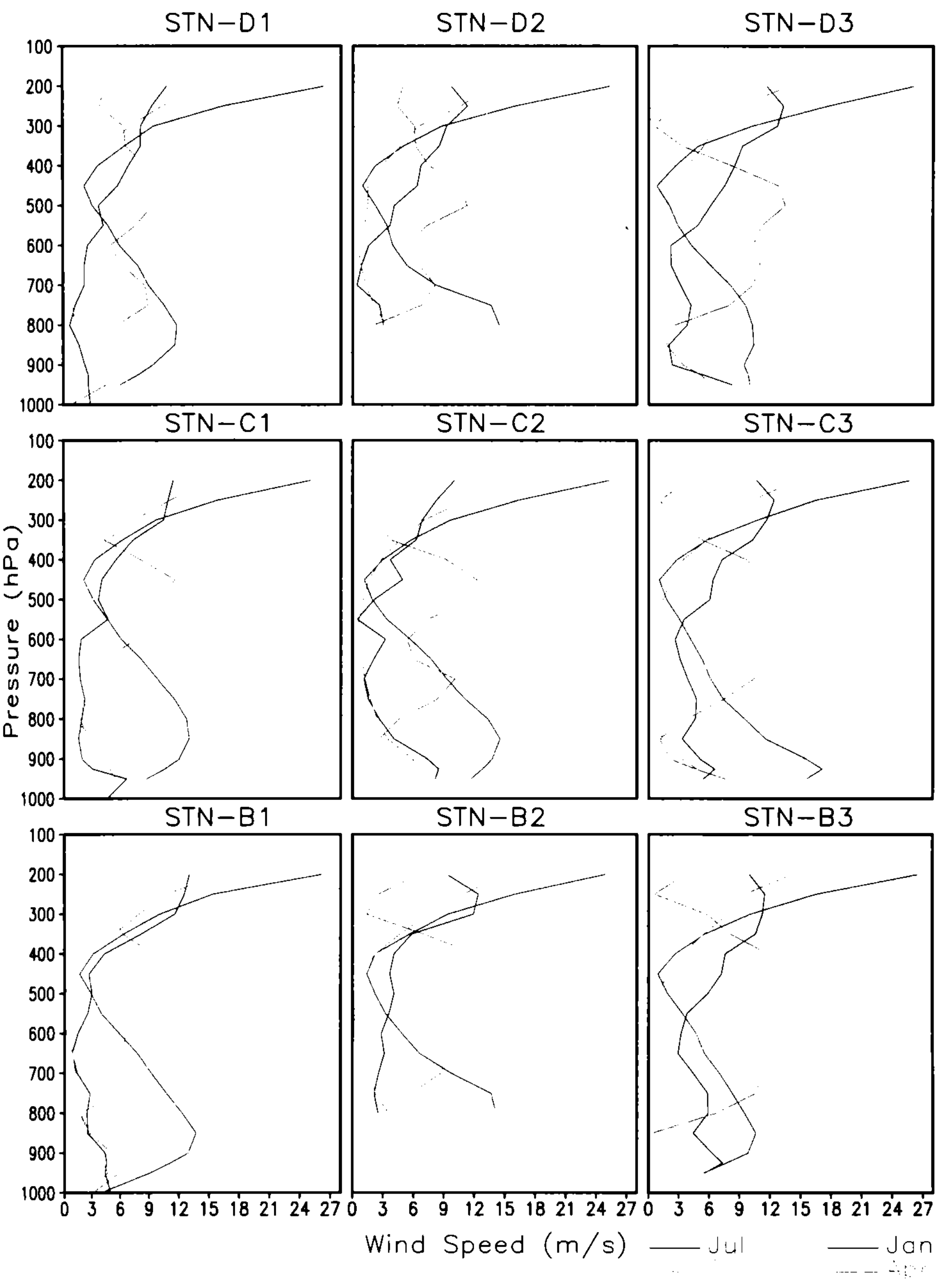


Figure 2.20: The vertical variation of wind speed at different stations of southern peninsular India during various season (model output for 20.30 IST).

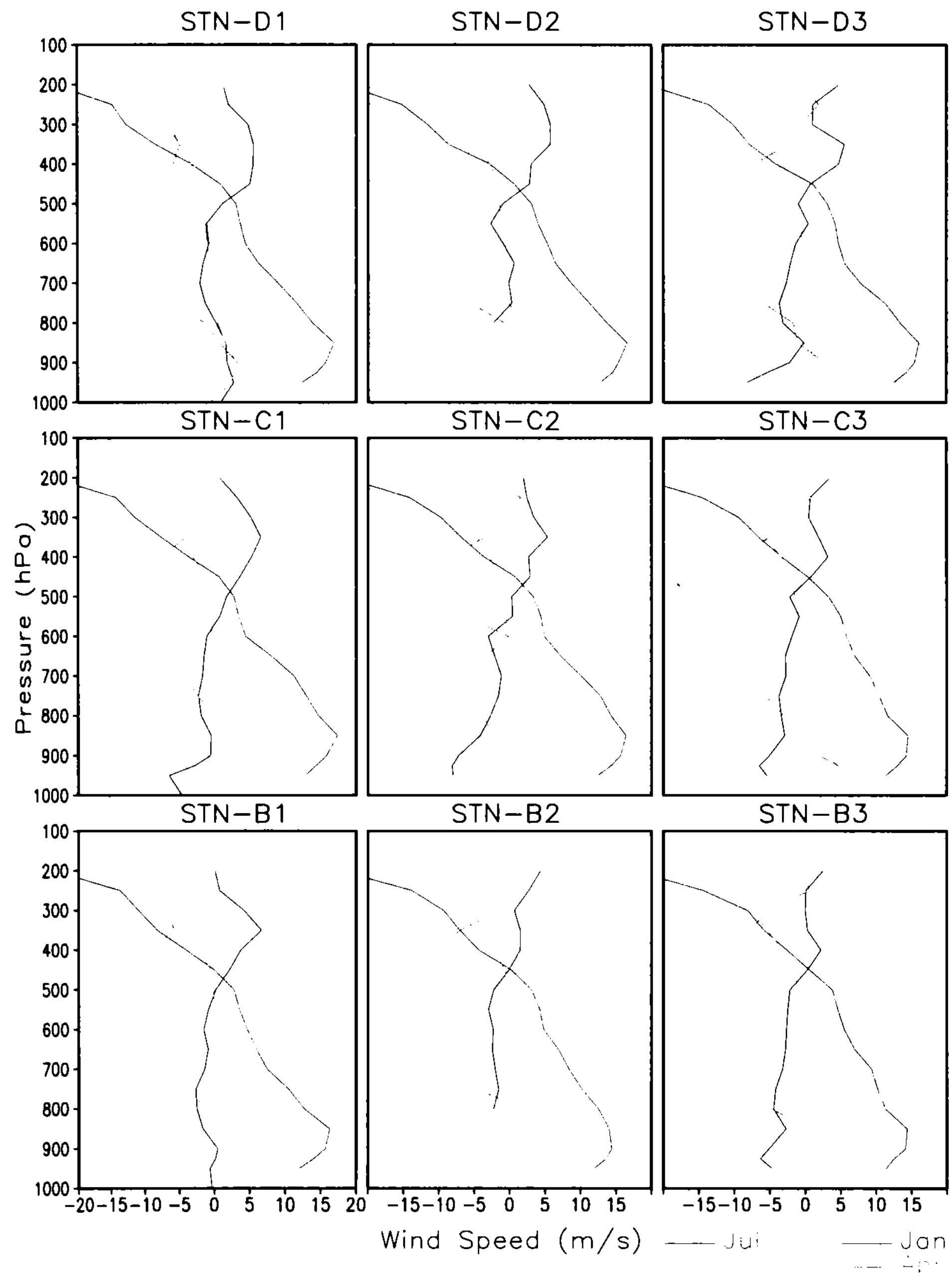


Figure 2.21: The vertical variation of U-wind at different stations of southern peninsular India during various season (model output for 20.30 IST).

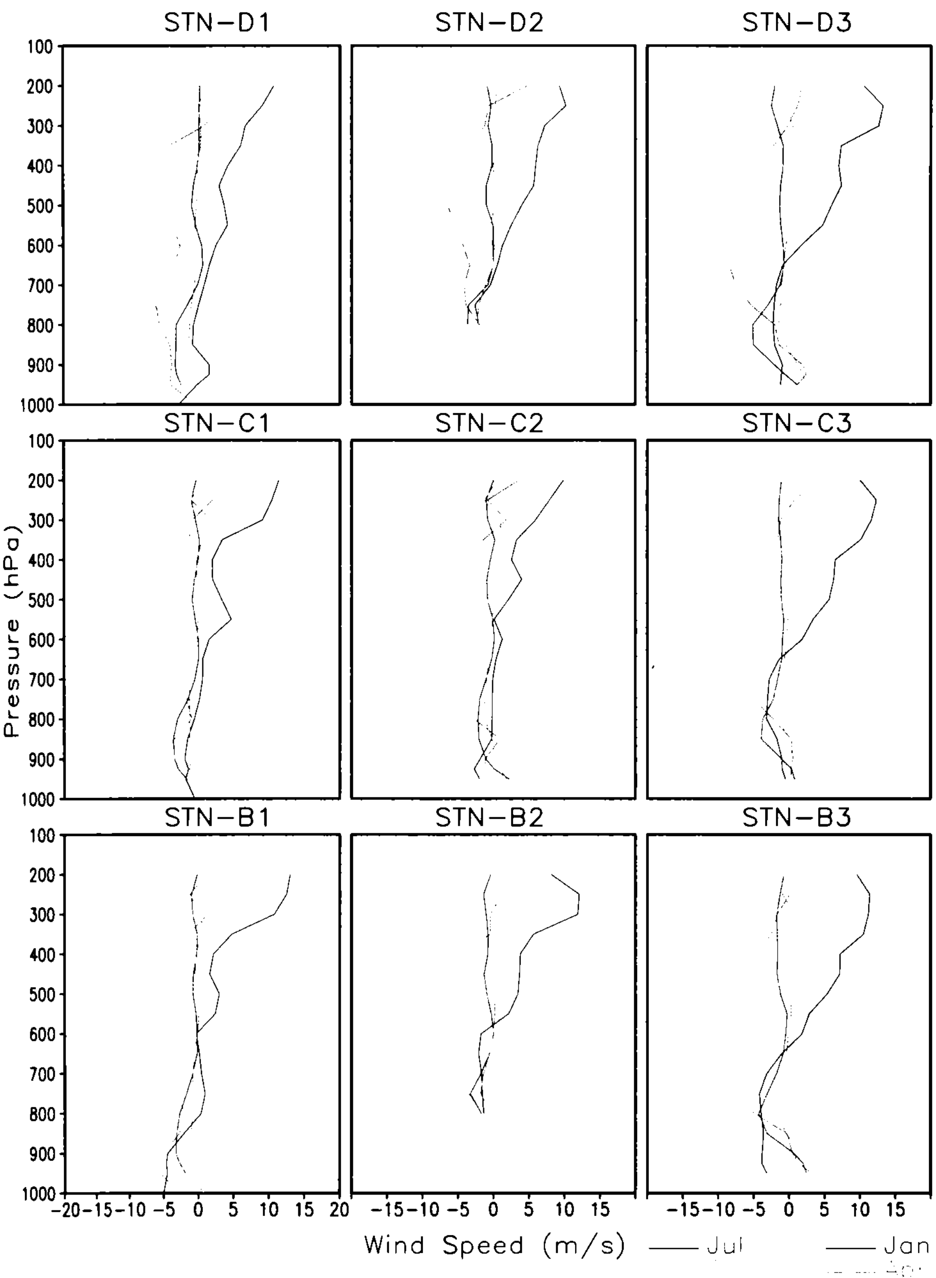


Figure 2.22: The vertical variation of V-wind at different stations of southern peninsular India during various season (model output for 20.30 IST).

only by the air temperature. Since temperature at high altitudes are low, vapour pressure in higher altitudes may be low, and the decrease is proportionately greater in the lower layers. Vapour pressure is climatically significant in three ways. First, it reduces its transmission of infrared radiation and to a lesser extent, solar radiation. Second, it influences the saturation deficit which is an index of bio-climatic significance sometimes termed the drying power of the air. Third, it affects the total air density inversely and this may also be important biologically in terms of the hypoxic effect of oxygen deficiency at higher latitudes. The fact of a vapour pressure excess in the mountain atmosphere should act to lower the condensation level, other factors remaining constant. It will also tend to reduce the transmission of infrared radiation, by comparison with the free air, thereby leading to higher atmospheric temperatures (*Storr*, 1970).

Palghat Gap clearly controls the moisture transport in all season. This is evident in the cross section analysis of vapour pressure through latitudes (fig.2.23). The down wind region of Palghat Gap is always experience a reduction in the moisture content. During Winter period the wind will be easterlies and the high value of the vapour pressure in the eastern side of the mountain is decreasing when it reaches the western side of the Ghat. The reverse is happening in the case of Summer season when the monsoon current is blowing from the west. A difference of 3-4 hPa is there in the upwind and the down wind regions of the Gap. The variation is minimum in the Autumn season. Vapour pressure shows an increase in the summit regions from the surrounding free air which is evident from the analysis along Anamalai and Nilgiri hills. Over summit the vapour pressure increases by 2-3 hPa than the surrounding free air at the eastern side. The valley region of the western side shows a general increase in the vapour pressure than any other part of the study region. During Winter season vapour pressure is coming down drastically from 8 to 2 hPa at the eastern side of the mountain both at the Anamalai and Nilgiri cross sections.

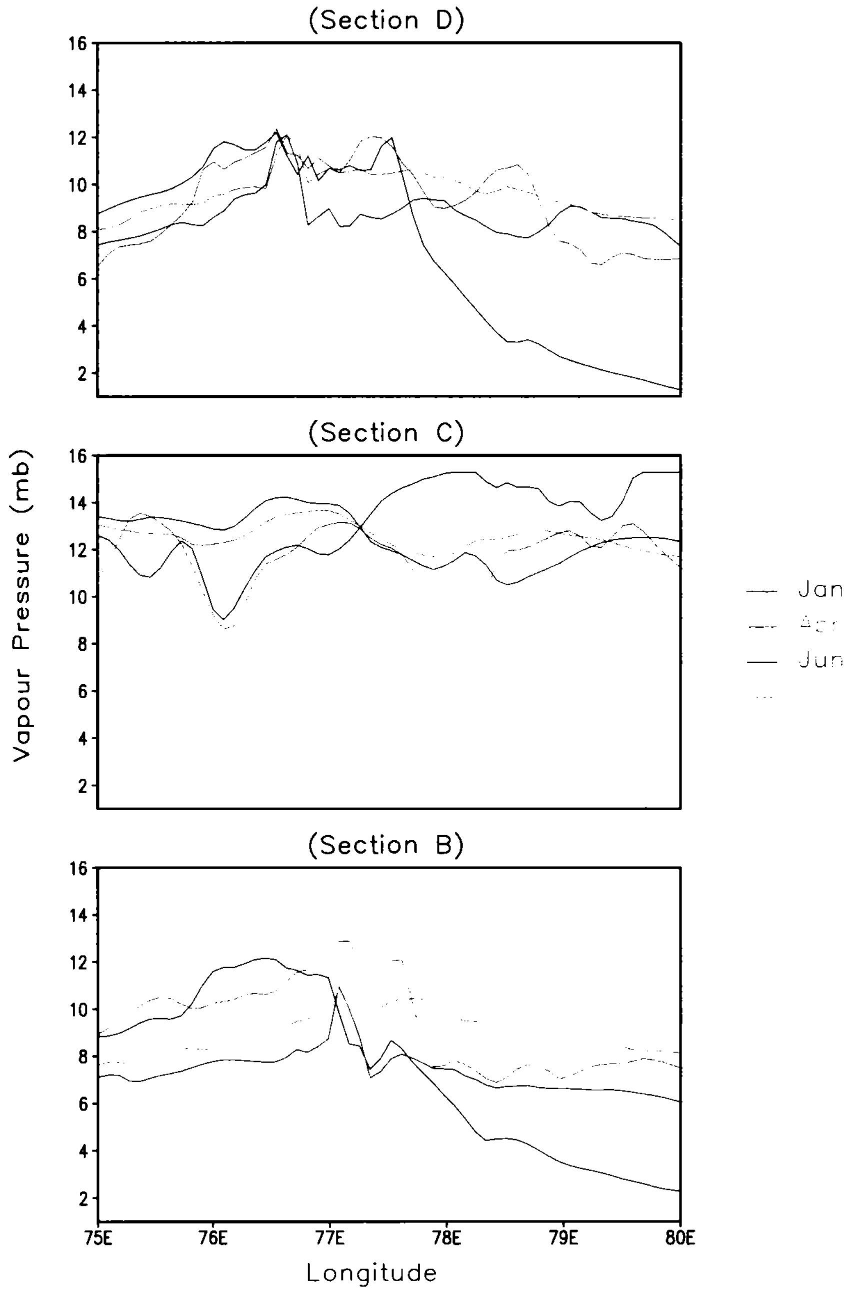


Figure 2.23: The latitudinal cross sections of vapour pressure for different season.

The vertical profile of vapour pressure at nine stations in the study region shows almost a linear decrease upwards (fig.2.24). Vapor pressure varies from 14 hPa at surface to 0.5 hPa at 200 hPa level in the study region. Over Tamilnadu stations, a dramatic reduction of vapour pressure is seen between the 1000 and 800 hPa level in winter season. At 400 hPa level it is observed that there is an increase in the moisture content in all stations. Since the temperature at high altitudes are low, vapour pressure also will be low and the decrease in the vapour pressure are greater in the lower layers of these tropical belt as seen by Fujimara and Yoshino for the middle latitude mountain region. Also the vapour pressure at the Western Ghats region is found to be more than about 2 hPa in Autumn and Spring than the free air at that level over plain stations which substantiate the observation of lower cloud ceiling in the region. As an average, vapour pressure shows a marked decrease of about 10-11 hPa when it moves from surface to 200 hPa level over all stations . There is a sharp decrease of about 7-8 hPa is seen between the levels 800 and 600 hPa over all stations during the Spring season.

Relative Humidity

By definition relative humidity is the amount of water vapour that a given quantity of air can contain. Relative humidity decreases with height. But just below clouds it will increase, since there is full saturation at that level. The diurnal variation shows that there is no clear pattern for the variation of relative humidity in the area (fig.2.25). But still we can see the oscillatory nature of that parameter in all stations. The variation is confined between 60 to 100% generally in these regions. An unusal reduction of RH is seen over the summit region in the morning hours (0830 hrs) during Spring season. The height of the summit stations (stn B2 & stn D2) taken for this analysis are about 800 hPa. No reduction in the RH is observed in the night time in any of the stations in the study region.

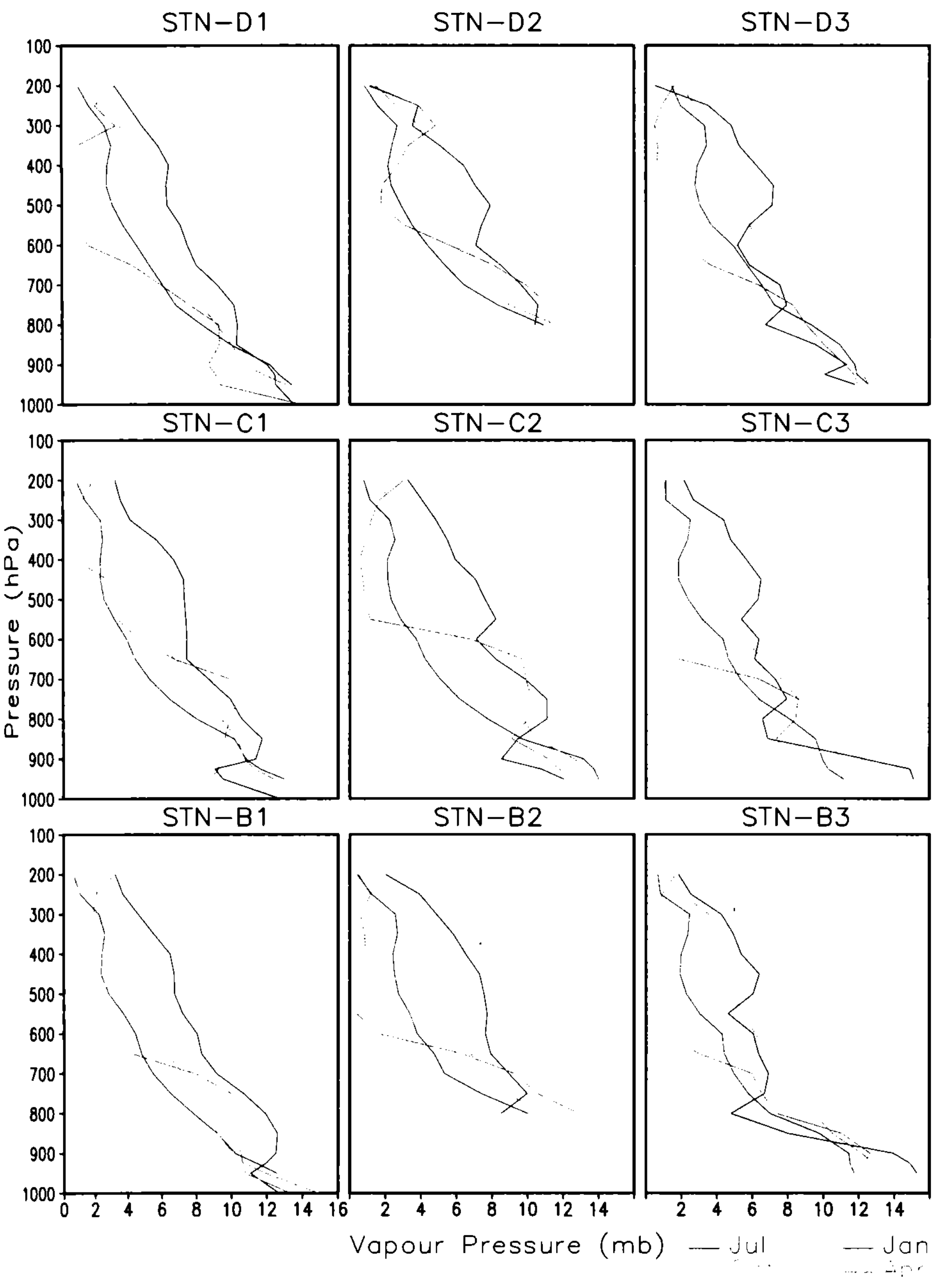


Figure 2.24: The vertical variation of vapour pressure at different stations of southern peninsular India during various season.

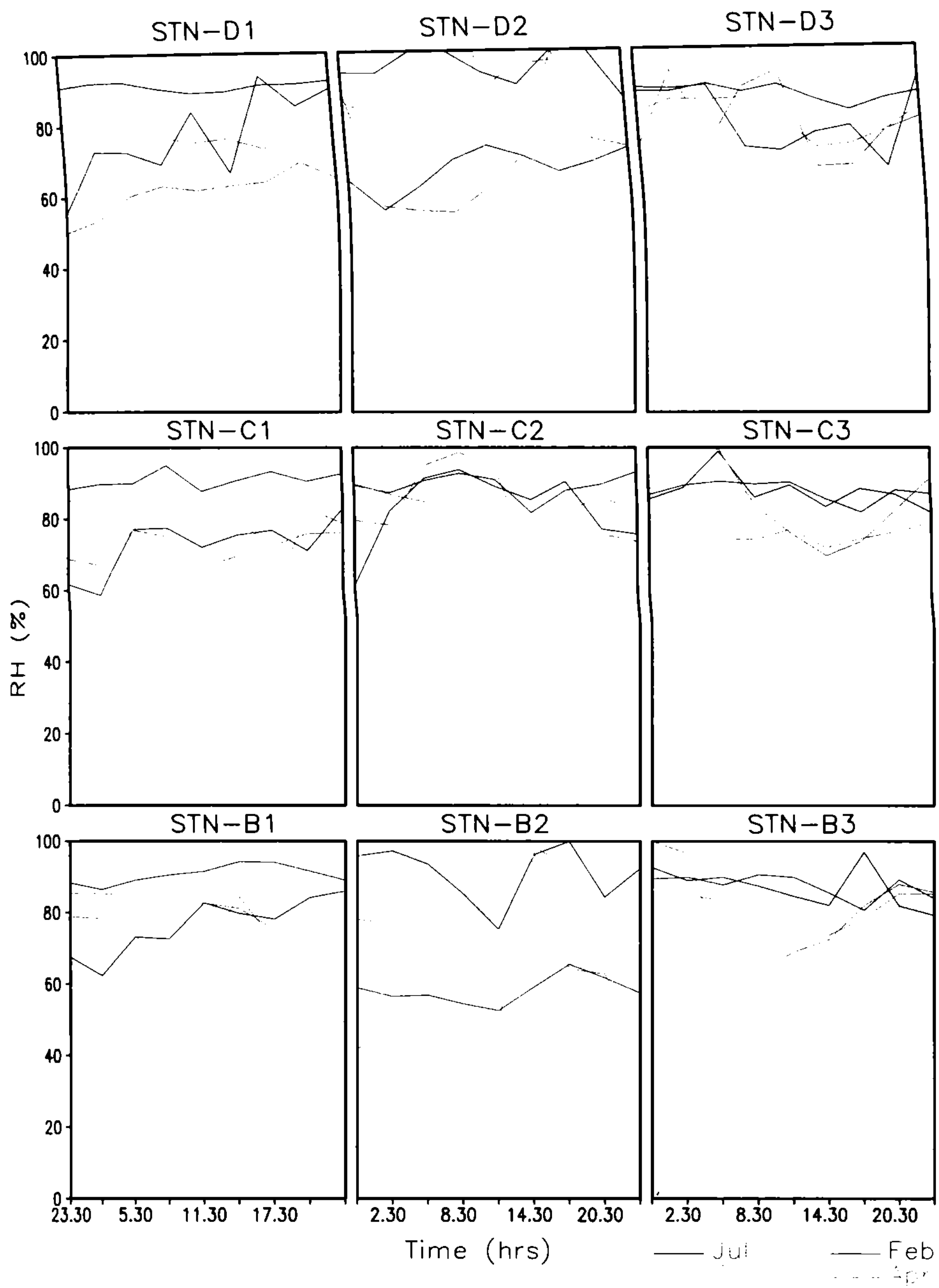


Figure 2.25: The diurnal variation of relative humidity at different stations of southern peninsular India during various season.

The vertical profiles of RH (fig.2.26) at plain stations as well as summit stations in the study region reveal some noteable results. The western side of the Ghats is showing more humidity in Summer season at the surface, while it is in Spring at the summit and Winter at eastern side of the mountain. The negative gradient of RH is maximum between 800 to 500 hPa in Spring at all stations while the gradient is minimum for Autumn season. Above 300 hPa there is a sharp increase of RH during the Spring season while a decrease is noted for all other season. Summit stations are more humid than the free air at that level over the plain stations. During Winter the value of RH touches 100% between 500 and 300 hPa level may be an indication for the formation of cloud at that level. Value of RH increases with height in winter season in all stations. The increase of RH at the Palghat Gap is also clear at the surface from the figure. An increase by about 10% is seen in RH at the Gap when compares with the windward side in Kerala during the southwest monsoon period.

While the annual course of relative humidity is governed by the large scale circulation pattern, diurnal changes are significantly correlated with the diurnal temperature variations, at least on the plains and plateaus (*Lengerke*). The study also shows that the afternoon humidity variations in these mountain regions are more prominent than the morning changes and this differs to the middle latitude mountain environment (above 2000 m) described by *Yoshino*. For a better understanding of the cause of the variation of relative humidity, precisely we have to incorporate the forest canopy also. Where ever high grown dense vegetational cover alternates with grass lands or cultivated fields, enormous micro climatic contrast have to be expected with additional vertical gradients within the ground layer of 2 m. Within the forest and the tea plantations relative humidity is always higher and diurnal changes are less pronounced than in the open particularly during the Autumn

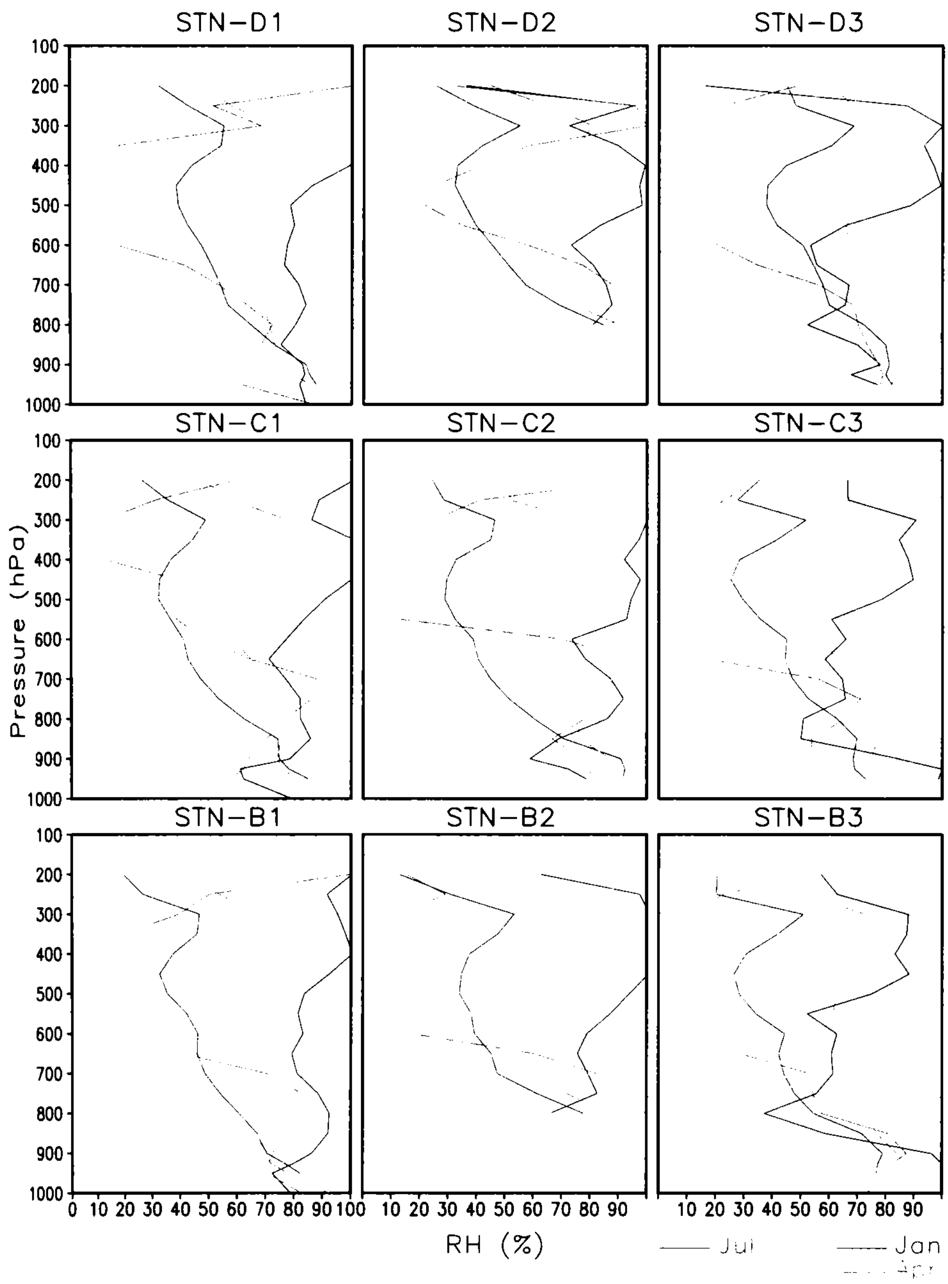


Figure 2.26: The vertical variation of relative humidity at different stations of southern peninsular India during various season.

season.

2.3.5 Density

The effects of reduced pressure and density with height are of particular importance in connection with the radiation conditions and for human bio-climatology. The decrease of density with height is a linear function and showing similar characteristics irrespective whether the station is in plains or in summits (fig.2.27). The mean density at the surface is about 1.1 kgm^{-3}, and it decreases with rate of 0.1 kgm^{-3} per 100 hPa as height increases in all stations and reaches 0.3 kgm^{-3} at 200 hPa level. The density variation do not show any difference irrespective of its geographical position. Cross section along the meridional and zonal direction also shows very minute difference in the density pattern (fig. 2.28). The cross section along the peaks shows that density is showing a small increase (0.005 kgm^{-3}) in the western valley and the summit regions than the eastern side. A sudden reduction to the eastern valley is clear from the analysis. The atmosphere is less dense during Spring and more in Winter on the western side of the mountain. At the eastern side of the mountain the maximum is occurring at the Autumn and minimum in Summer. Palghat Gap controls the distribution of density which is evident from the increased value at the mouth of the Gap in the eastern side. In the summit regions the density at the 800 hPa level has been plotted to know whether the peak shows any difference with the surrounding air. It do not showed any marked variations at the summit. This gives an idea that the airmass present in the peninsular region is having a homogeneous characteristics horizontally.

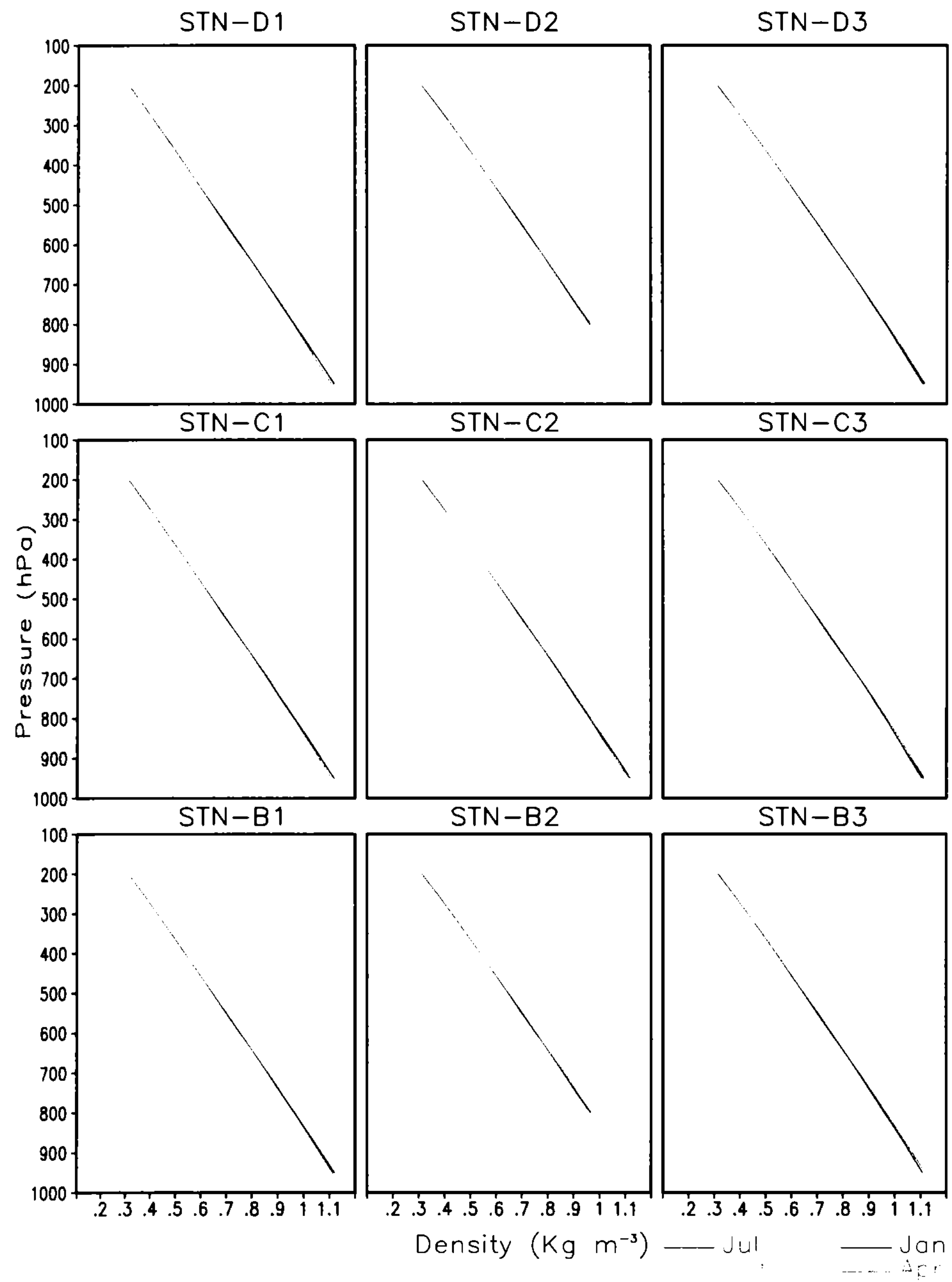


Figure 2.27: The vertical variation of density at different stations of southern peninsular India during various season.

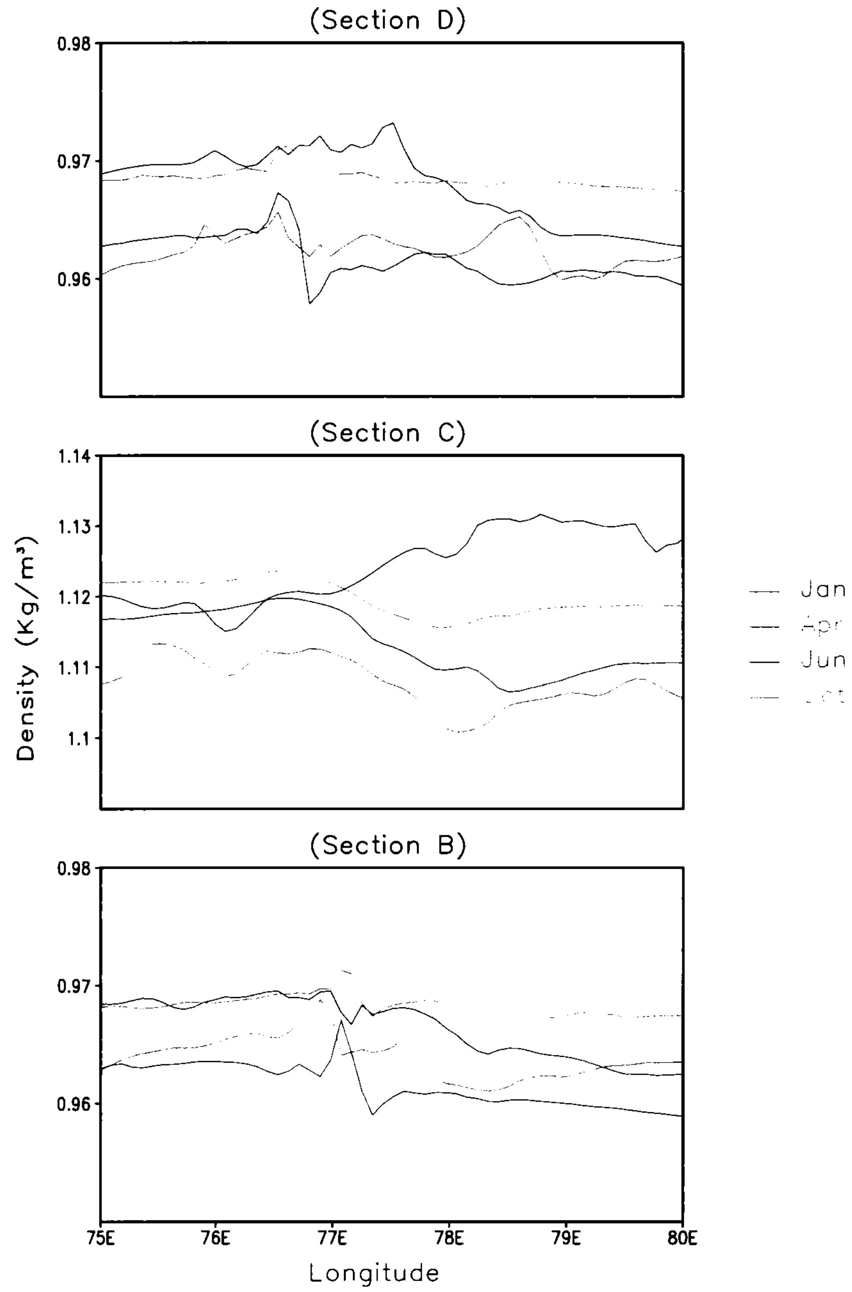


Figure 2.28: The latitudinal cross sections of density for different season.

2.3.6 Radiation and Clouds

Radiation

Mountain observatories were of special importance in early studies of solar radiation and the solar constant. For real atmosphere, the effect of absorption of radiation by water vapour and of attenuation by particulate matter must be taken into account, in addition to absorption by the atmospheric gases and molecular scattering. Generally in mountain areas, the aerosol content tends to be low and most of the atmospheric water vapour is below about 700 hPa, reducing these effects. For an ideal atmosphere (pure and dry), the direct solar radiation received at the 500 hPa level is 5-12 percent greater, according to solar altitude, than at sea level. This corresponds to an average increase of 1-2 per cent per km.

The net radiation has been calculated by geometrically adding both the incoming and outgoing short wave as well as long wave radiations . It is found that net radiation will be maximum at all stations between 1200 and 1500 hrs LT (about 900 Wm^{-2}) and reaches equilibrium by 2030 hrs LT (fig.2.29). Among the plain stations, in Winter season receives minimum net radiation 200 Wm^{-2} in the forenoon hours and as we go northward the minimum is getting in Summer season. But the variability in the summit station is quite different than the plain station. The noteworthy point in this regard is that, at the summit stations a drastic reduction of net radiation is occurring in Spring season which is about a deficit of 600 Wm^{-2} by 1430 hrs. The unusual reduction of net radiation can be attributed to the high amount of medium clouds formation over the summit region in the noon hours. A deficit of net radiation is not seen over the plain stations in any season.

The cross section analysis shows that (fig.2.30) the valley region of the western side gets maximum surplus radiation in Winter and Spring. Kerala receives minimum radiation

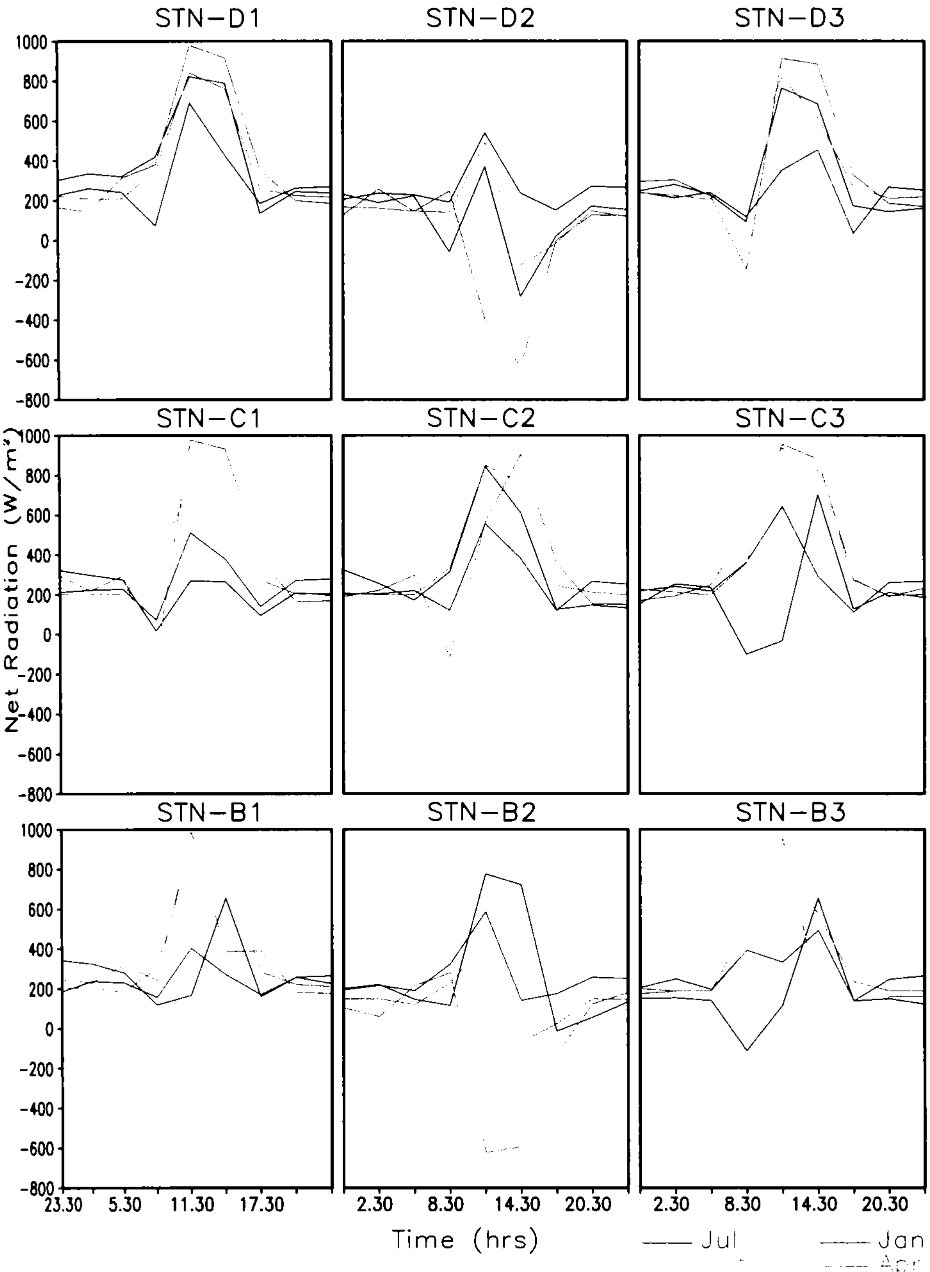


Figure 2.29: The diurnal variation of net radiation at different stations of southern peninsular India during various season.

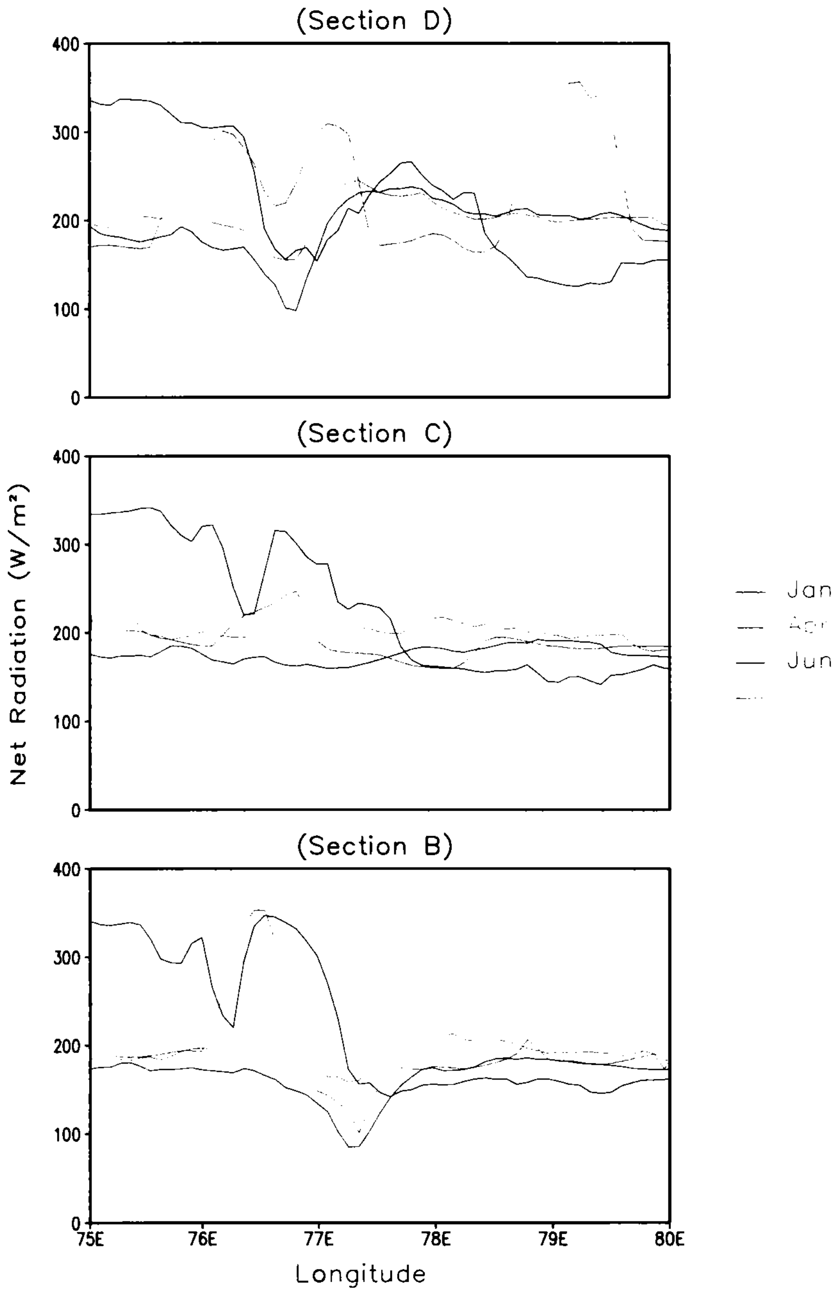


Figure 2.30: The latitudinal cross sections of net radiation received at the surface for different season.

in Summer and Tamilnadu in Winter. A decrease of net radiation is there in the summit region and there is a steady distribution at the eastern side of the Ghat. An average of 200 Wm^{-2} of net radiation is getting along any latitudinal cross section. The analysis of the nocturnal radiation along the latitude reveals (fig.2.31) that an average of 200 Wm^{-2} is loosing in the night which is same as the amount of surplus net radiation in the area. The variability of nocturnal radiation between the season is maximum at the western side of the Ghat and at the eastern side it is uniform as in the case of net radiation. The nocturnal radiation is maximum at the eastern side of the Ghat and the maximum difference between the east and the west is about 100 Wm^{-2}. The absence of the medium clouds over Tamilnadu especially during Spring season can be the reason for high value of the terrestrial radiation loss there. Over Kerala a difference of 100 Wm^{-2} is noticed between the monsoon and the other months. The proximity of Western Ghat to the coast may be the reason for the large variation of net radiation in the western side of the mountain.

Clouds

The variation of low clouds is given in fig.2.32. Low clouds are less in the Spring season at all stations. Lack of moisture supply and increase of wind speed in upper level in this season may be the reason for this reduction of cloud amount. During Summer when the southwest monsoon is active over the region the cloud is distributed uniformly in the study region. In Autumn season the Tamilnadu coast is having more low cloud fraction than the Kerala coast. Also more variability of the cloud amount is occurring in Winter period everywhere. No specific pattern is seen over the Palghat Gap region in the case of the variation of low clouds. Medium clouds are more in the Winter season (fig.2.33) and its meager presence over both coastal areas are noteworthy. During Summer and Spring season, the medium cloud amount are very low (below 0.5 fraction) throughout the study area. Presence of medium clouds are more in the mountain regions and the western side of Palghat Gap in

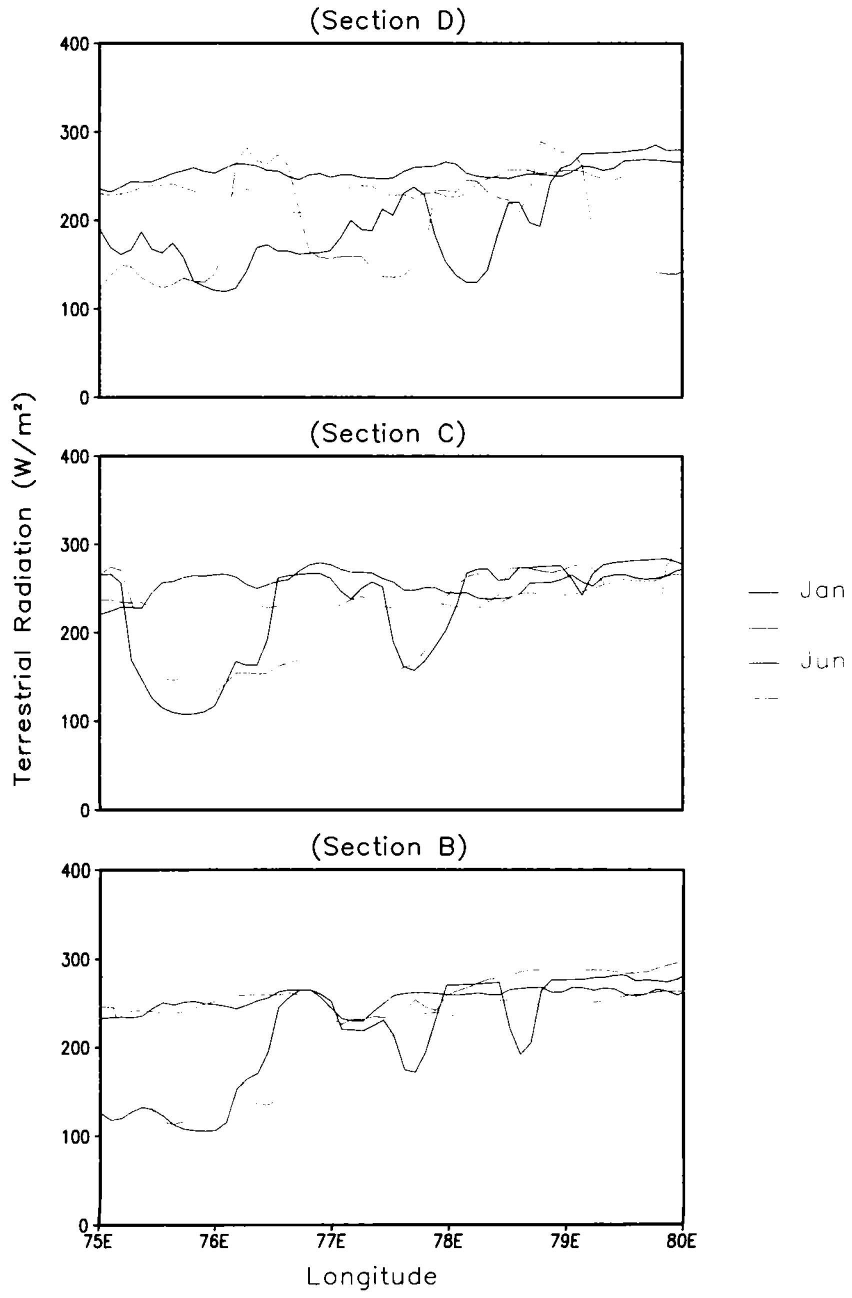


Figure 2.31: The latitudinal cross sections of terrestrial radiation emission at the surface for different season

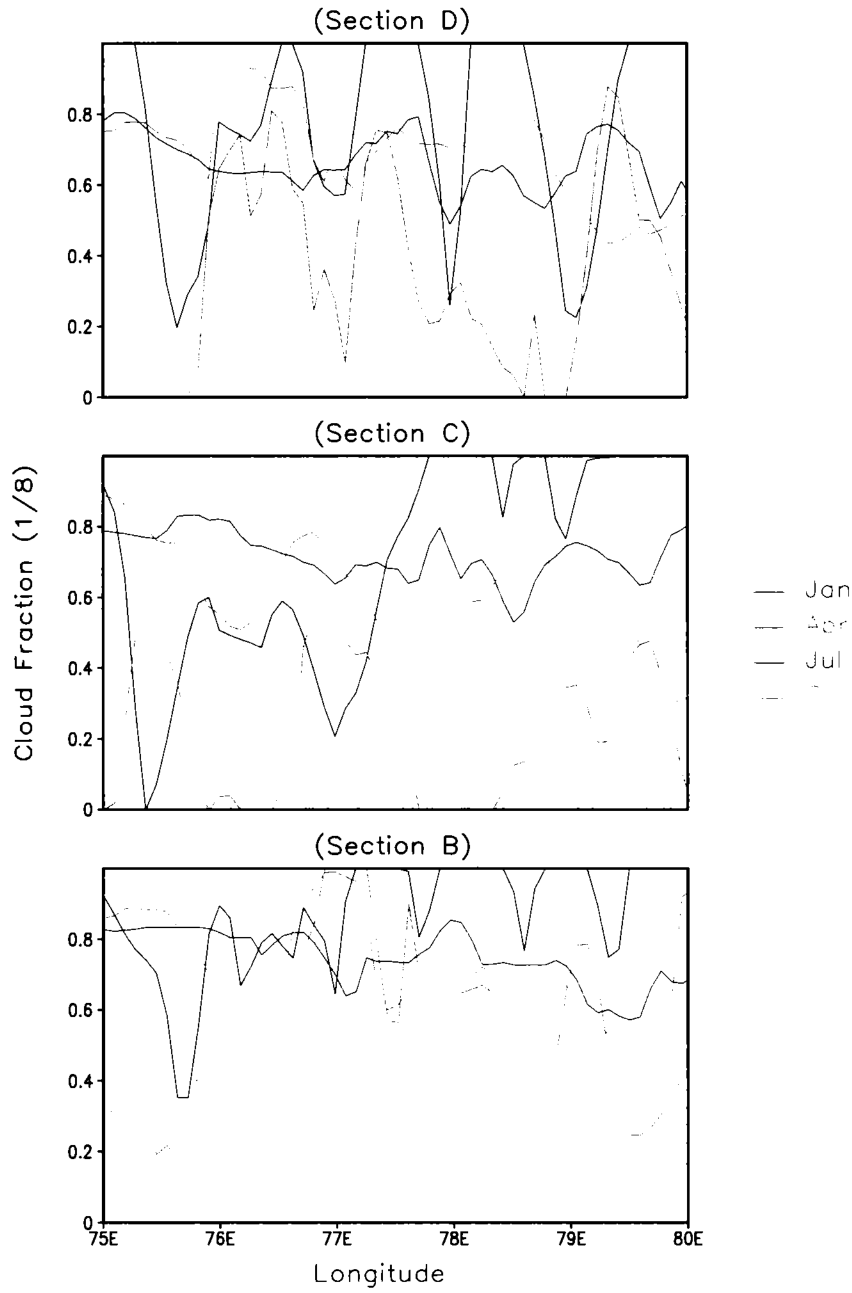


Figure 2.32: The latitudinal cross sections of low cloud fraction for Winter season in the study area

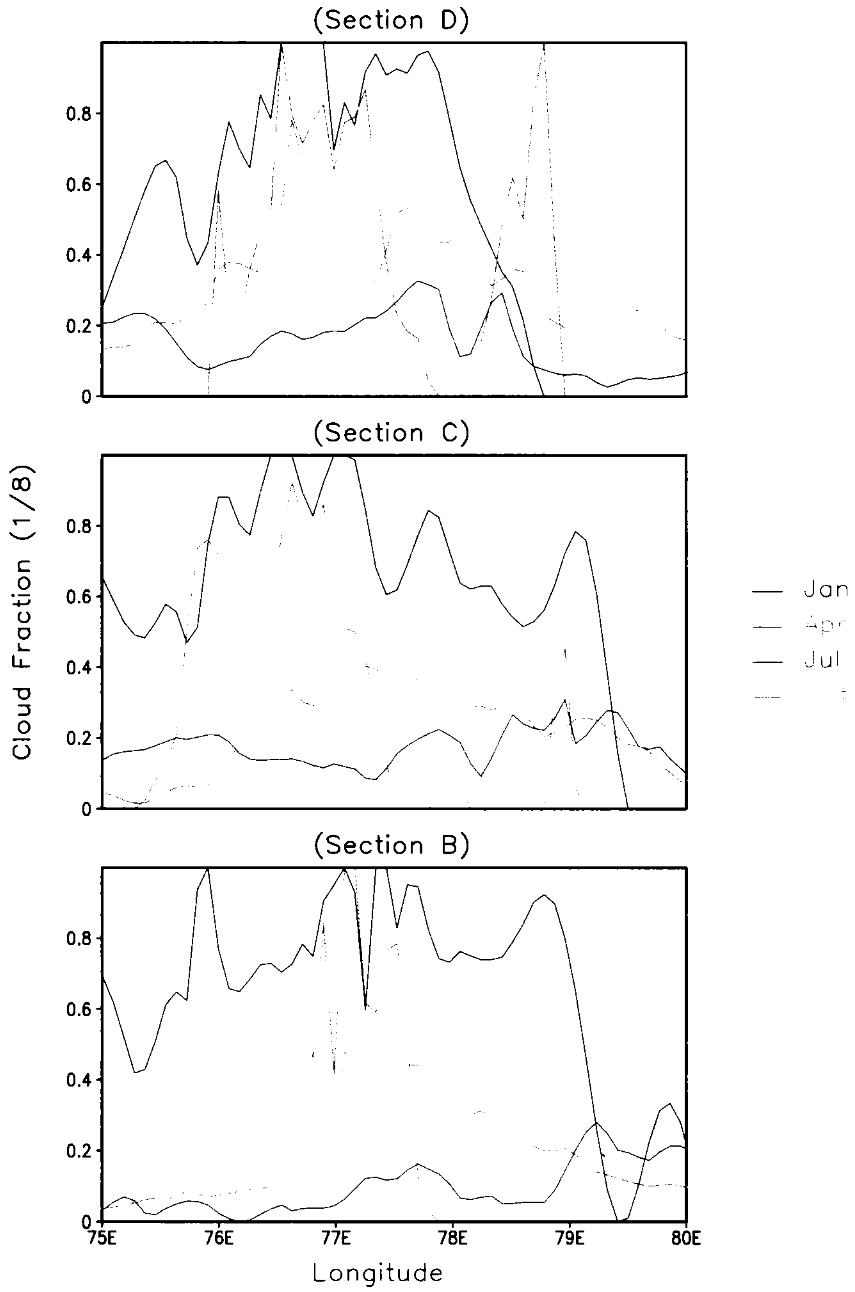


Figure 2.33: The latitudinal cross sections of medium cloud fraction for Winter season in the study area

Kerala. Diurnal variation of cloud fraction shows that it is not affecting the high clouds at all (fig2.34). A semi-diurnal pattern is feebly visible in the variation of low and medium cloud amounts. At 1430 hrs there is a reduction of the cloud amounts can be seen in many stations. Over Kerala there is a reduction of low cloud amount in the morning hours and it increases in the evening hours. Tamilnadu also shows an increase in the low cloud in the evening hours but the diurnal pattern is not as clear as Kerala side.

2.4 Ground Truth of Meteorological Parameters

Output of the model is compared with the observed climatological mean of the parameters published by India Meteorological Department for 9 different stations which is situated in Kerala, Tamilnadu and two summit stations Kodaikanal and Coonoor. The compared parameters are temperature, mean sea level pressure, relative humidity and surface wind (figs.2.35 to 2.38).

The difference of the modeled value and the observed mean value of each parameters is divided with the observed value itself to get the error. It is then expressed in percentage. This is calculated for every month and the average of these monthly values are taken as the annual value. The annual error value for each station for every parameters is then averaged for the nine stations to get the average percentage of error for a single parameter in the study region. The average percent of error for different parameters varies from 1.9% to 43.6%. It is found that the mean sea level pressure shows the minimum error of 1.9% follows temeperature with 9.9%, 13.6% on relative humidity and wind speed with 43.6%. Since the magnitude of the wind speed is very less (about 2-3ms^{-1}), the error in the windspeed will not make much difference for a diagonostic study. Thus in general the model value of basic meteorological parameters agrees very well with the observed values.

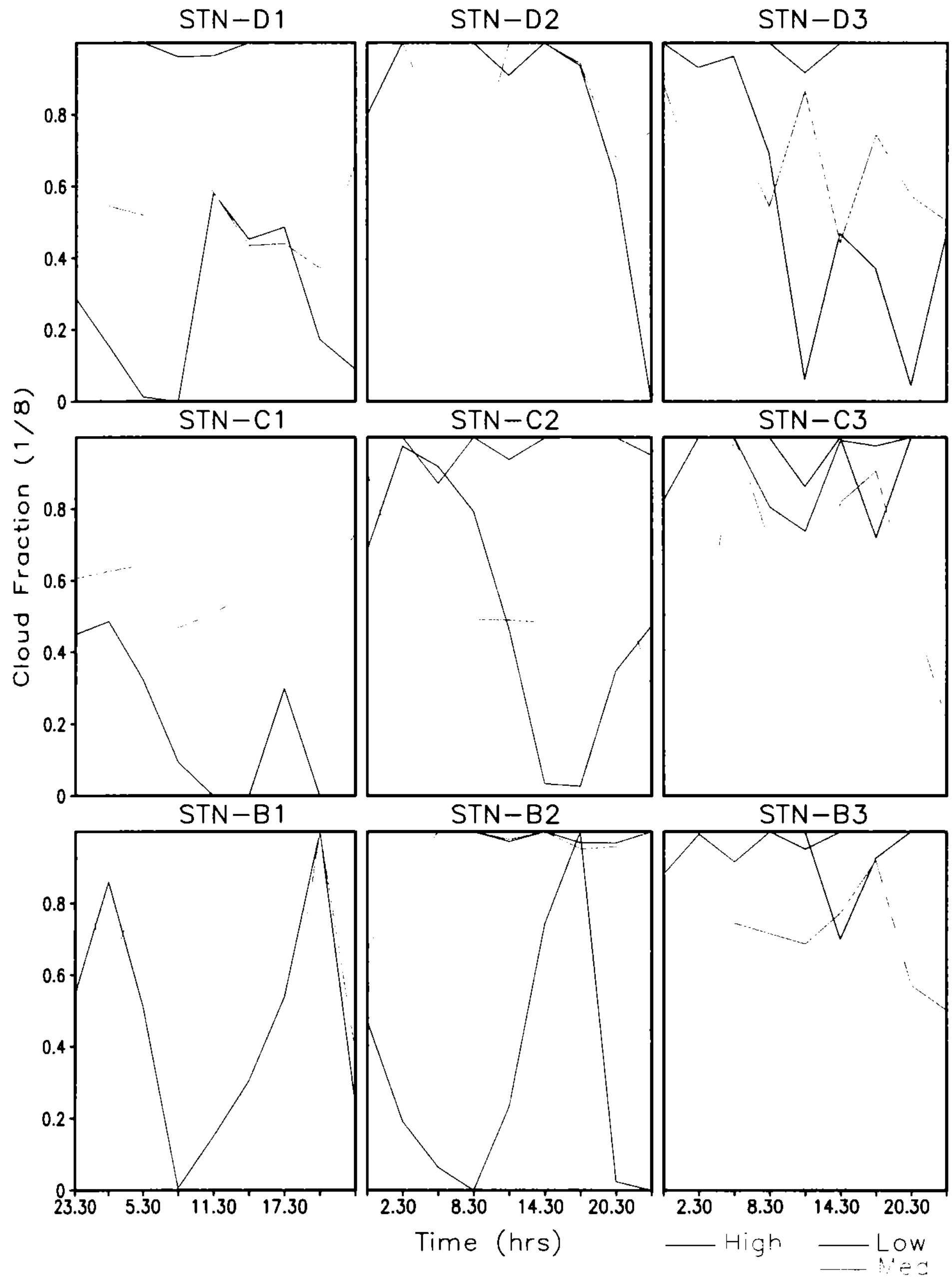


Figure 2.34: The diurnal variation of low, medium and high cloud fractions for Winter season in the study area

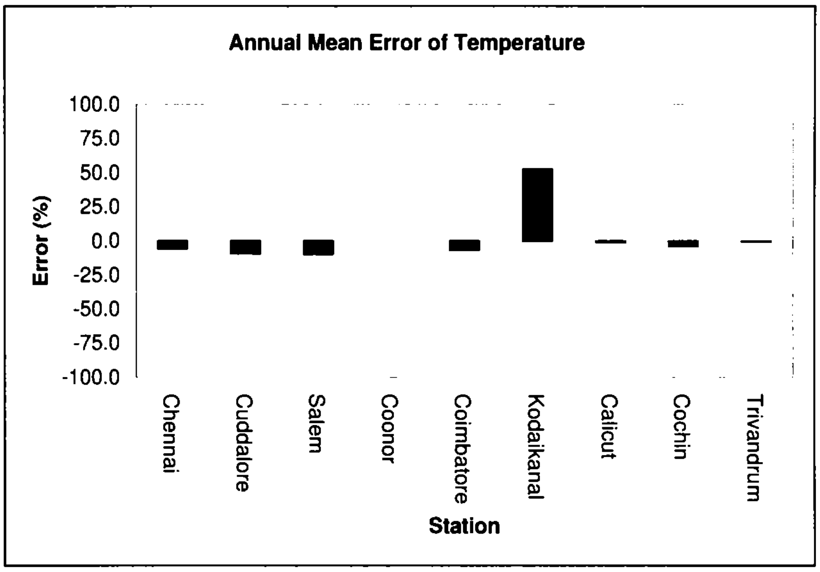


Figure 2.35: The annual mean error of temperature

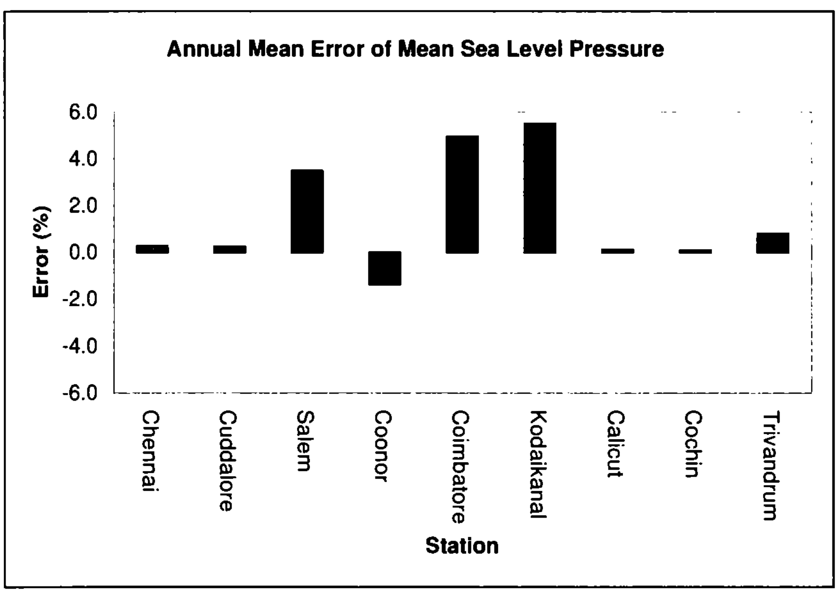


Figure 2.36: The annual mean error of mean sea level pressure

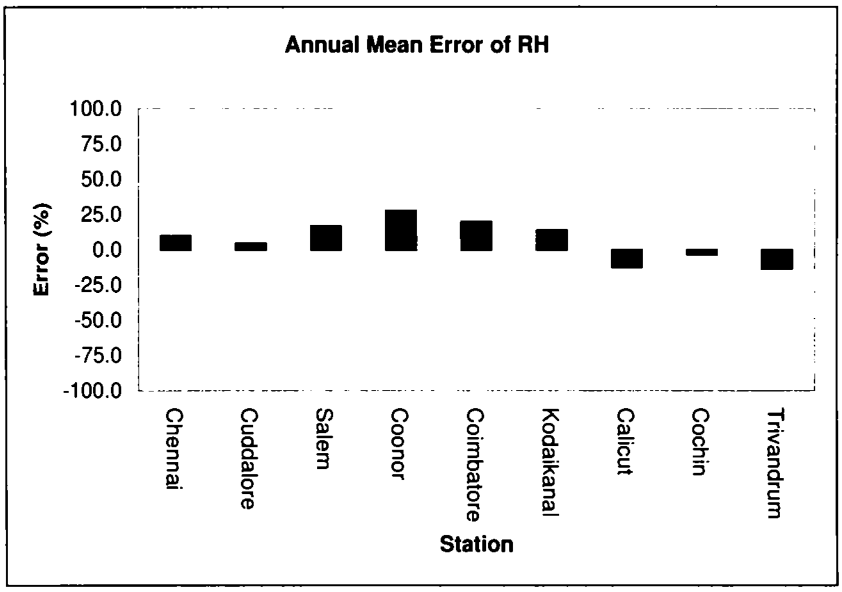


Figure 2.37: The annual mean error of relative humidity

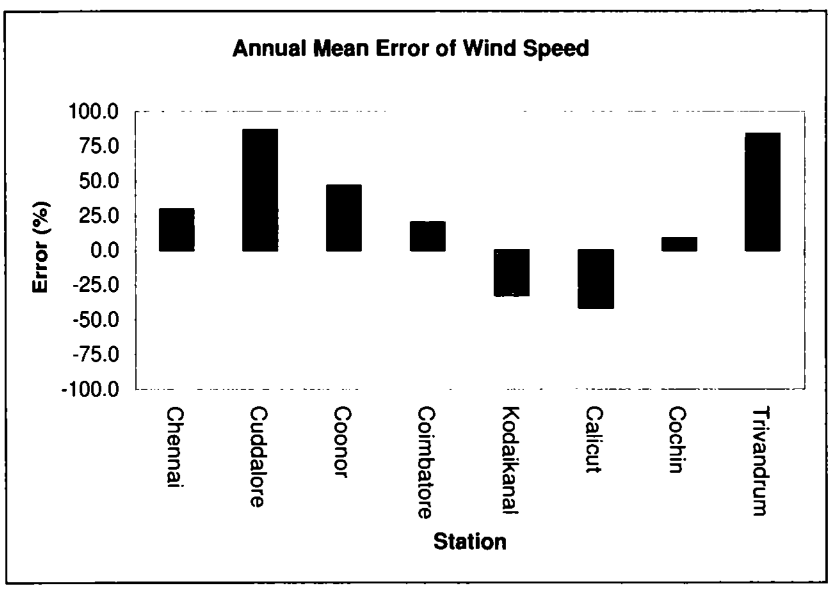


Figure 2.38: The annual mean error of wind speed

2.5 Conclusions

Most of the latitudinal effect on climate is evident in higher mountains above 3000 m height. In order to understand the latitudinal factors affecting in the diurnal and seasonal climatic rhythms, we should know the daily sun's path at different latitudes. More surface observations should be needed in order to study this effect on Western Ghats. Generally speaking the effect of seasonal variation of climatic rhythm is less dominant than the diurnal variations in the tropical mountains and which is evident in the north-south analysis of the meteorological parameters carried out around the Western Ghats.

The diurnal variation of ground temperature shows a marked variation in the north-south direction which is more prominent than the seasonal variation. The maximum amplitude of the temperature wave is at 1430 hrs with a maximum amplitude of 5°C along the Palghat Gap and 2.5°C at the plain stations on both sides of the Western Ghats. As expected, the Winter season brings minimum temperature in the region even in the summit stations. Eastern coast will be cooler than the western coast during this period. The Deccan plateau is controlling the temperature in the northeast part of the study region that comes in Tamilnadu state. Narrow region of low lying area is situated in the north-western side of the mountain, whereas there is a wider area of elevated land mass with average 800 m height is located in the north-eastern side of the study region, which contribute much to the climate of that region. During the Summer season, the western coast will be cooler than the eastern side of the mountain.

Deccan plateau stands like an isolated area from the surroundings when the temperature is considered. Northeast monsoon brings cooler air to Deccan plateau in Autumn season while Tamilnadu is still warmer. Palghat shows higher temperature of 2°C in all season than the surrounding areas. Mean deviation of temperature shows a sudden change when we cross the Western Ghats from west to east. The range of the deviation of the extreme temperatures becomes double over Tamilnadu than Kerala. The mountain thus imparts its influence on the higher temperature of the Tamilnadu region especially at the down wind region of the Gap. Also the terrain height of 1200 m over the Western Ghats mountain controls the surface temperature dramatically. The plain stations do not receives much flux from the subsurface soil as sensible heat, when compare with the summit stations . The penetration of monsoon rainfall to the subsurface soil reduces the soil temperature at the 10 cm level more in the plain stations in Kerala. This can also be seen in summit station but with reduced intensity but not at all seen over Tamilnadu stations where there is not much water intrusion into the subsurface soil during that period. Thus the variation of soil temperature is also different in the eastern side of the mountain than the western side or summit region.

The horizontal variation of mean sea level pressure is minimum in the study region. Since the orientation of the pressure pattern is following the terrain closely, especially the 400 meter contour and the northern part of the western coast will be different from the rest of the region. During most of the season pressure gradient will be maximum at the western side of the mountain than the eastern side which is primarily due to the steep valleys present in the western side. Winter season shows more pressure than any other season. Even though the temperature is less in Winter the density is more in the season which is contributing to the increase of pressure over the stations. The semi diurnal pressure wave is very clear with an average amplitude of 1 hPa in all stations and its amplitude is the same in both the oscillations in a day. The phase of the pressure wave matches with the phase of the temperature variation. The long Gap at Palghat is not influencing the pattern of pressure at all.

Winter brings easterlies towards the peninsular region and it tries to cross over the eastern side through the Palghat Gap and the Aryankavu Pass which is towards the south of Cardamom hills in the Western Ghats. Peninsular region will be under the grip of westerlies even in the month of October and it will slowly move back for the arrival of the northeasterly winds which must have invaded the central India by that time. In Spring and Winter, easterlies will be prevailing and it will converted into strong westerlies by the end of May. Easterlies coming through the Palghat Gap from Tamilnadu intensifies when it reaches the down wind region of Kerala at Malappuram and Palghat districts except Summer season. The channeling of the northerlies by the mountain to the southern latitudes are more in the western side of the Ghat.

Also between the 1130 and 1430 hours LT the maximum wind is obtained in all stations which is again coinciding with the phase of temperature and the pressure wave. The diurnal wind pattern is feeble but more clear in Summer season over the region. The zonal component of wind is stronger than the meridional component in all stations. The variation of the V-wind will be between -5 to 5 ms^{-1} in the lower troposphere in all stations and its influence is small during the monsoon months. The variation of U-wind is clear in Kerala but not in Tamilnadu. Undulating wind speed characterizes the mountain regions. Another notable feature is that in Autumn season, wind speed increases above 850 hPa level. Strength of the southerlies increases in Spring and Winter at the upper troposphere and the influence of meridional component is meager at all levels in the Autumn season. Wind speed generally increases from the month of May onwards in all stations in the study region and the average annual wind speed is found to be 3 ms^{-1} in Kerala, while it is 4.8 ms^{-1} in Tamilnadu and 5 ms^{-1} over the summit regions.

An increase of vapour pressure is observed at the summit regions than the free air surrounding it and the control of the Western Ghats over the moisture transport is seen in the reduction of the vapour pressure at the eastern side of the mountain. The decrease of the vapour pressure is greater in the lower layers as observed in middle latitudes. The variation in the seasonal pattern of moisture is very small in the north-south direction. That clearly shows the moisture variation is depending on the air mass type present and the uniform variation in all stations expose the homogeneity of the air mass present in the peninsular region. The effect of the Palghat Gap in regulating the moisture is visible in the upwind and the downwind region of the Gap.

Relative humidity in the region is not going beyond 60% in any season except over summit in the Spring season. A small increase in RH is seen in the afternoon hours in the study area which differs from the middle latitude mountain areas and the value of RH increases with height in winter in all stations. In the density pattern also the variability is meager. There is an increse of $0.005 Kgm^{-3}$ density over the summit than the surrounding free air.

Autumn and Summer season creates a blanketing effect on the peninsular region by cutting the insolation due to massive cloud masses and hence generally the net radiative flux is found to be less during that period. Summit region also shows a reduction in the net radiation. Net radiative surplus is there in all season except over summit in the Spring season when the medium cloud amount obstruct the net radiation at those regions. From the nocturnal radiation analysis it is found that the summit region cools more than the plain or valley station in the night. Tamilnadu cools faster than Kerala in the night time due to the reduced amount of clouding in the sky.

Summit regions shows much clouding than the rest of the region in the study area .

Low clouds are more throughout the region in any season while medium clouds are less in Autumn and Spring season. Low and medium clouds are more over Kerala than Tamilnadu. High cloud do not show any variation in the diurnal range and during noon hours we can see the amount of medium and low clouds increases in the region which in turn coincides with the diurnal increment of relative humidity in a station. The modeled data of surface meteorological parameters are compared with the observed mean data of IMD and it is well agreeing with the ground conditions existing in the study region.

CHAPTER 3

Circulation System Related to Western Ghats Orography

3.1 Introduction

Even-though the circulation system around a mountain can be studied easily, the local variation of the winds due to the topographical specialties are so complex. The high density observational network is needed for this type of study. Around the Western Ghats these type of integrated study has not been done recently. The model predicted wind is tested with ground observations and found reasonable accuracy. For the study of the gravity flows high resolution data of every meter is needed in the lowest 30 meters of the atmosphere over the valley region. The effect of topography on air motion operate over a wide range of scales and produce complex circulation systems through the mechanism of dynamic and thermal factors. The major Gap of Palghat controls the circulation at the central districts of Kerala and Tamilnadu which in turn decides local climate of the region. The wind systems in a mountain environment is modified by the dynamical or thermal effects. In the following sections a detailed analysis of the wind modifications and its influence on the planetary and synoptic scale variations of meteorological parameters have discussed.

3.2 Dynamic Modification

The three major type of dynamical processes can be categorized as first extensive mountain ranges set up planetary scale wave motion through large scale rotational effects, second, the mountains give rise to modifications of synoptic scale weather systems and thirdly, topography on all scales introduces wave motion through local gravitational effects. Even though these categories are not always sharply differentiated from one another, they provide a convenient basis for the analysis.

3.2.1 Planetary Scale Effects

Effects of Conservation of Absolute Vorticity

On the planetary scale, airflow over mountain is affected by the earth's curvature and rotation which setup horizontal wave motion with a wavelength of about 5000 km. The large scale effects of an orographic barrier on an airflow crossing it are usually explained as a consequence of the relationship between divergence and vorticity. This is illustrated by the equation for the conservation of potential vorticity

$$\frac{(\zeta + f)}{\Delta p} = constant \tag{3.1}$$

where

ζ = Relative vorticity about a vertical axis

f = Coriolis parameter

Δp = Thickness of air column in pressure units.

It is assumed that the atmosphere is incompressible and that the air motion is adiabatic. The above equation shows that, if the expression on the left hand side is to remain constant as an air column approaches a mountain range and Δp decreases, then there must be a corresponding decrease in $(\zeta + f)$. In other words vertical shrinking of the column must be matched by lateral expansion, implying horizontal divergence. For $(\zeta + f)$ to decrease, either the air stream undergoes anticyclonic curvature or the air must be displaced equator ward where f is small. Conversely, the downward side of the barrier, Δp increases again with the opposite effects. From the earlier findings in middle latitude the curvature effect is predominant in those regions. However a slightly different class of thought is put forwarded by Smith, in which he proposes that an air parcel crossing a range in a quasi geostropic flow undergo volumetric expansion as they rise and this creates anticyclonic vorticity and the effect of the expansion does not cancel out, but causes a non-vanishing circulation. Even though the effects described in this sections will be seen in synoptic scale, the impact of these may be transformed into planetary scale in the form of large scale circulation or mountain waves.

Curvature Effect on Western Ghats

It is assumed that the atmosphere is incompressible and the air motion is adiabatic. As an air column approaches Western Ghats the air flow diffluence is happening for the stream. South of the axis of the flow barrier effect reduces the value of 'f' deflecting the current equator ward. On the northern side of the axis current is deflected poleward. The flow pattern observed on the major mountain ranges indicate that the effect on the curvature (relative vorticity) of the air flow is predominant. In Western Ghats also the curvature effect dominates and the strong cyclonic and anticyclonic vorticity fields are developing over the high peaks.

There is a seasonal change in the wind pattern over the Western Ghats in an year. It is found that the strong westerlies blowing during the Summer season over the southern peninsular India will be present in reduced intensity even from the second half of Spring season, that is the end of April and May. The flow will be easterlies in the rest of the season. The vertical profile of wind (see fig.2.20) shows that the maximum wind speed of about 16 ms^{-1} is occurring during the Summer season at 850 hPa level and the easterlies will be attaining a speed of about 16 ms^{-1} in the mid-tropospheric level during the Spring season. The wind again increases to above 25 ms^{-1} in the regime of upper level easterly jet. In the earlier studies in middle latitudes it is found that a narrow jet stream flow may be deflected anticyclonically, so as not to cross a mountain range , if the wind speed is below a particular threshold.

It is found that for zonal flow encountering the 2 km high 1000 km wide barrier, the critical speed is 20 ms^{-1} (*Reiter*). If the curvature of the flow is cyclonic (anticyclonic), this critical value will be correspondingly less (greater), respectively. Secondly, if we consider the cyclonic and anticyclonic side of the jet stream axis, the vorticity relationships can lead to air stream diffluence. South of the jet axis, where the absolute vorticity $(\zeta + f)$ approaches zero, the mountain barrier affects the flow leads to a reduction of f, deflecting the current equator ward. On the northern side of the jet axis the current is deflected poleward, assuming conservation of absolute vorticity.

Hence if we analyze the wind field at the 800 hPa level, we can see that the vorticity over the mountain ranges are making an adjustments to stabilize the flow and keep the potential vorticity conserved. Both a cyclonic and anticyclonic rotation is initiated over the peak for this adjustments. thus the mountain induced diffluence is seen over the Western Ghats region. The analysis of the wind field in the different season over

Anamudi is given in fig.(3.1). During the westerly regime the poleward end of the flow will be having an anticyclonic vorticity while the equator ward side is having a cyclonic rotation. The magnitude and spatial distribution of the anticyclonic field will be more than the cyclonic field over the mountain environment of the Western Ghats. Similarly in the easterlies which prevails over the region during Autumn and Winter season, the reverse pattern is formed around the summit. This clearly shows that as in the case of mountain ranges of middle latitudes, the tropical mountains also dominates with the curvature effect (change in relative vorticity) rather than the Coriolis term. In the Nilgiri range also the Curvature effect is very distinct as in the case of Anamalai hills (fig.3.2) and it is absent in the Palghat Gap region (fig.3.3). This clearly shows that effect is purely due to the vorticity adjustments over the mountain region. The model value of the anticyclonic vorticity term is found to be 1×10^{-4} s^{-1} over the Anamudi range, where the Coriolis term is only 2.532×10^{-5} s^{-1}. Hence it is evident that the effect of vorticity term is one order higher than the Coriolis term in the mountain terrain of the study region.

So the conservation of absolute vorticity of the air flow over the mountain region of southern peninsular India is achieved effectively by the adjustment of relative vorticity. These type of vorticity changes and the conservation of absolute vorticity will be the reason for the planetary scale waves and the mountain anticyclones forming in the downwind side of the major mountain ranges which comes under the jet stream regime of different latitudinal belts. The amplitude of the wave disturbances will be depending upon the latitudinal extend of the barrier strongly.

Turbulent Kinetic Energy Transfer Over the Region

When wind blows, the turbulence is mainly created by the frictional effects induced by the thin laminar layer and the surface layer of the Planetary Boundary Layer (PBL). Thus the

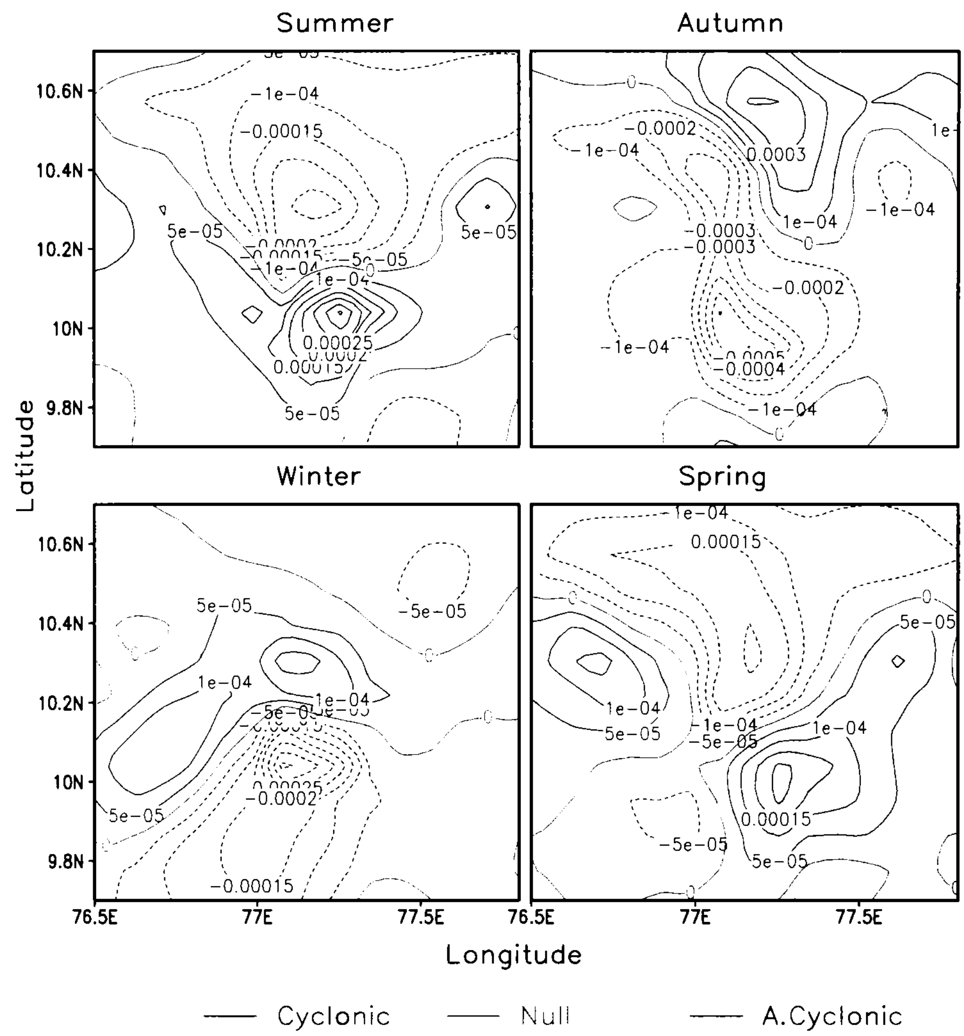


Figure 3.1: The vorticity profile over Anamudi range in different season.

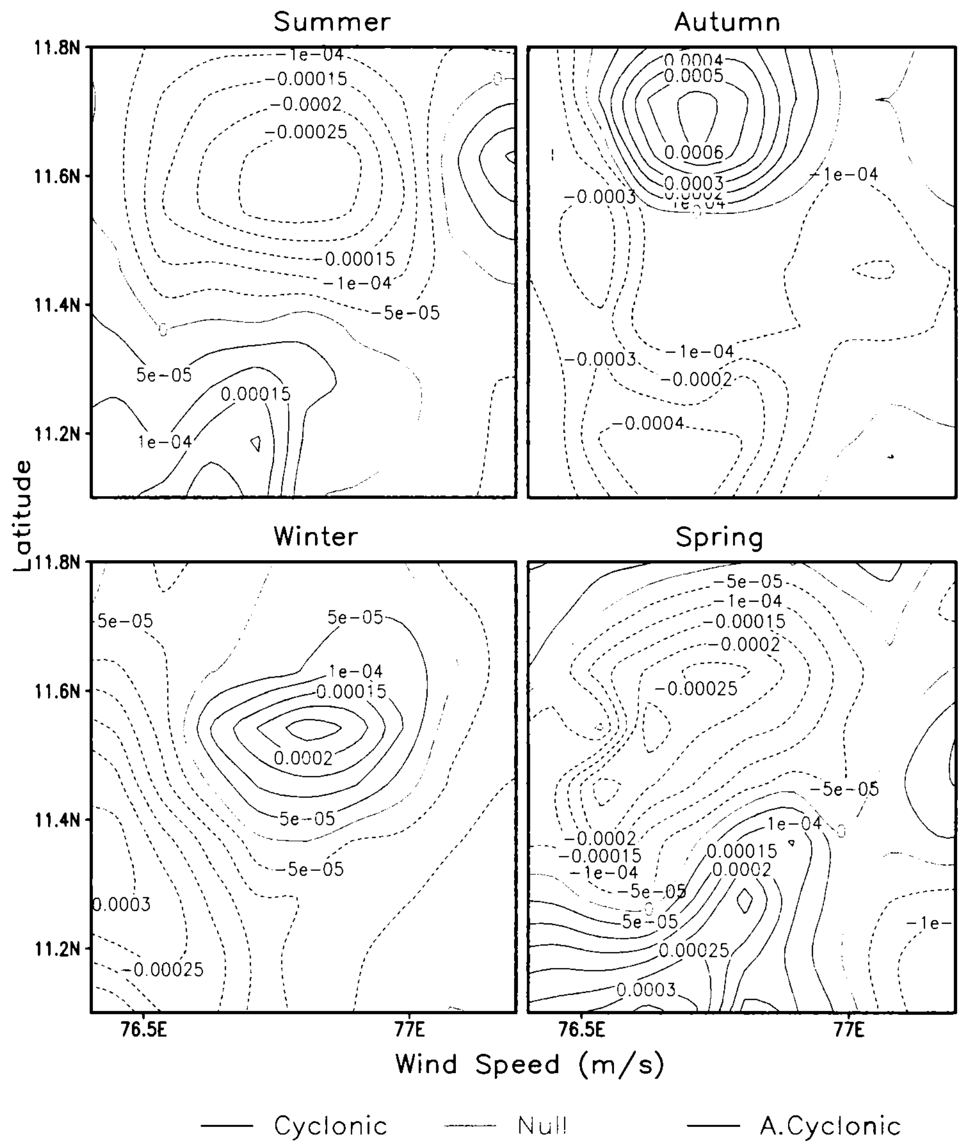


Figure 3.2: The vorticity profile over Nilgiri range in different season.

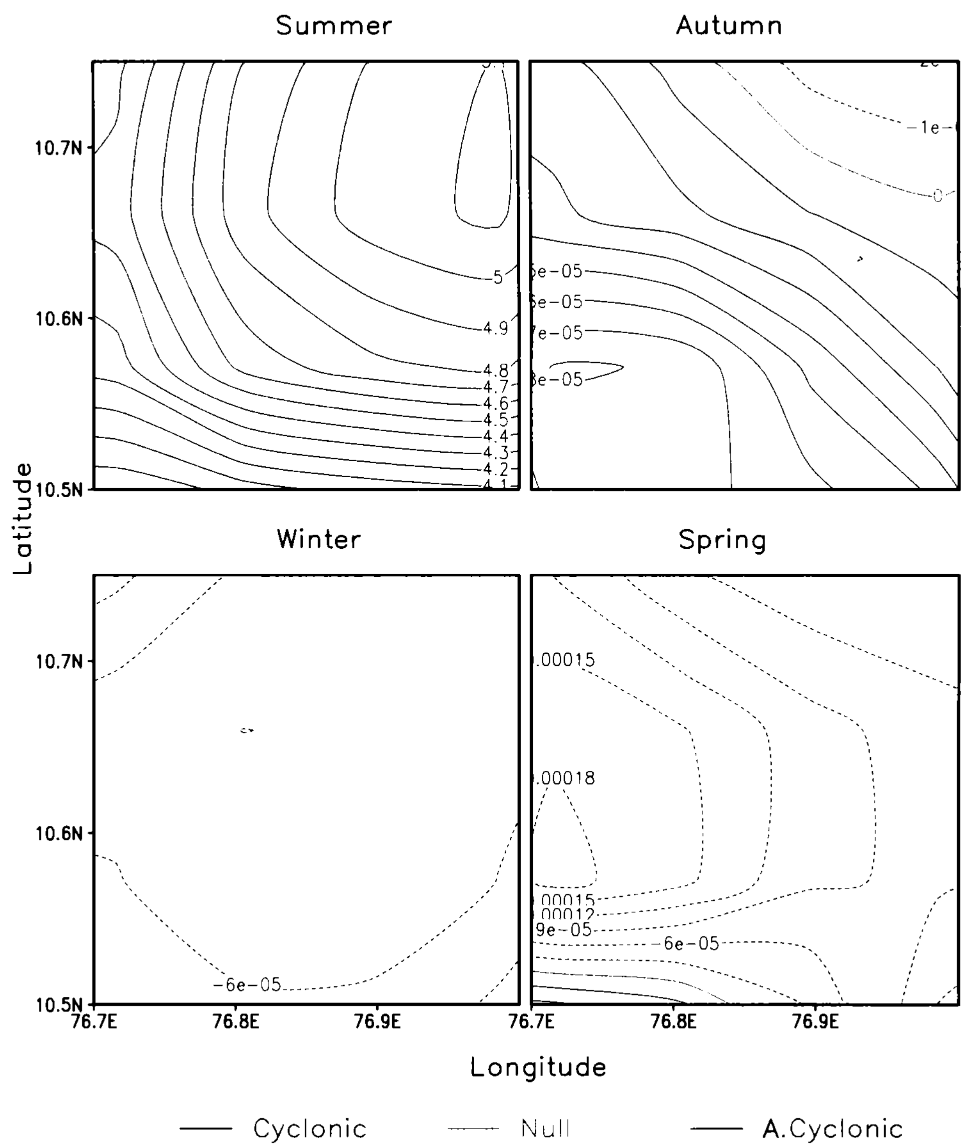


Figure 3.3: The vorticity profile over Palghat Gap in different season.

turbulent kinetic energy (TKE) is mainly depending upon the terrain in which the wind is blowing and also the wind speed. In the study region we have seen that the surface winds is maximum at the noon hours between 1130 and 1430 hours. The monthly variation of turbulent kinetic energy shows that the maximum value is attaining in the month of July in the region during the noon hours between 1130 and 1430 hrs. The value of the turbulent kinetic energy varies from 0.2 to 3 Jkg^{-1} in the PBL. Upto 800 hPa it is decreasing and becomes negligible. But it is found that the mountain peaks reaching upto 800 hPa level will impart the turbulent kinetic energy upto 700 hPa level when the winds are strong.

The distribution of turbulent kinetic energy during Summer and Spring season are given below. At the surface the TKE attains a value of 2 Jkg^{-1} and upto a level of 700 hPa which is above the peak of the mountain by 100 hPa at that level and the mountain is transferring the energy with a magnitude of 0 to 8 Kg^{-1} (fig.3.4). But in Spring season as

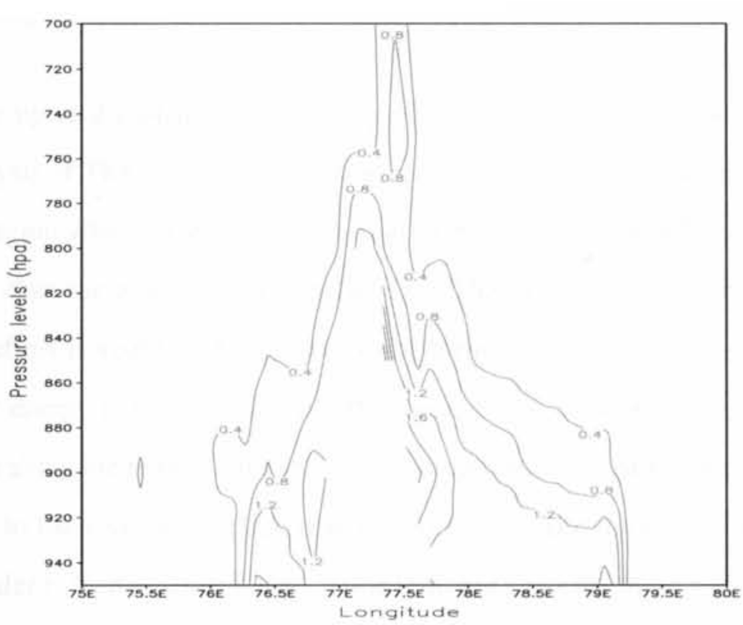


Figure 3.4: Turbulent kinetic energy (JKg^{-1}) transfer along the cross section of Anamudi hills during Summer season.

the winds are lighter the TKE also reduces to 1.4 Jkg^{-1} in the surface (fig.3.5). There is a

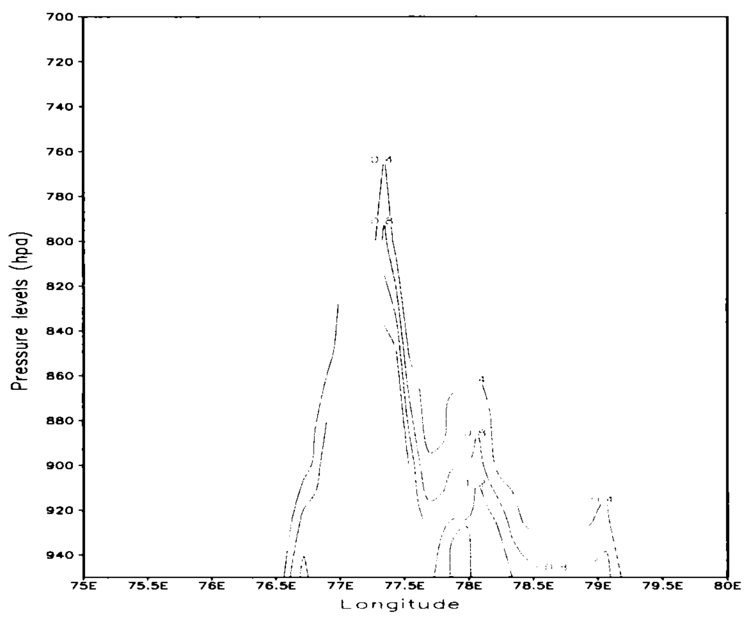


Figure 3.5: Turbulent kinetic energy (JKg^{-1}) transfer along the cross section of Anamudi hills during Spring season.

reduction in the upward propagation of energy (0.4 Jkg^{-1}) which reaches only upto 760 hPa level. Analysis of TKE transfer at the Palghat Gap shows the accumulation of contour over the Gap region which clearly indicates that high amount of turbulence is occurring over the region than the rest of the region (fig.3.6). The surface value is reaching upto 2 Jkg^{-1} and the effect is visible upto 830 hPa level during south-west monsoon. Along the Gap the kinetic energy is transferring upto the coast. Even in the weak wind system the transfer is there along the region. This indicates that mountain is redirecting the Turbulent Kinetic Energy to the vertical direction than the horizontal. But during the Spring season the energy transfer is feeble (0.4-0.8 Jkg^{-1}) and it do not cross the 900 hPa level (fig.3.7).

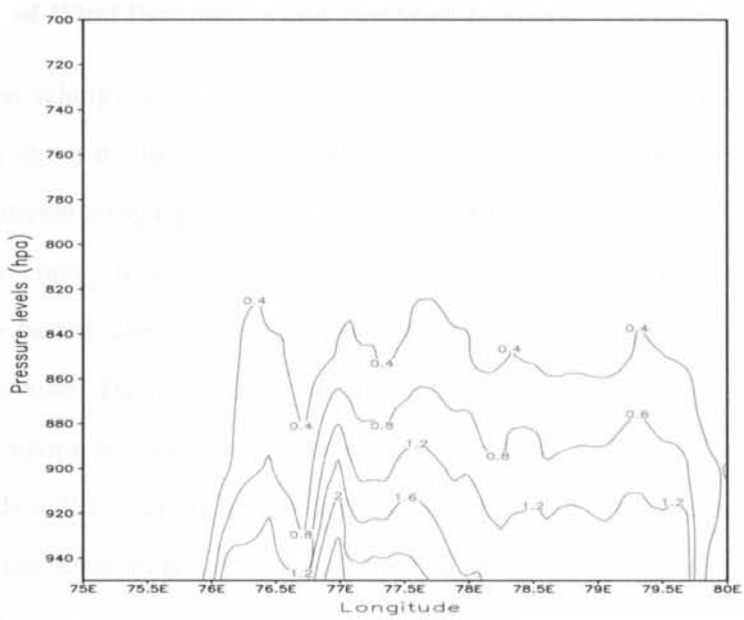


Figure 3.6: Turbulent kinetic energy (JKg^{-1}) transfer along the cross section of Palghat Gap during Summer season.

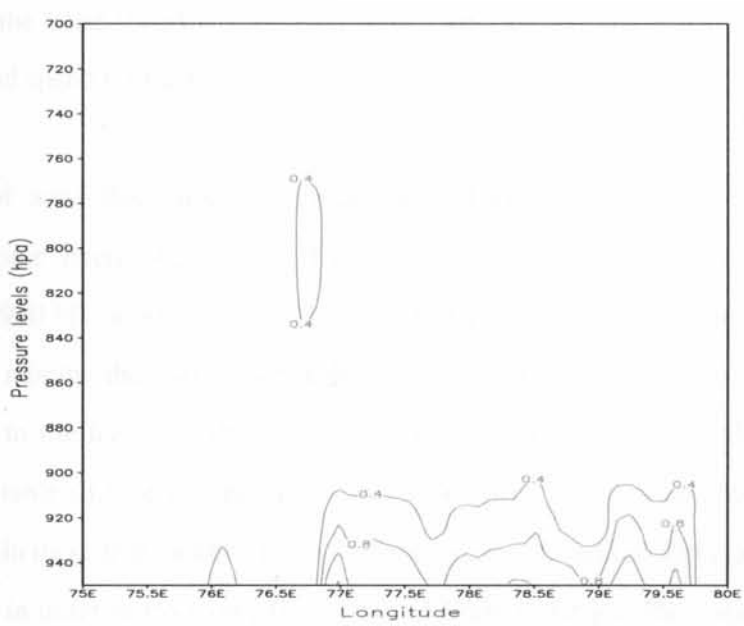


Figure 3.7: Turbulent kinetic energy (JKg^{-1}) transfer along the cross section of Palghat Gap during Spring season.

Critical Values of Wind Parameters and Potential Temperature Over the Study Area

An air flow approaching a mountain should posses minimum energy in order to overcome the terrain and move to the leeward side. The classical theory states that the kinetic, potential and internal energy possessed by the wind flow will be utilized for overcoming the barrier. The energy level possessed by the air flow and the qualitative response of the wind to the barrier can be assessed reasonably well by looking the wind speed and potential temperature. This pattern has been adopted successfully in the middle latitude region. While looking the wind pattern existing in the study region, we can see that the maximum winds will be getting in the Summer season in which the Summer monsoon is getting. The low level jet is having an axis at 850 hPa level and the wind shear is also there towards the lower layers. A strong westerly flow prevails over the region during the four months (June-September) of the southwest monsoon period. Also the strong easterlies prevails in the boundary layer during November which represents the Autumn season. Rest of the months the wind speed will be less. Hence we can take these five months which shows high wind speed for the following analysis.

The analysis of wind flow along a latitude belt which passes through a summit region reveals some interesting results. The wind speed and the potential temperature analysis at the 950 hPa level has been given in the figs.(3.8 to 3.10). Among the southwest monsoon months the surface wind during the month of July is only crossing the Western Ghats to the lee side. This is not seen in November when easterlies are there. The following table (3.1) gives the values for wind speed and potential temperature at different levels in these five months. From the table we can formulate three criteria for the wind to posses in order to overcome the terrain of Western Ghats. They are higher wind speed, potential temperature and a strong positive wind shear from surface to 850 hPa level.

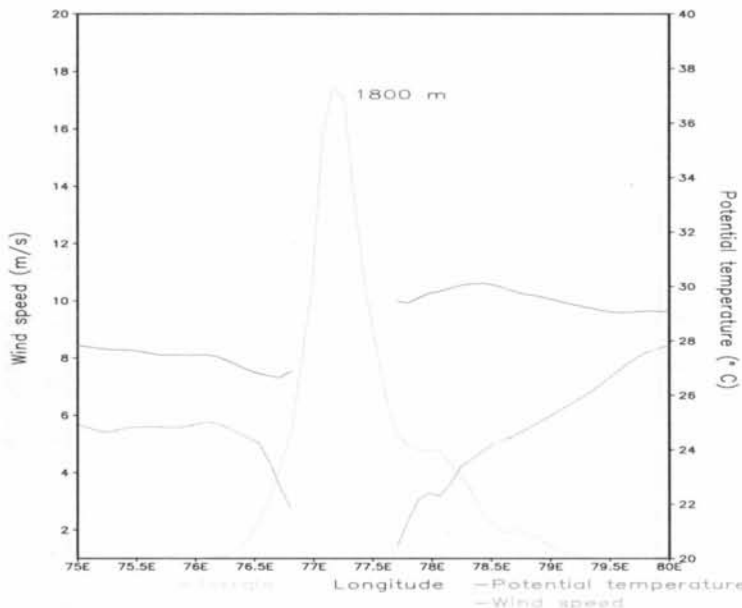


Figure 3.8: Cross section analysis of wind speed and potential temperature at 950 hPa level along 10.2°latitude in June.

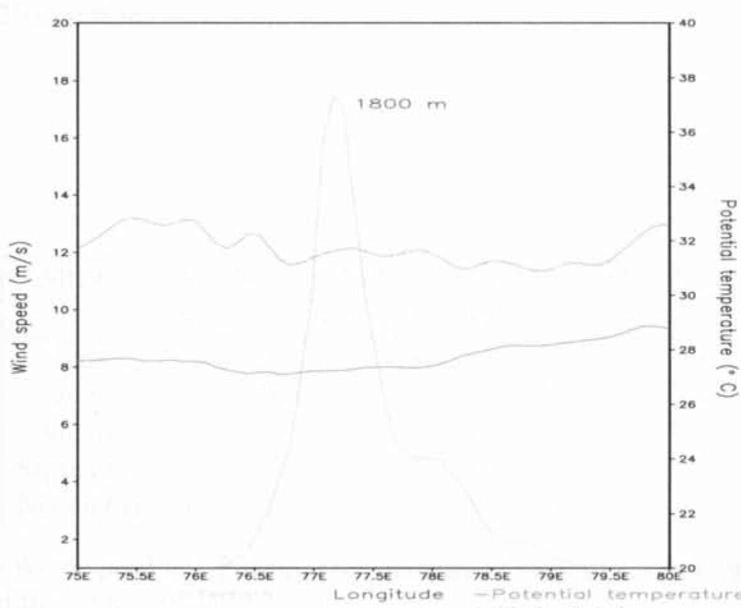


Figure 3.9: Cross section analysis of wind speed and potential temperature at 950 hPa level along 10.2°latitude in July.

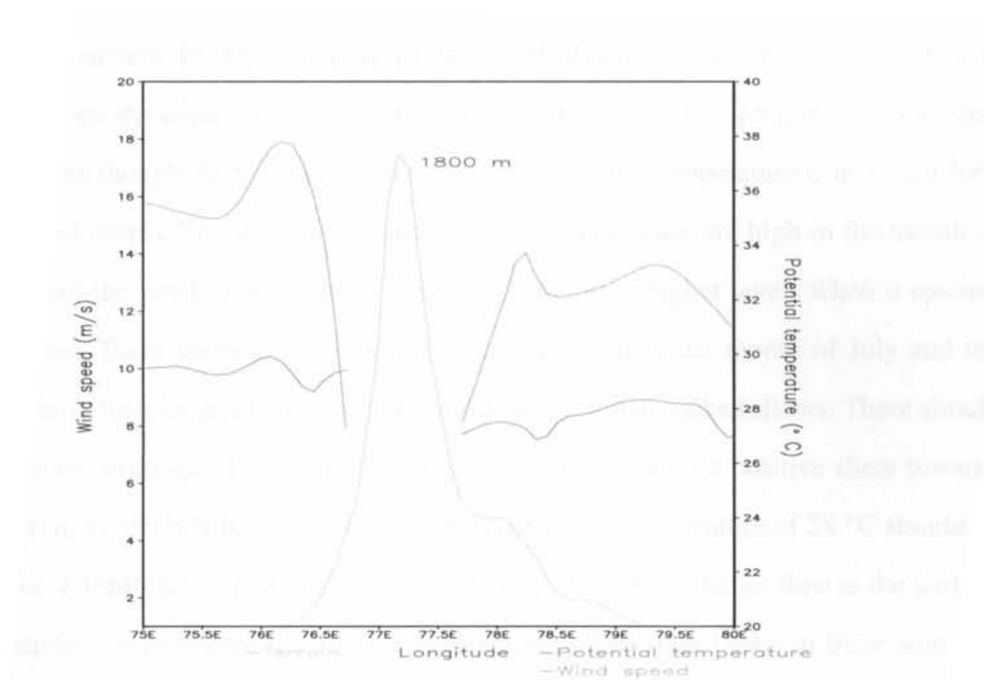


Figure 3.10: Cross section analysis of wind speed and potential temperature at 950 hPa level along 10.2°latitude in November.

Month	950 hPa		925 hPa		900 hPa		850 hPa	
	WS	PT	WS	PT	WS	PT	WS	PT
June	6	28	6	28	6	30	4	33
July	12	28	13	28	14	29	17	32
August	10	27	12	27	13	28	14	31
September	8	27	9	27	10	28	9	31
November	11	27	13	28	14	29	12	33

Table 3.1: The Wind speed and Potential temperature at various levels along the latitude 10.2°N during different months

The analysis is done around the Anamalai hills (along 10.2°N) where the average peak is 1800 meters. In the beginning of June even though the potential temperature is high at all levels the wind speed is less in the region. This is same for September also. But in August even though the wind speed picks up, the potential temperature is less than June and July at all levels. The wind speed and potential temperature are high in the month of November but the positive wind shear is not maintaining at higher levels when it reaches 850 hPa level. These three conditions are maintained well in the month of July and the general criteria for a hydraulic jump to occur can be formulated like follows. There should be a minimum wind speed of 12 ms^{-1} at the 950 hPa level with a positive shear towards the vertical upto 850 hPa level and the minimum potential temperature of 28 °C should be there at the 950 hPa level. If these three conditions follows then the air flow at the surface will be capable to overcome the 1800 m high terrain of Western Ghats in these southern peninsular region.

3.2.2 Synoptic Scale Effects

Modification of Temperature over the Region

While changes of the planetary flow are of major importance to global climate, modifications to synoptic systems are of more immediate consequence for conditions in the mountains themselves. Dynamic and thermodynamic effects of orography results from the forced ascent of air over the barrier, which leads to distortion of temperature structure through adiabatic process. The change in the temperature pattern is shown in the figs.(3.11 to 3.14). From the figures we can see that in the southwest monsoon period the temperature pattern is linearly oriented along the north-south direction in the western side of the mountain with 23°C and the valley region shows 22.5°C. But the eastern side of the Western Ghats shows a higher temperature of 25°C. Since the winds are strong westerlies during this period there will be an ascent of the air in the western side on the Ghats. As we go higher to 900 hPa

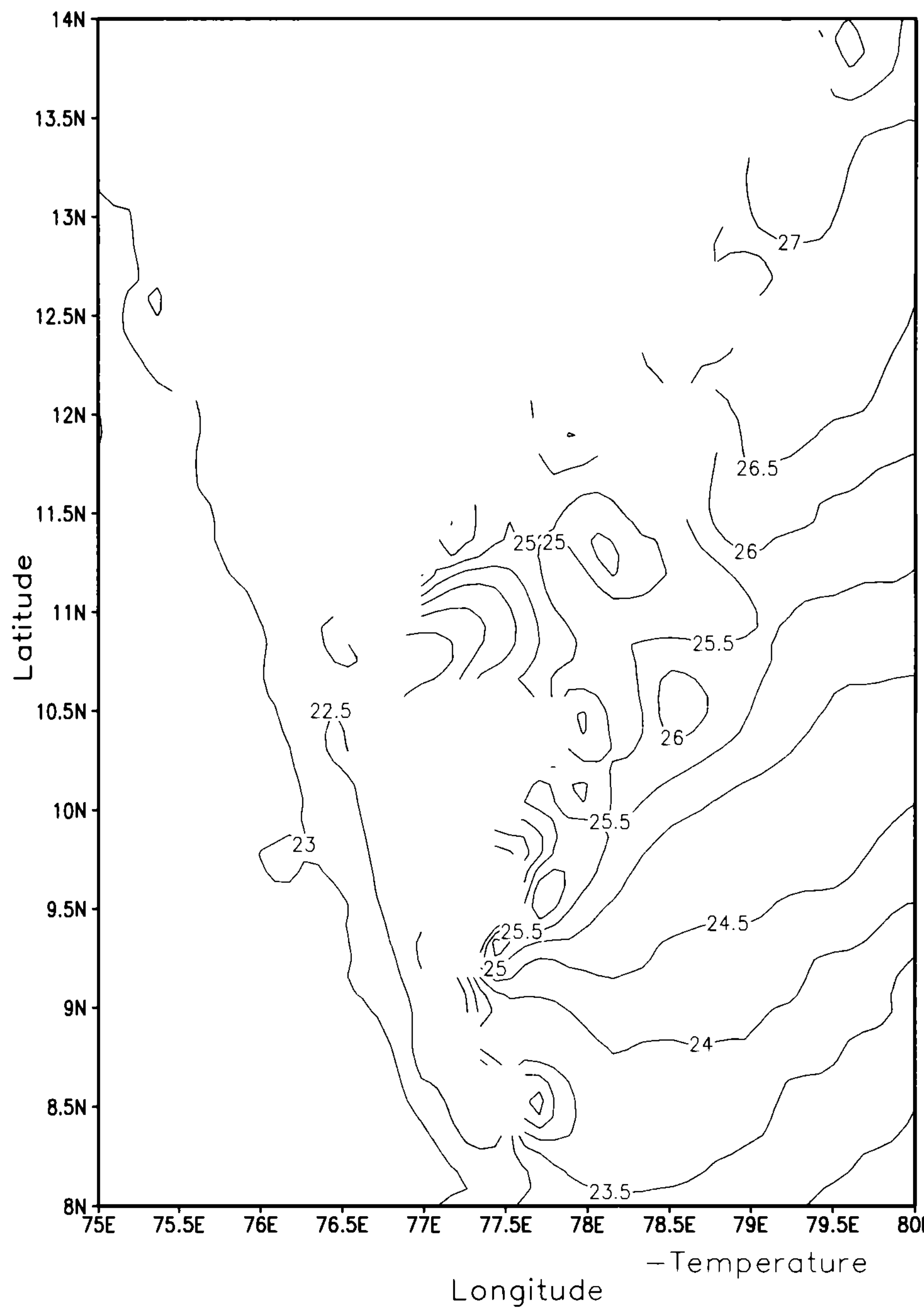


Figure 3.11: The 950 hPa temperature profile over the study region during Summer season.

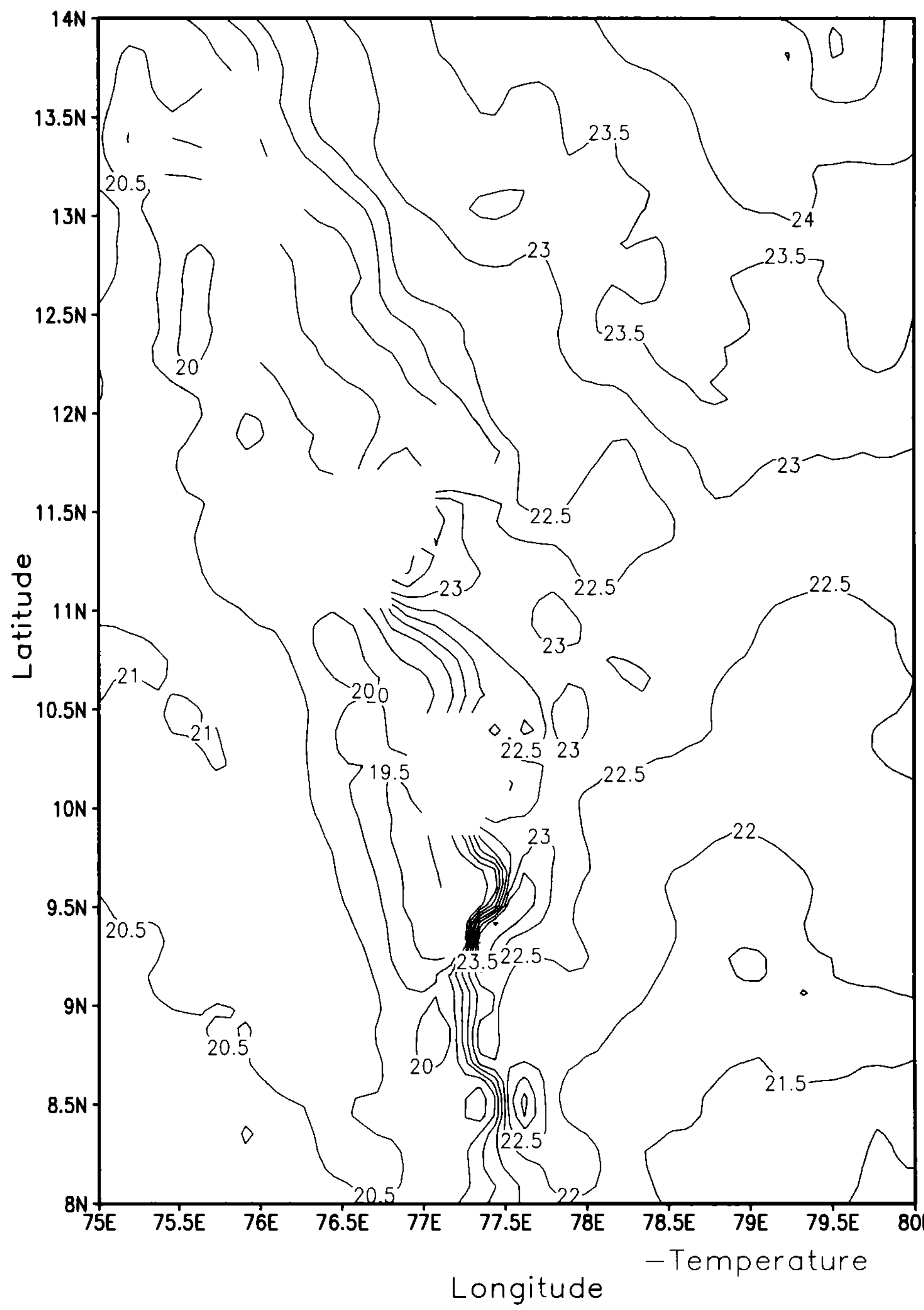


Figure 3.12: The 900 hPa temperature profile over the study region during Summer season.

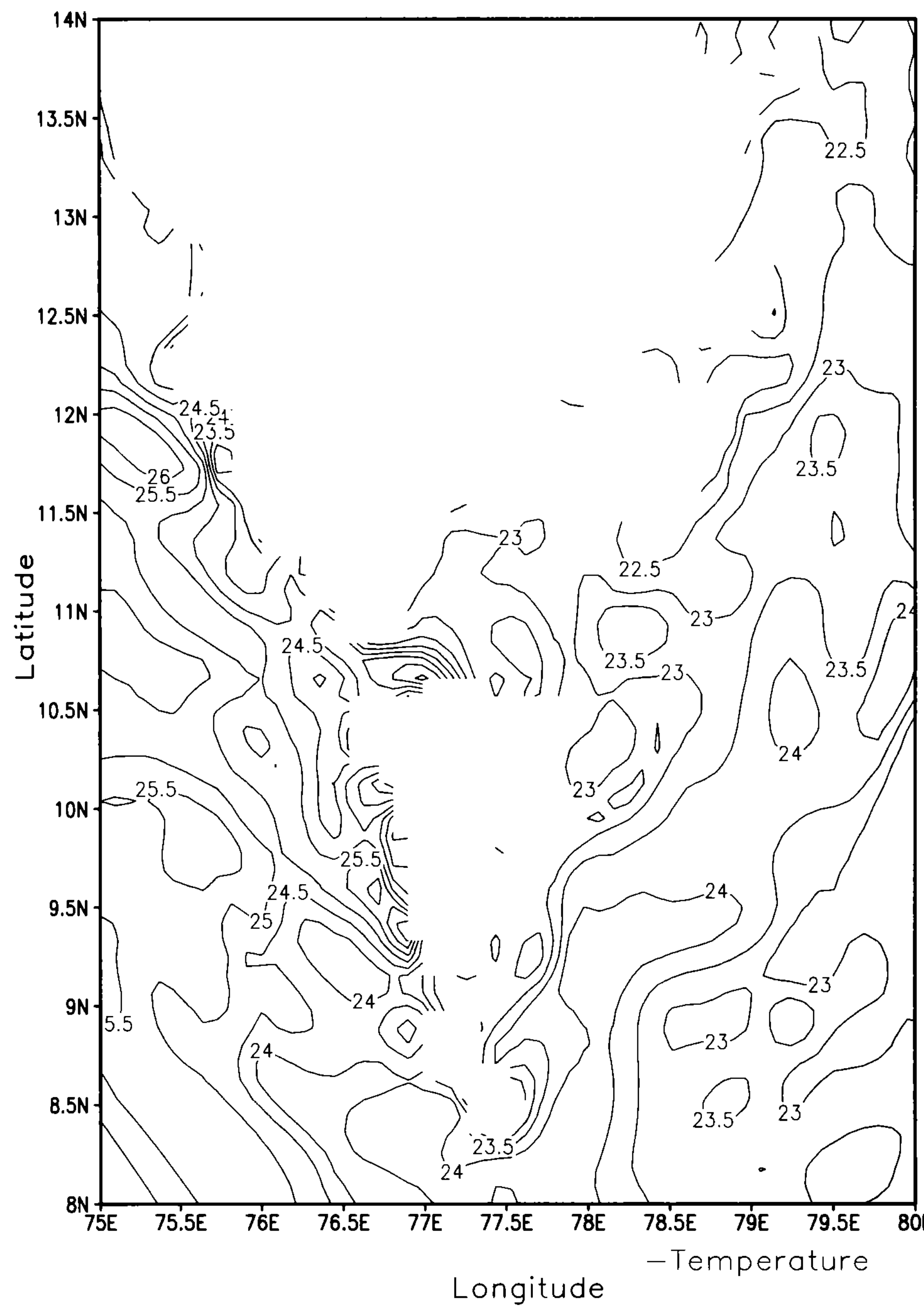


Figure 3.13: The 950 hPa temperature profile over the study region during Autumn season.

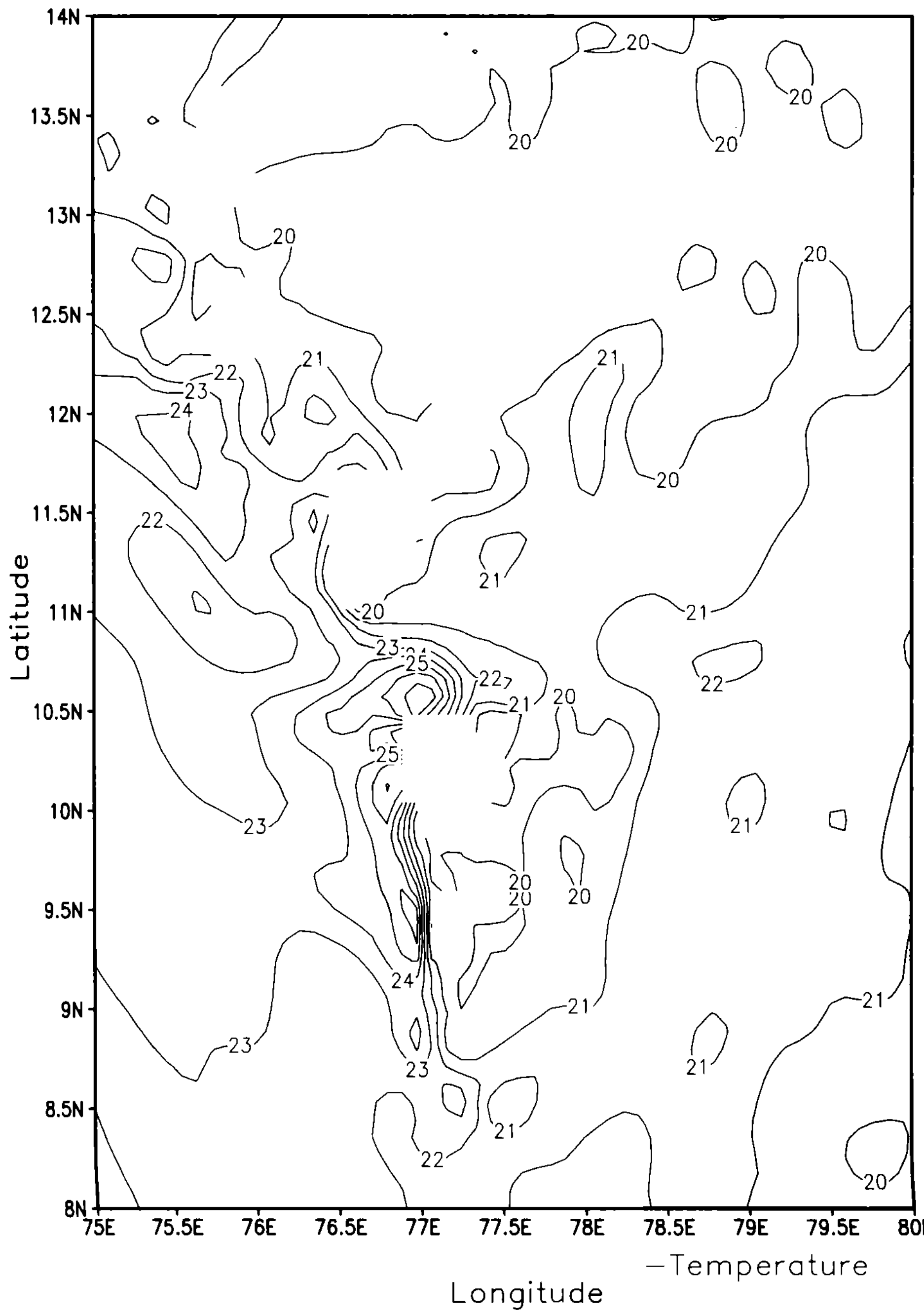


Figure 3.14: The 900 hPa temperature profile over the study region during Autumn season.

level the temperature again drops to 20°C. in the western side of the mountain and at the same time it is 22.5°C in the eastern side. The adiabatic cooling of 2.5°C is very clear over wind ward side (western side). Since the average height of the terrain over that area is about 1 km and the orographic lifting is not strong enough due to low wind speed at the lower layers, the maximum change of the temperature is occurring at the lower layers rather than above 1 km height. This can be seen in the entire stretch of the Western Ghats.

Modification of Relative Humidity over the Study Area

Forced ascent can also lead to humidity changes. When the uplift on the windward slope results in precipitation the humidity increases on that side. The increase of humidity on the wind ward side (western side) during westerlies over the region is well established in the analysis . As in the case of temperature humidity also shows a linear variation in the 950 hPa level in the western side of the Western Ghat mountain (figs. 3.15 & 3.18). In the eastern side, RH is below 90% everywhere at 950 hPa level. This can be seen in the 900 hPa level also. But when the air current is from the eastern side the reverse is happening. The relative humidity is varying from 90 to 100% in the eastern side of the mountain and nowhere in the western side of the Ghats we could see that much humidity values. Thus the control of the mountain is very clear in making synoptic scale changes in the temperature and humidity field over the study region.

Corner Effects of Wind on Western Ghats

The anticyclonic deformation of streamlines over a ridge creates an intensified pressure gradient at the left end of the ridge viewed downwind (in the northern hemisphere), referred to as the corner effect by Bergeron for middle latitudes. The gradient causes local wind maximum in the left side of the region which is generally observed in the north-westerly airflow over the middle latitudes. We have earlier seen in our study that

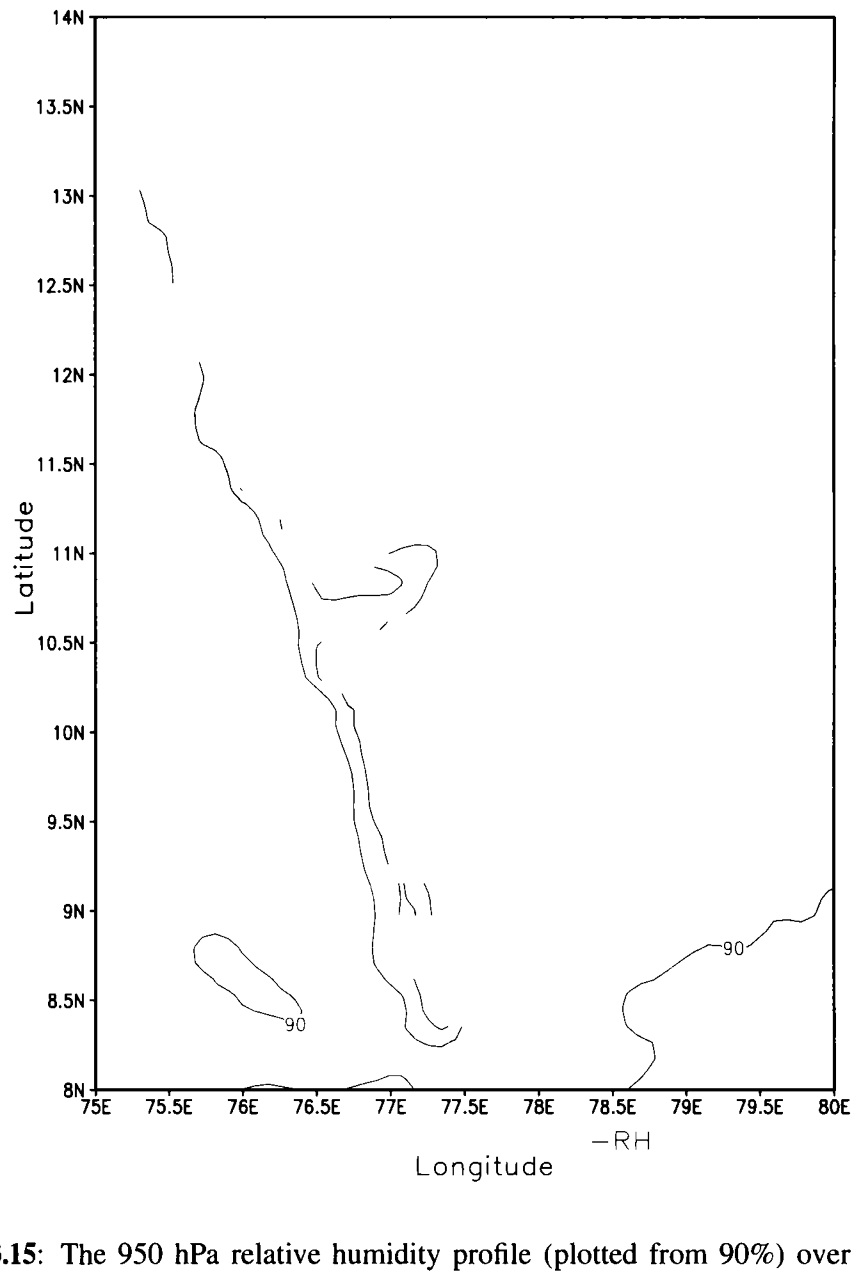


Figure 3.15: The 950 hPa relative humidity profile (plotted from 90%) over the study region during Summer season.

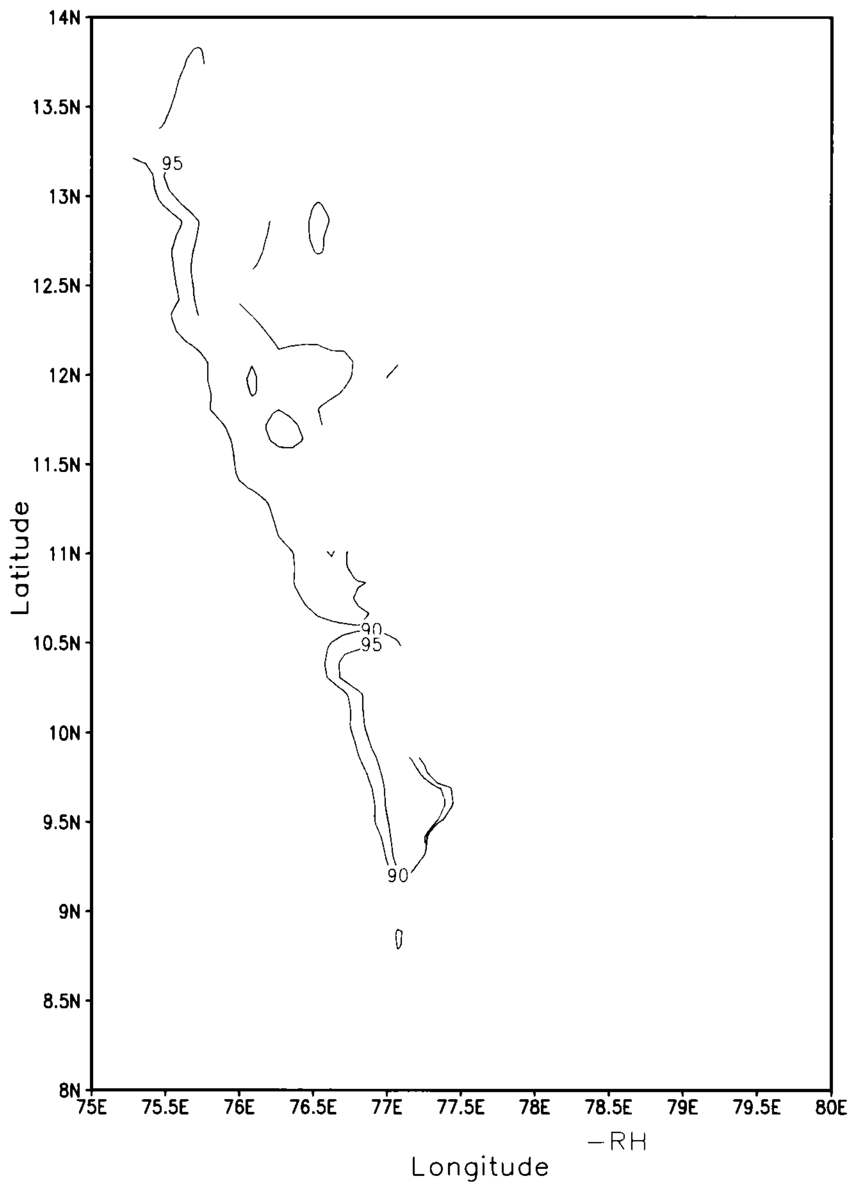


Figure 3.16: The 900 hPa relative humidity profile (plotted from 90%) over the study region during Summer season.

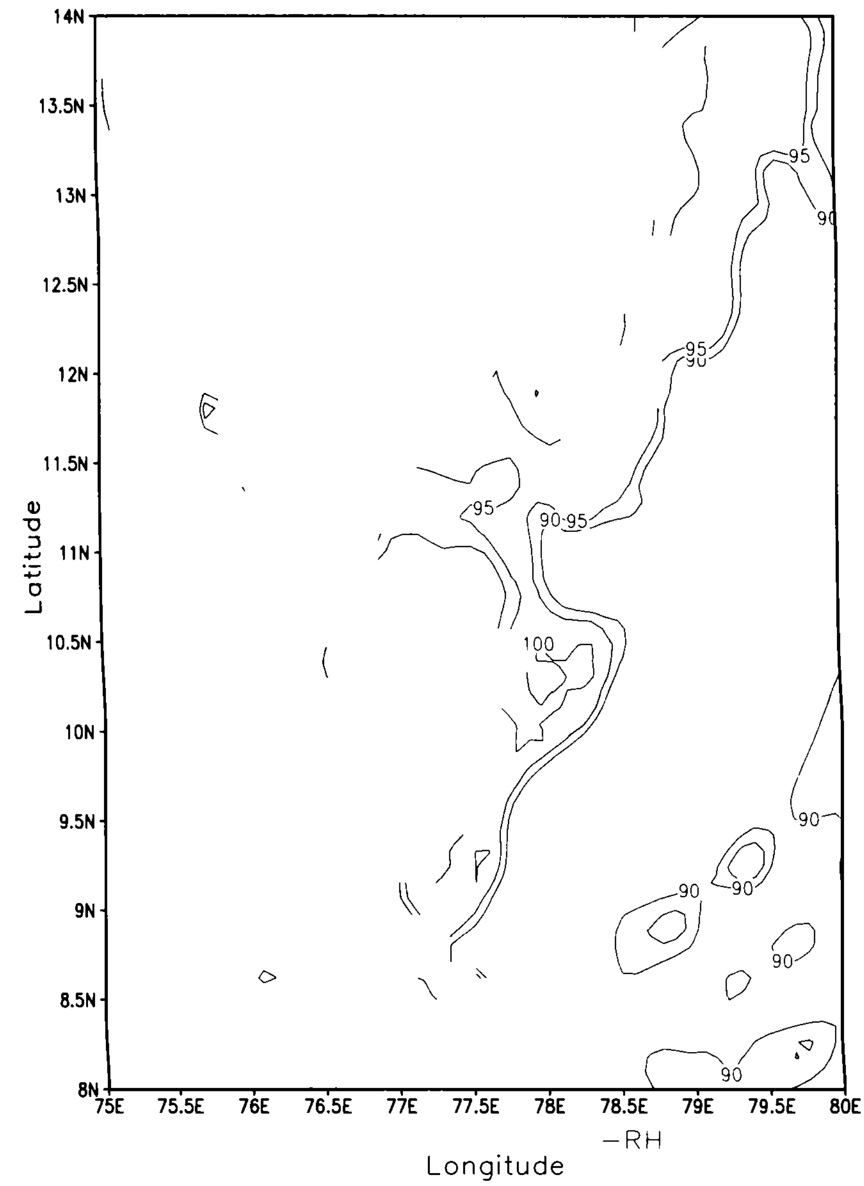


Figure 3.17: The 950 hPa relative humidity profile (plotted from 90%) over the study region during Autumn season.

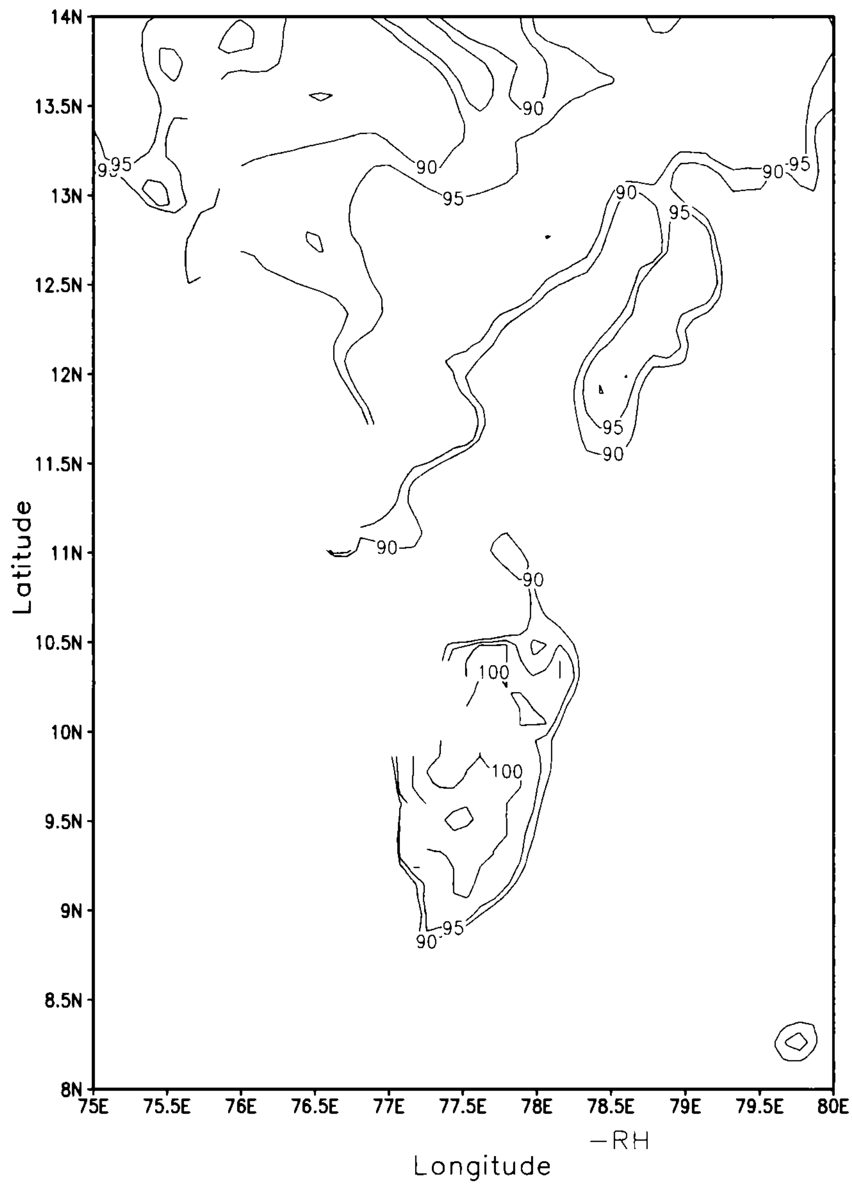


Figure 3.18: The 900 hPa relative humidity profile (plotted from 90%) over the study region during Autumn season.

the curvature effect is more around the Western Ghats and saw the change in position of the vortex field with different season around the peak. Hence with the positioning of the anticyclonic vorticity the local winds will be varying over the summit and the valley regions. The analysis of the wind field at 850 hPa level reveals the corner effects of the wind over the study region.

The analysis of the wind field for different months are given in figs. (3.19 to 3.21). The wind prevailing over the region during Winter (January) is north-easterlies and at the southern end of Nilgiri hills we can see the convergence of wind at 11°N, 76.5°E which is an indication of the increased pressure gradient over the region. The anticyclonic curvature of the flow is very clear over the western side of the mountain. But similar convergence of wind is not seen at the Anamalai hills at that time because of the absence of anticyclonic vorticity at the western side of the mountain. In Spring (April) the corner effect is feeble over both mountain peaks of Nilgiri and Anamalai when the winds are north-westerlies. But during the beginning of the Autumn season (October), the influence of strong westerlies will be there in the southern peninsular region. The effect is very clear over the Anamalai hills at 10.4°N, 77.2°E and also visible at Nilgiri hills but with reduced intensity. Thus the corner effects which is seen over the middle latitude mountain region is found to be affecting the Western Ghats mountain region also in either westerlies or easterlies, when the winds are strong. The corner effects will be the reason for the local air flow modification and there by gusty winds prevailing over the valley region around the high peaks of Anamudi as well as Nilgiri hills.

3.2.3 Local Air Flow Modification and Wave Formation

Theories of airflow over mountains are mathematically complex. Airflow over mountains involves motions with a horizontal scale of 1-100 km, apart from the major long wave

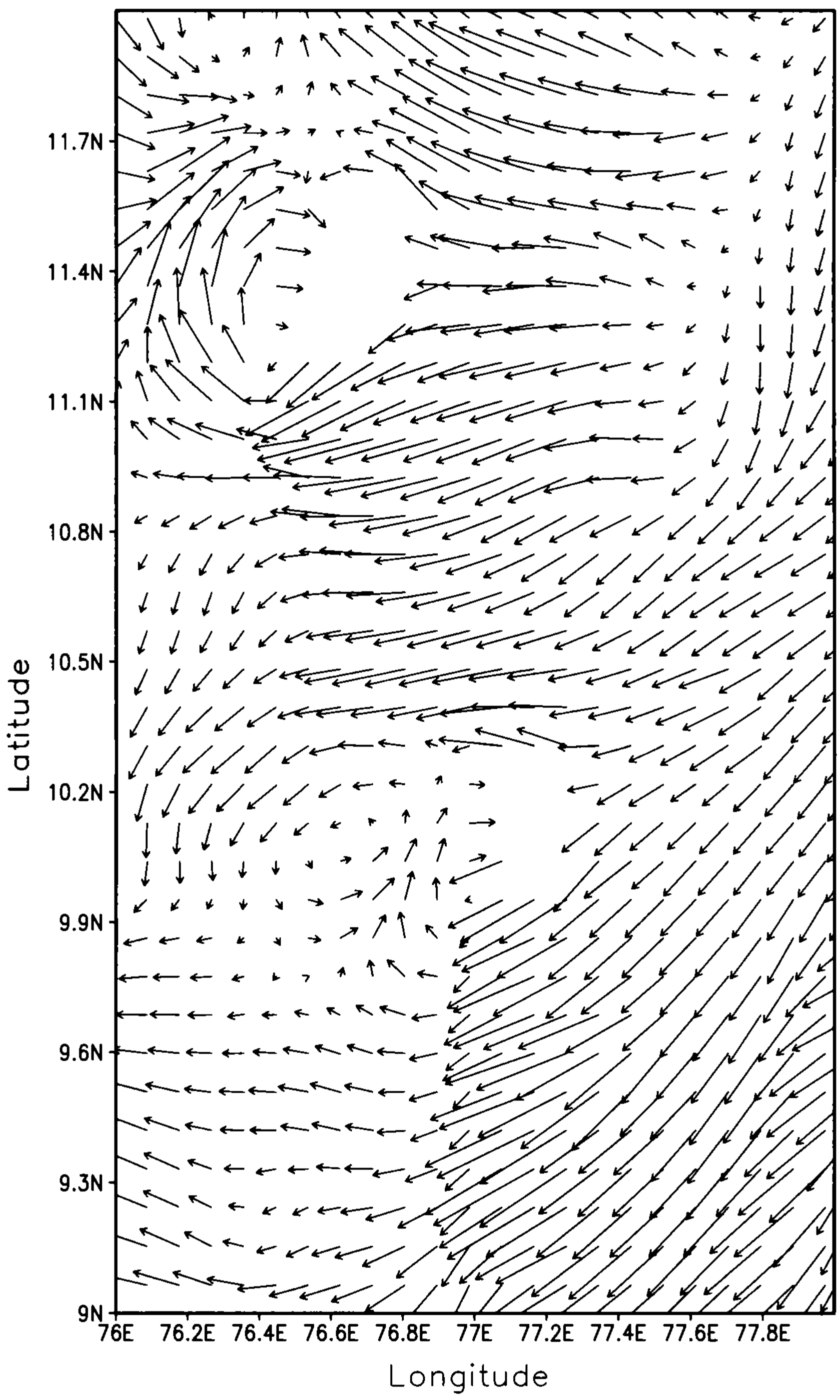


Figure 3.19: The 850 hPa wind profile over the study region during the month of January.

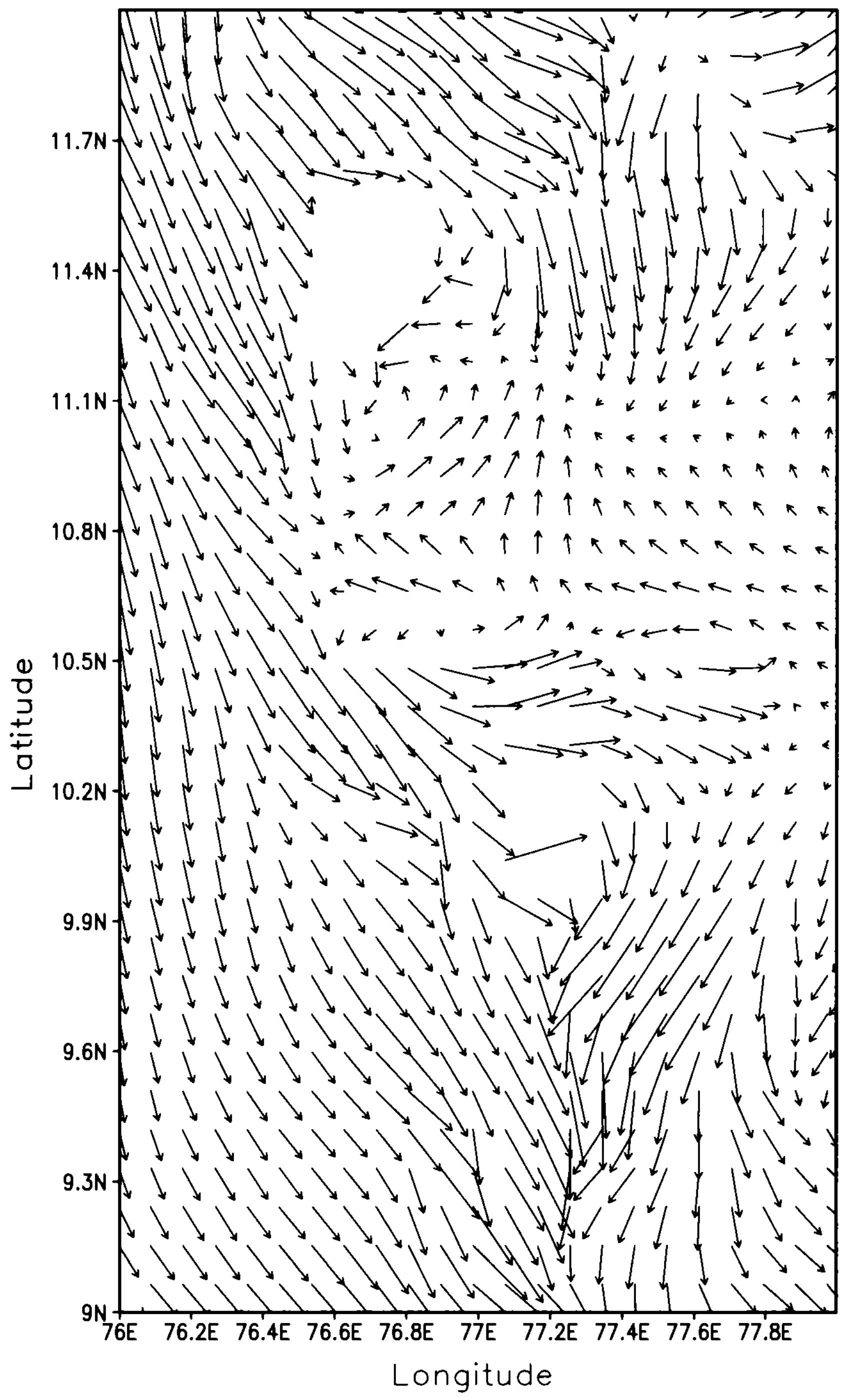


Figure 3.20: The 850 hPa wind profile over the study region during the month of April.

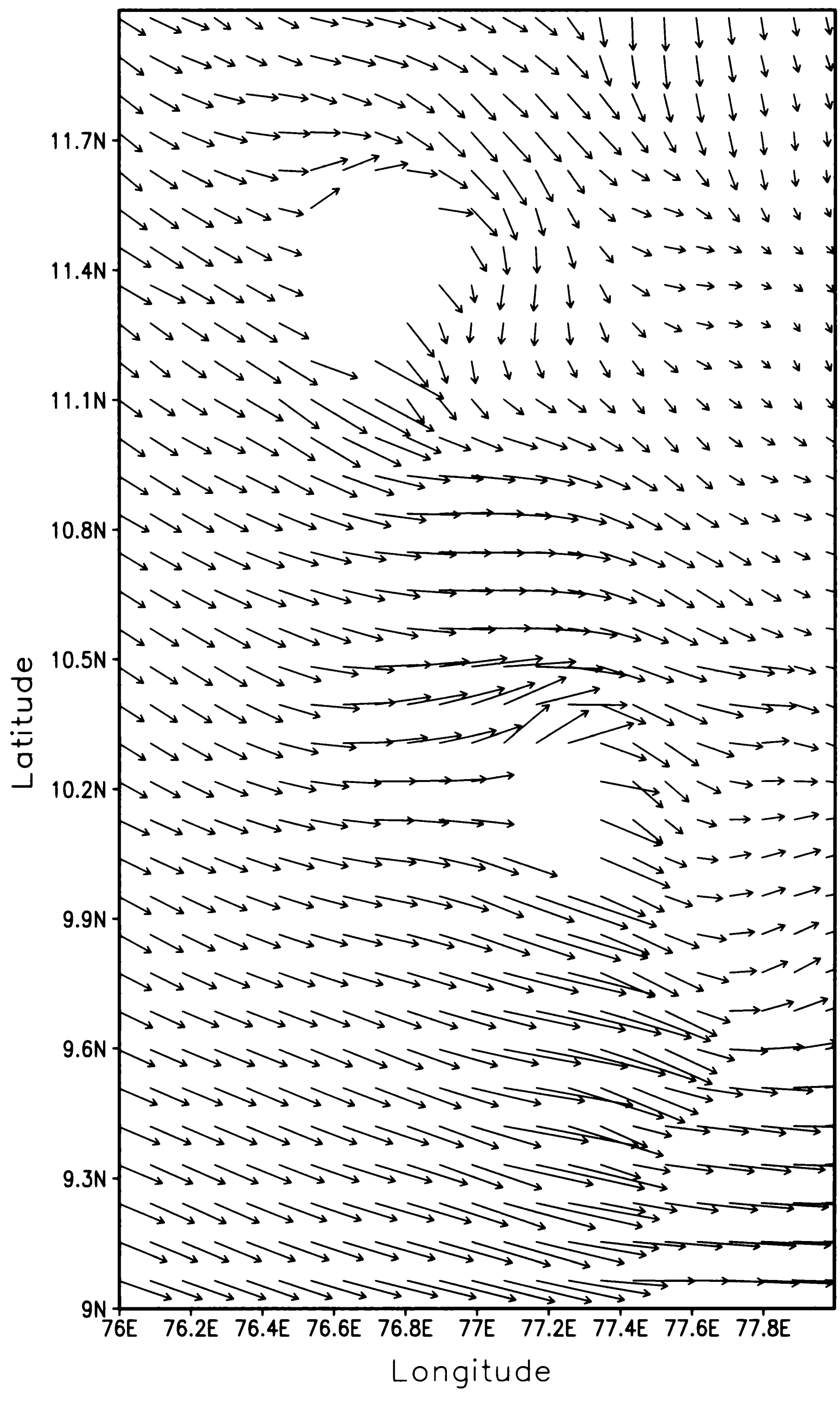


Figure 3.21: The 850 hPa wind profile over the study region during the month of October.

features discussed earlier and these perturbations to the flow are of great importance to the weather in the immediate area. The behaviour of an airflow over an obstacle depends principally on *(1) the vertical wind profile, (2) the stability structure and (3) the shape of the obstacles*. First we can examine the simple long ridge perpendicular to the airflow for the case of a stable atmosphere, where the potential temperature increases with height. For these conditions, three basic type of flow have been distinguished by Forchgott, according to the vertical profile of wind speed. With light winds which remain essentially constant with height, the air flows smoothly over the ridge in a shallow wave and there are only weak vertical currents. This is known as laminar streaming. When the wind speed are some what stronger and show a moderate increase with height, the air overturns the lee side of the barrier forming a standing eddy. With a more intense vertical gradient of wind speed, the oscillation caused by the mountain sets up a train of lee waves which may extend 25 km or more at the downwind. As Nicholls criteria the wind speed must increase upward, with a minimum horizontal velocity of about 7 ms^{-1} at the crest for the low ridges (1 km) and 15 ms^{-1} for ranges 4 km high.

Critical Parameters of Lee Waves formation over Western Ghats region

A topographic barrier initiate a vertical displacement in air crossing it, and on the lee side this is counter acted by the restoring force of gravity. The air commonly overshoots the equilibrium position and thereby develops vertical oscillations as it flows downwind. If the atmosphere is stable and the winds are light, the oscillation period is short whereas, in situations with low stability and strong winds, slow oscillations of long wavelengths are formed. The natural frequency of vertical oscillations for a compressible medium , in the absence of frictional effects, is referred to as the Brunt-Vaisala frequency (N). Also the general class of flow for an ideal fluid encountering an obstacle can be described with reference to the Froude number (F) which is the ratio of the internal viscous force to the gravitational forces.

For the Western Ghats region we have calculated the Froude's number, Brunt-Vaisala frequency, Scorer parameter and the wavelength of the possible Lee wave by using the following set of equations. Thus the Froude's number can also be calculated from the potential temperature field with the help of equation (3.2).

$$F = \frac{U}{(g\frac{\Delta\Theta}{\Theta}H)^{\frac{1}{2}}} \tag{3.2}$$

where

U = Mean velocity of the air in motion

g = Acceleration due to gravity

$\Delta\Theta$ = Difference of upper and lower layer potential temperature

Θ = Average potential temperature of the layer in motion

H = Height of the mountain

The hydraulic jump is a well known phenomena occurring usually in the mountain atmosphere. A wave disturbance formed by the barrier propagates upstream ; the deeper flow is drawn down over the obstacles, becoming shallow on the lee side before jumping back to a higher level. In models with stratified flow over three dimensional hills, jumps occur for F $\geq$ 0.4. It has an inverse relationship to the bulk Richardson number, F $\sim Ri_B{}^{-2}$. If F$\ll$1 the stratification is considered to be strong, while F$\gg$1 it is near neutral. Thus Froude's number also provides the criteria for the possible generation of lee waves and separation of the flow in the lee of the hill. By knowing the Froude's number.

We can calculate the Brunt-Vaisala frequency from the equation (3.3).

$$N = \frac{U_0}{(FH)} \tag{3.3}$$

where

U_0 = Wind speed at the surface

F = Froude's Number

H = Height of the boundary layer

Brunt-Vaisala frequency is the natural frequency of internal gravity waves or lee waves and it has a magnitude of the order of $10^{-2}\ s^{-1}$. We can calculate the wavelength of the possible Lee wave formation over the mountain from this Brunt-Vaisala frequency with the help of equation (3.4).

$$\Lambda = \frac{U}{(2\Pi N)} \tag{3.4}$$

where

U = Mean Wind speed of the flow

F = Froude's Number

N = Brunt Vaisala Frequency

The wavelengths tend to increase with the day time reduction in the lapse rate in the lower layers. In the evening hours, conversely the wavelength may gradually decreases. The Scorer's parameter (l), which is a measure for the stability of the air can also be calculated by the equation (3.5) by knowing the Brunt Vaisala Frequency (N).

$$l^2 = \frac{4\Pi^2 N^2}{U^2} \tag{3.5}$$

It is interesting to note that waves form only downstream of a mountain barrier. In fluid flow the speed of motion of wave crests (phase velocity) exceeds the rate of energy propagation (group velocity). The phase velocity in a standing wave has to be equal and opposite in direction to the mean wind speed, $\overline{U}$. Thus, $\overline{U}$ exceeds the group velocity, and advection by the mean wind dominates the transport of wave energy downstream away from its source at the obstacle. The wave energy is reflected up and down between the ground and the upper region where l^2 is small.

As we have seen from the earlier analysis of wind speed and potential temperature in this chapter reveals that there is a dependence of wind speed, wind shear and potential temperature exists for the crossing of the air flow over the Western Ghats. There we have seen that in the beginning of July months (during the period of monsoon), when the above said conditions are met, the wind crosses over to the other side of the Western Ghats. Here in the following table we have given the calculated value of Froude's no., Scorer's parameter and the Brunt-Vaisala frequency of the oscillations possible. From these the possible wavelengths of the lee waves have been calculated. The calculated parameters are given in Table (3.2). The parameters given in the table are as follows.

U2 = Wind speed at 925 hPa level

U6 = Wind speed at 800 hPa level

Θ 2 = Potential temperature at 925 hPa level

Θ 6 = Potential temperature at 800 hPa level

$\Delta\Theta$ = U6 - U2 & Θ = (U2+U6)/2

H = Height of the mountain

g = Acceleration due to gravity

H_B = Height of the boundary layer

F = Froude's No.

N = Brunt-Vaisala frequency

l_1 = Scorer's parameter in 925 hPa level

l_2 = Scorer's parameter in 800 hPa level

Λ = Possible Wavelength of the Lee waves

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
U2 (ms^{-1})	2.5	1.7	1.8	2.6	2.6	4	8.9	6.7	5.9	2.9	7	5
U6 (ms^{-1})	0.7	2.9	7.9	0.4	2.5	3.7	14.9	12.2	8.2	3.1	8.5	1.2
Θ 2(K)	300.6	299.9	300.3	301.7	302.1	300.3	299.9	299.1	299	299	299.6	299.3
Θ 6 (K)	306.3	306.1	307	308.2	307.8	307.6	306.4	306	306.2	306	305.6	307.5
Mean U (ms^{-1})	1.6	2.3	4.9	1.5	2.6	3.9	11.9	9.5	7.1	3	7.8	3.1
$\Delta\Theta$ (K)	5.7	6.2	6.7	6.5	5.7	7.3	6.5	6.9	7.2	7	6	8.2
Θ (K)	303.5	303	303.7	305	305	304	303.2	302.6	302.6	302.5	302.6	303.4
H (m)	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800
g (ms^{-2})	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81
H_B (m)	70	125	120	250	400	650	750	550	450	350	100	150
F	**0.088**	**0.121**	**0.246**	**0.077**	**0.140**	**0.187**	**0.612**	**0.471**	**0.344**	**0.148**	**0.414**	**0.142**
N (Hz)	**0.260**	**0.152**	**0.165**	**0.078**	**0.045**	**0.032**	**0.026**	**0.037**	**0.046**	**0.058**	**0.187**	**0.146**
l_1 (m^{-1})	**O/R**	**O/R**	**O/R**	**0.927**	**0.317**	**0.100**	**0.030**	**0.079**	**0.140**	**0.460**	**O/R**	**O/R**
l_2(m^{-1})	**O/R**	**O/R**	**O/R**	**O/R**	**0.330**	**0.109**	**0.018**	**0.044**	**0.101**	**0.430**	**O/R**	**O/R**
Λ (m)	**N/W**	**N/W**	**N/W**	**N/W**	**9.1**	**20.1**	**54.6**	**29.2**	**20.6**	**8**	**N/W**	**N/W**

O/R - Value out of range   N/W - No wave is forming

Table 3.2: Critical parameters calculated from model value for a day in every month of the year over the Western Ghats Region

The value shows that the Froude's number for the month July, August and November are above the critical value of 0.4. The possibility of a hydraulic jump can occur on these three months and the rest of the periods have neglected. the Scorer's Parameter is minimum during July and it indicates the favourable condition of the energy propagation up and down at that time.

Among this three cases, only in the month of July there is sufficient wind speed, positive wind shear and potential temperature to cross over the flow to the lee side. The possible wavelength calculated in the region is found to be 54.6 meters in July and the small wavelength can be attributed to the low Scorer's parameter existing in July. The cross sectional analysis of potential temperature in July at 2330 hrs clearly shows the perturbation of the lee waves in levels from 850 hPa to 600 hPa in an interval of 50 hPa (fig.3.22). The disturbance is clear in the 850 hPa level and when it goes in the upper layers there is a phase lag and vanishes at 650 hPa level. This simulation is the mean condition for the second day of the month of July. This condition may persist for entire July, sometime it can be seen on late June or any day in which these conditions are satisfied. Analyzing each day of June or July is beyond the scope of this study and not necessarily needed for formulating the criteria for the hydraulic jumps and wave formation over the Western Ghats.

3.2.4 Fall Winds

When the synoptic situation is favourable, the mechanical and thermodynamic effects of topography on air flow can give rise to distinctive winds blowing down the slopes of a mountain range. These so called 'fall winds' include the Fohn (or Chinook in Colorado) and the Bora winds which are known in their local names in other parts of the world. In the simplest terms, the Fohn wind is defined with reference to a downslope wind that causes

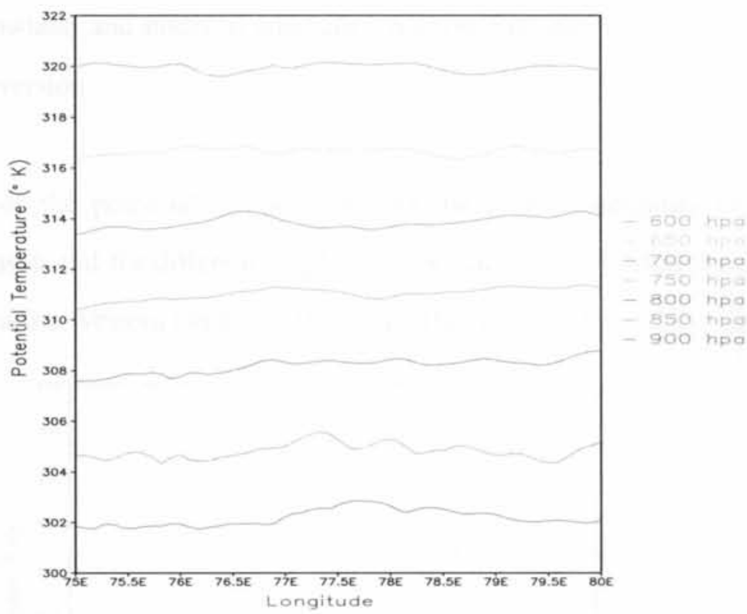


Figure 3.22: The cross sections of potential temperature at different levels (from 900-600 hPa in an interval of 50 hPa) along 10.2°N in July at 2330 hrs showing the lee wave formation.

the temperature to rise and relative humidity to fall on the lee side of a mountain range, where as the corresponding Bora causes temperatures to fall. Both may be gusty.

Fohn Winds

The classical mechanism used to account for the Fohn phenomenon begins with the ascend of moist air against a mountain range, causing cloud build up and precipitation and an increase of relative humidity on the wind ward slope. The rising air cools at saturated adiabatic lapse rate (5-6°C km^{-1}) due to latent heat release by condensation above the cloud base, whereas on the lee slope the descending, cloud-free air warms at the dry adiabatic lapse rate of (9.8°C km^{-1}). Thus the potential temperature are higher on the lee side. In many instances, however, Fohn may occur without moisture removal on the windward slope. Hence it is sufficient for air to descend from the summit level to the surrounding lowland and undergo adiabatic compression, due to blocking of air at low levels by an inversion.

The analysis of the potential temperature and the relative humidity over the region for various season and for different heights shows that the Fohn wind is occurring at the lee ward side of the Western Ghats in all season. The figs. (3.23 to 3.28) shows the cross

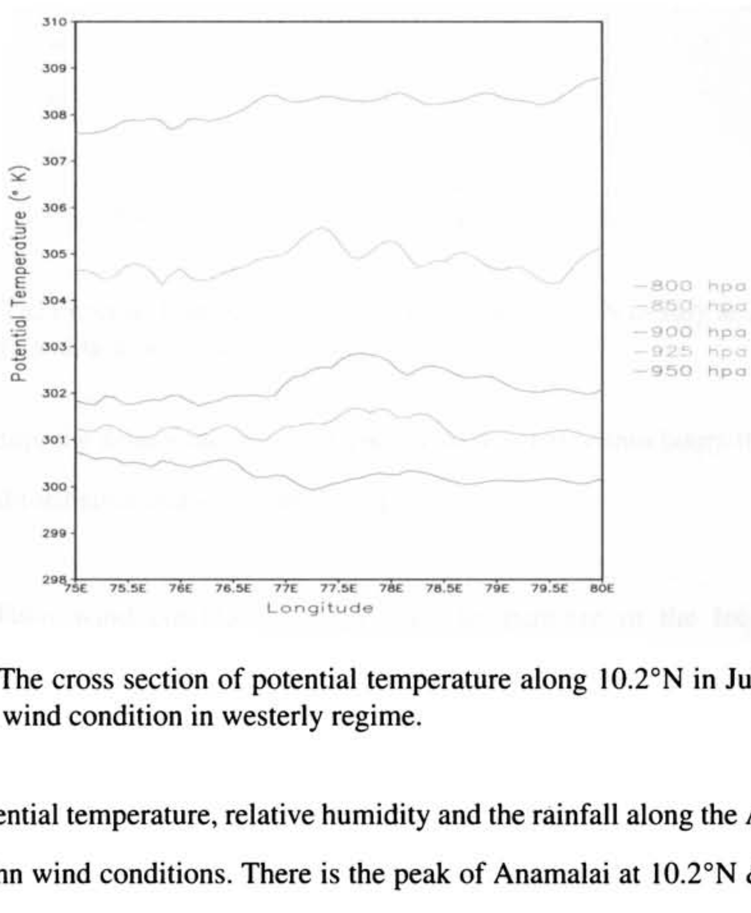


Figure 3.23: The cross section of potential temperature along 10.2°N in July at 2330 hrs showing fohn wind condition in westerly regime.

section of potential temperature, relative humidity and the rainfall along the Anamalai hills during the Fohn wind conditions. There is the peak of Anamalai at 10.2°N & 77.2°E with a height of about 1800 m in the cross section is making the discontinuity in the figures during that month. But in the July month we have already seen that the winds are capable to cross over the mountain and that is why we cannot see the discontinuity in those figures. The figs. (3.29 to 3.31) shows the condition prevailing over the region during the time when Fohn winds are not there. the non-Fohn wind condition exists at 2030 hrs which is

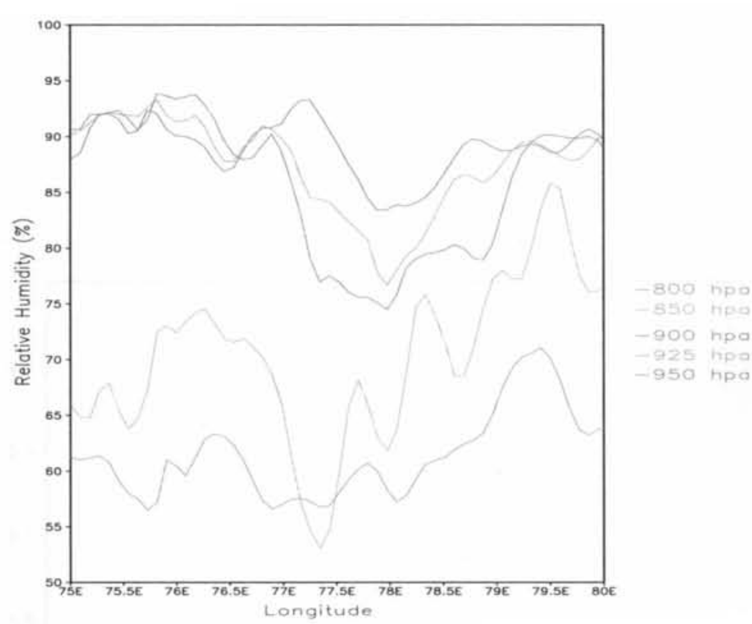


Figure 3.24: The cross section of relative humidity along 10.2°N in July at 2330 hrs showing fohn wind condition in westerly regime.

three hour before the fohn wind occurs. Hence it shows that within hours the condition of the Fohn wind formation changes over the region.

During the Fohn wind condition the potential temperature in the lee ward side is modified by the down wind to increase and at the same time the relative humidity is reduced drastically by about 15-20 % and also an increase of rainfall at the windward side of the mountain. The cloud free air in the lee side will not favour the rainfall in that side and can be seen in the absence of rainfall in the figure on the lee side. Modification is comparitively small in the surface level because the down wind is not that much strong enough to reach at the surface except in July when the strong low level jets are there in the wind regime. Occurence of the Fohn winds are freequent in a day itself in the Winter season. This is evident from the formation of Fohn wind at 0800, 1130 and 1430 hrs in Winter (February) which is not that much frequent during the Summer season (July).

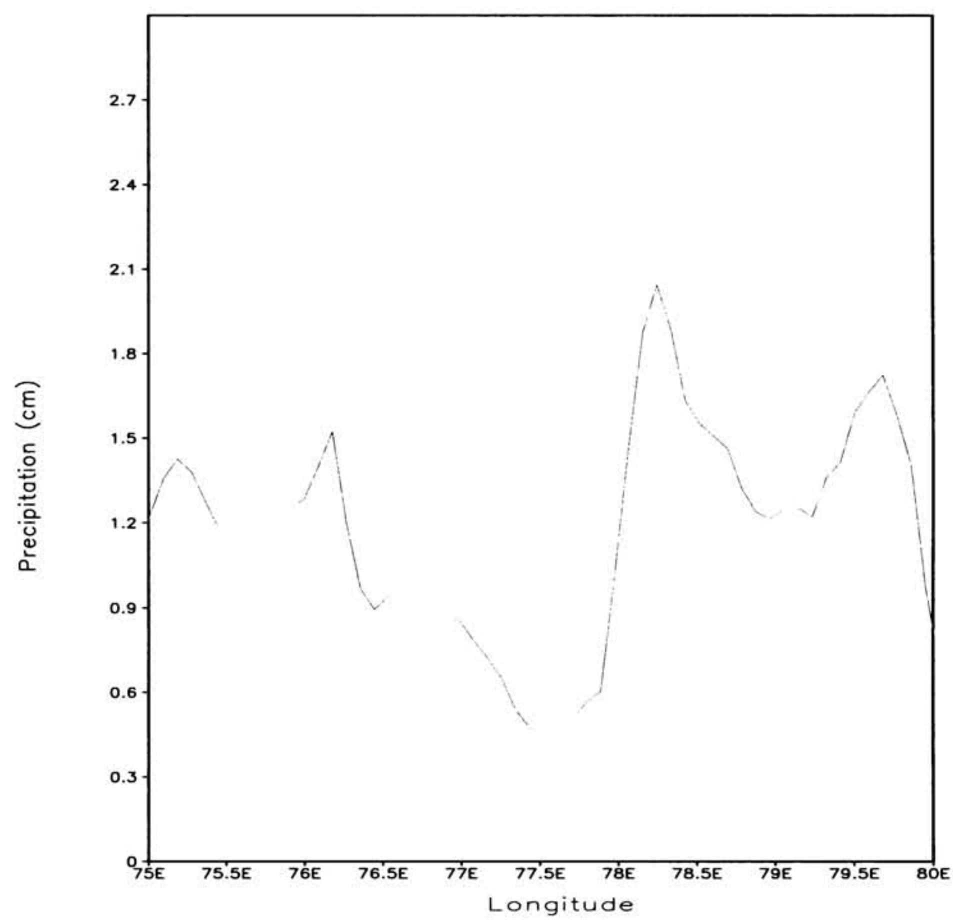


Figure 3.25: The cross section of rainfall along 10.2°N in July at 2330 hrs showing fohn wind condition in westerly regime.

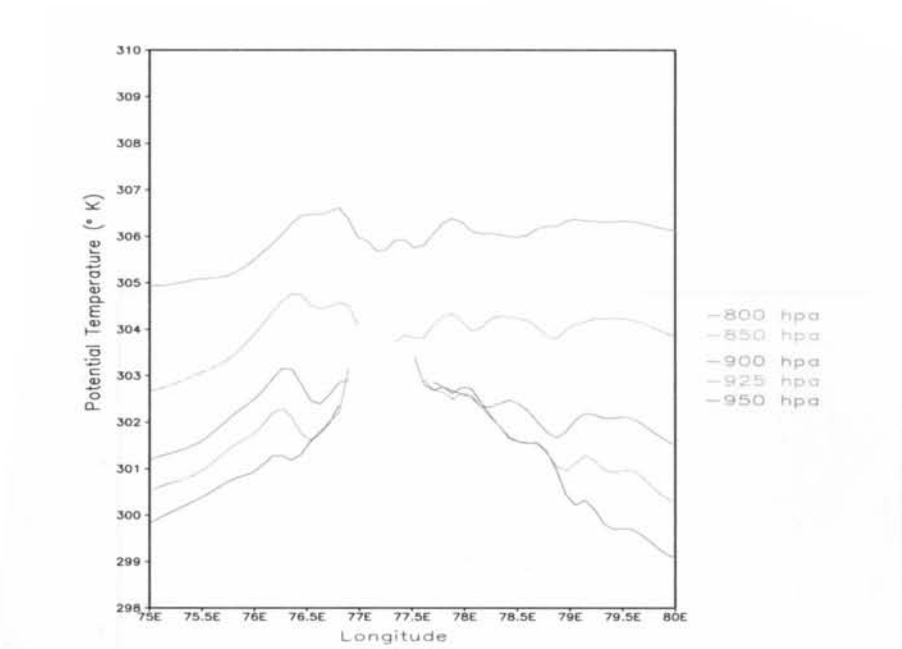


Figure 3.26: The cross section of potential temperature along 10.2°N in February at 1430 hrs showing fohn wind condition in easterly regime.

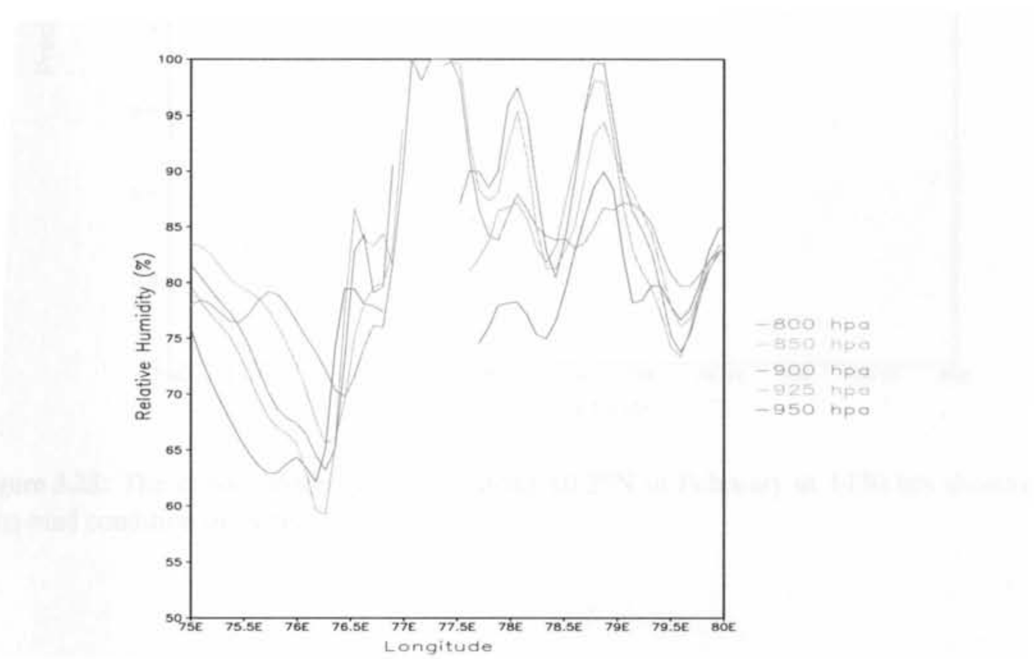


Figure 3.27: The cross section of relative humidity along 10.2°N in February at 1430 hrs showing fohn wind condition in easterly regime.

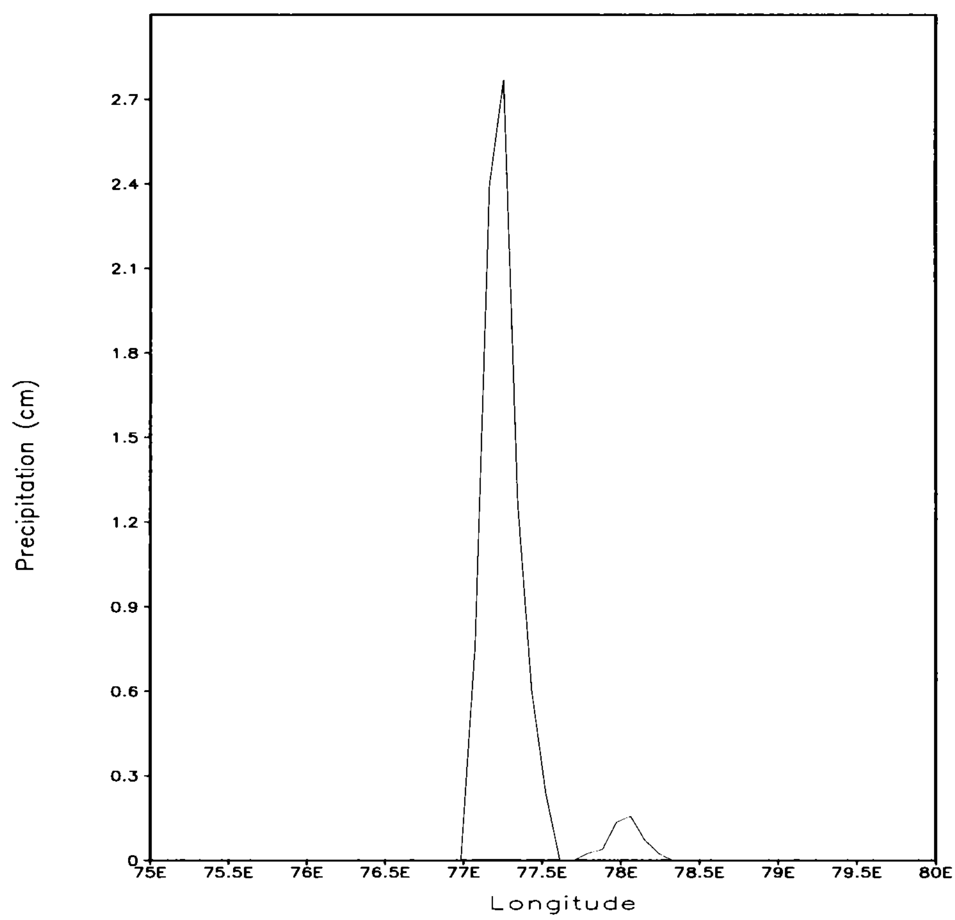


Figure 3.28: The cross section of rainfall along 10.2°N in February at 1430 hrs showing fohn wind condition in easterly regime.

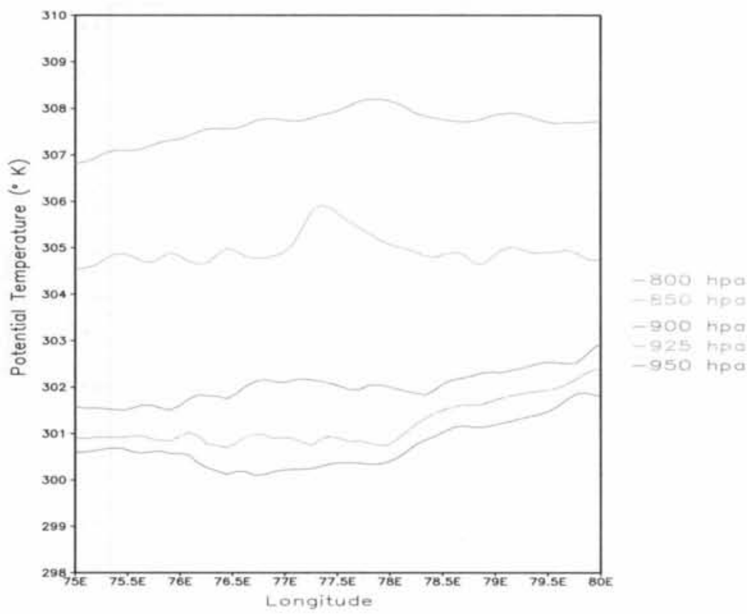


Figure 3.29: The cross section of potential temperature along 10.2°N in July at 2030 hrs showing non-fohn wind condition.

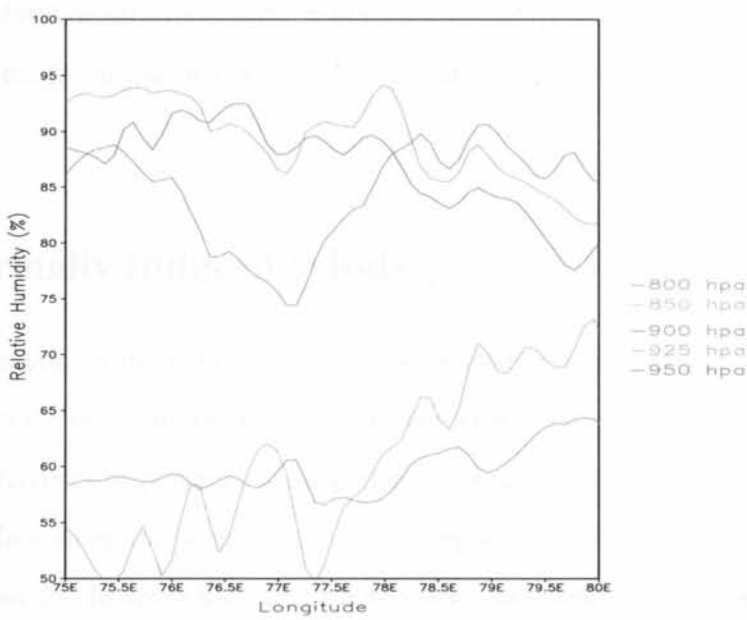


Figure 3.30: The cross section of relative humidity along 10.2°N in July at 2030 hrs showing non-fohn wind condition

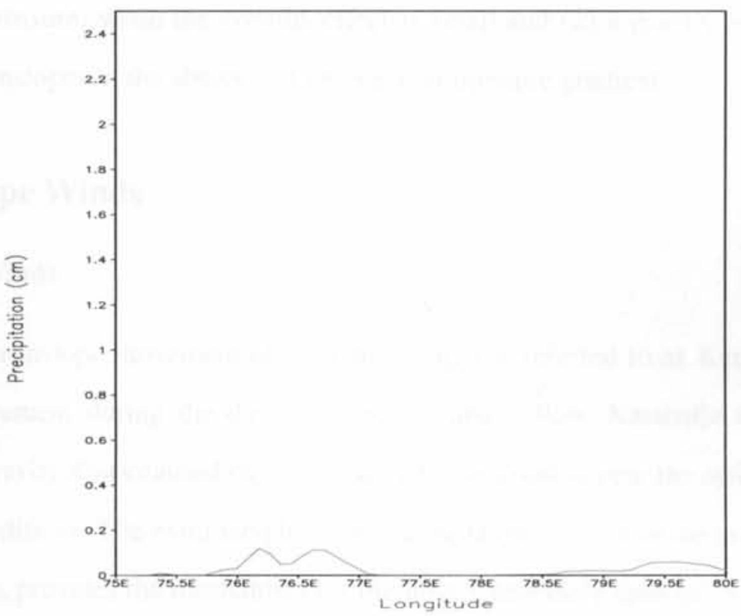


Figure 3.31: The cross section of rainfall along 10.2°N in July at 2030 hrs showing non-fohn wind condition

There is no uniform modification to the potential temperature, relative humidity or rainfall favourable for the formation of Fohn wind condition during some hours of the same day itself.

3.3 Thermally Induced Winds

The thermal patterns of the topography give rise to characteristic systems of air motion, especially when the regional pressure gradients are weak. The primary forcing agents are elevational differences in potential temperature, causing vertical motion and differential heating or cooling along the slopes which may setup air circulations with horizontal and vertical components. In some locations such systems are sufficiently frequent and pronounced in their effects as to create distinctive and semi permanent topoclimatic pattern. The basic dynamical processes involved are (1) antitriptic wind component directed towards low pressure, when the coriolis effect is small and (2) a gravity wind component directed downslopes in the absence of any general pressure gradient.

3.3.1 Slope Winds

Katabatic Winds

In general downslope movement of cold air at night is referred to as Katabatic flow and upslope movement during the day is termed Anabatic flow. Katabatic winds are local downslope gravity flows caused by nocturnal radiative cooling near the surface under calm clear sky conditions. The extra weight of the stable layer, relative to the ambient air at the same altitude, provides the mechanism for the flow. Conversely upslope flow is associated with day time slope heating and buoyancy induced by this. It is found that the maximum wind speed (about 2-3 ms^{-1}) for both upslope and downslope winds are occurring at a height of 27 m in the middle latitude region.

The analysis at the Anamalai hills shows that there is a flow from the summit region to the down slopes on both sides of the Western Ghats during the night time when the cooling is taking place. This is seen at any season and prominent during the Winter season. The fig. (3.32) gives the analysis of the wind speed during 2330 hrs at the Anamalai hills. The fig.(3.33) shows the variation of ground temperature and the temperature at 2 meter height at the same time. From the above figures it is clear that from 76.5°N to 78°N there is a reduction in the ground temperature than the above lying layer of the air. This is due to the cooler air is coming down to the surface and due to gravity it moves downward in both direction of the peak. The wind speed is maximum at the upper region of the slope and it decreases as the slope decreases. The maximum wind speed of 3 ms^{-1} is seen at the higher slope region. The earlier studies in the middle latitude shows the maximum wind zone is concentrated above 20 meter level which cannot be verified here because of the

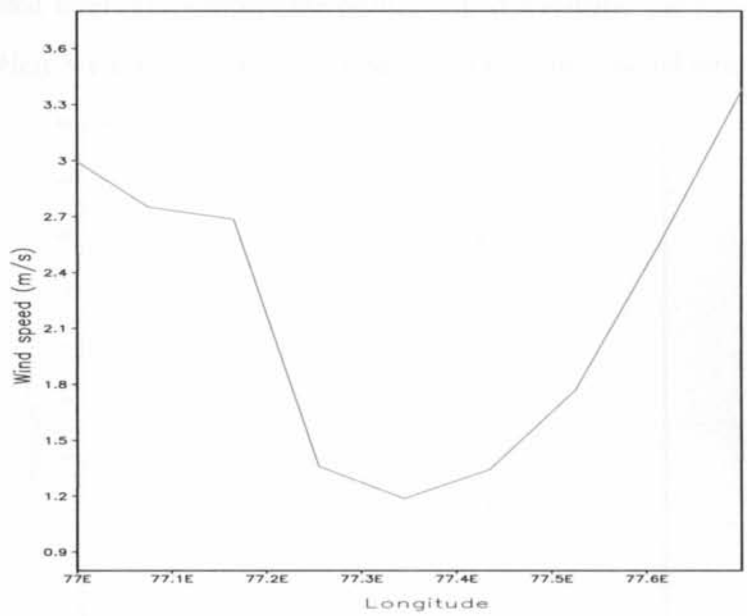


Figure 3.32: The wind pattern over Anamalai hills during the Katabatic wind condition in January at 2330 hrs

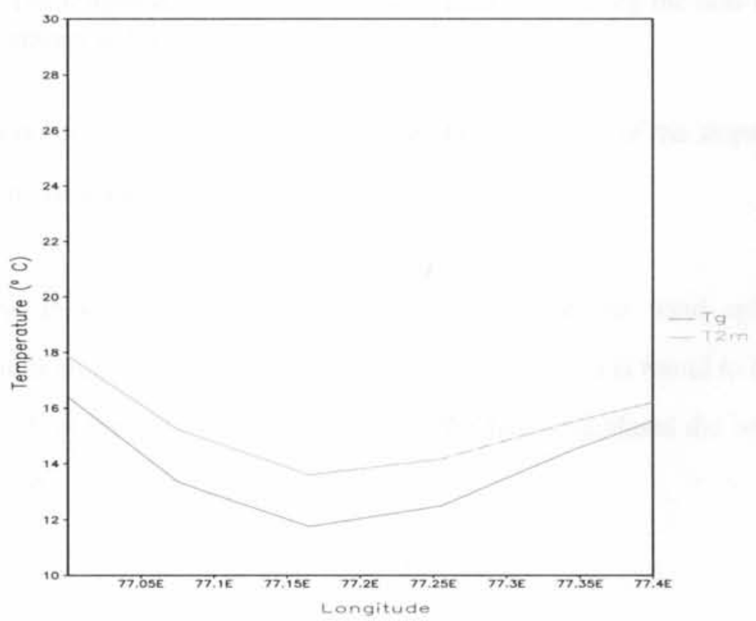


Figure 3.33: The temperature patterns over Anamalai hills during the Katabatic wind condition in January at 2330 hrs

data Gap in that level. The temperature profile of non Katabatic wind condition is given in fig(3.34). Here we can see that the difference between the ground temperature and the

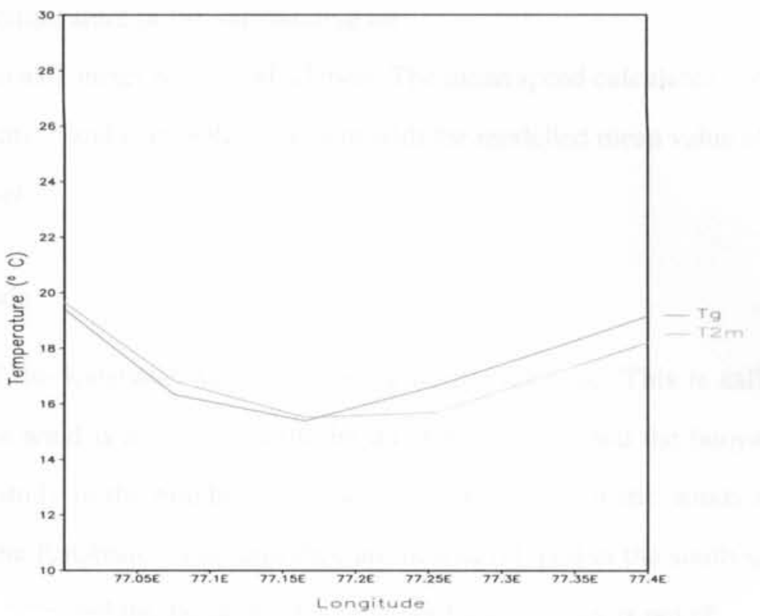


Figure 3.34: The temperature patterns over Anamalai hills during the non-Katabatic wind condition in January at 0830 hrs

2 m air temperature is minimum at 0830 hrs and the formation of the slope winds are not possible during these periods.

Several expressions have been developed for estimating the wind speed associated with slope winds and the most appropriate for our study region is found to be the equation of Reiher based on the temperature differences. We have calculated the wind speed with the equation (3.6).

$$V = \left(\frac{2gh(T' - T)}{T'}\right)^{\frac{1}{2}} \tag{3.6}$$

where

V = Velocity of the slope wind

g = Acceleration due to gravity

h = Height above the surface of V

T = Temperature of the cold slope air

T' = Warmer temperature of the surrounding air

The 'h' is taken as 2 meter for the calculation. The mean speed calculated with the Reiher formula is 2.6 ms^{-1} and is in well agreement with the modelled mean value of 2.1 ms^{-1} at the 2 meter level.

Anabatic Winds

The reverse of the Katabatic winds will occur in the day time. This is called Anabatic winds. Upslope wind is associated with the day time heating and the buoyancy induced by them. The study in the middle latitudes shows that the Anabatic winds are generally stronger than the Katabatic winds and they are best developed in the south facing slopes. But in our study around the Western Ghats the net radiative flux is not changing much in the north-south direction and there is not much development is seen in the south facing slope. But the variation is more in east-west direction and the fluctuation of net radiation in the day time is found to be more in Spring season, which is evident from the diurnal variation analysis of the net radiation over the region.

The wind speed and the temperature pattern during April, when the maximum temperature gradients are occurring over the region, for the Anamalai hills are given in figs.(3.35 & 3.36). The wind speed increases towards the downslope in both direction indicating minimum wind variation of below 1ms^{-1} at the summit. This is due to the low temperature gradient occurring at the summit region which is evident from the temperature analysis. At the down slope, temperature difference goes upto 3°C while at peak it will be 1°C during 1430 hrs of the day. Here it is seen that as opposite to the Katabatic wind condition, the temperature at the 2 meter level is less than the ground temperature and a

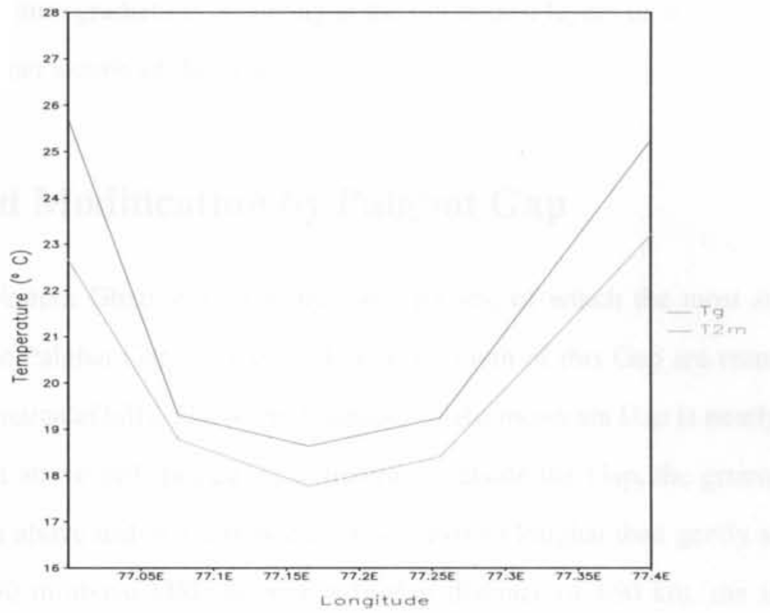


Figure 3.35: The temperature patterns over Anamalai hills during the Anabatic wind condition in April at 1430 hrs

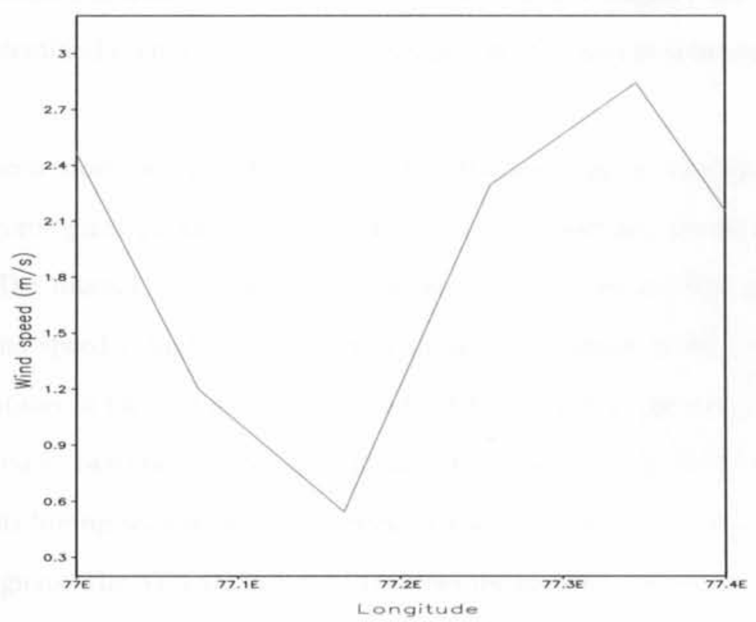


Figure 3.36: The wind pattern over Anamalai hills during the Anabatic wind condition in April at 1430 hrs.

positive temperature gradient is occurring at the lowermost layers of air. This is not much prominent in other season of the year.

3.4 Wind Modification by Palghat Gap

The wall of Western Ghats is broken by some passes, of which the most significant is the 25 km wide Palghat Gap. To the north and the south of this Gap are respectively the Nilgiri's and Anamalai hills. The lower boundary of the mountain Gap is nearly horizontal at about 100 m above msl. In east-west direction, outside the Gap, the ground first rises to about 300 m above msl at a distance of 50 km east of Palghat then gently slopes down eastward to 150 m above MSL through a further distance of 150 km, the latter giving a downward slope of the ground as 1 m km^{-1}. There is a funnel mouth opening of the Palghat Gap about 80 km downwind to the east. The station Pollachi is situated at the center of the mouth and Udumelpet in south and Coimbatore to slightly north of the exit. Udumelpet is identified even for greater wind energy potential area in some earlier studies.

As we have seen from our earlier analysis that Palghat Gap is modifying some of the basic meteorological parameters like temperature and pressure drastically over the study region. The diurnal variation of wind at the Gap is given in STN C2 of the fig (2.16). The wind speed is higher in the Gap than the other region in the study area. As in the other stations in the east and the west side of the mountain the maximum wind is occurring at around 1430 hrs and the amplitude is maximum during Summer season. In April, represents Spring season, the wind speed increases at the Gap than the down wind and up wind regions. The STN C2 in fig(2.19) shows the monthly variation of wind speed over the Palghat Gap. It can be seen that there is a continuous increase of wind speed from January to September and then in October it decreases. The minimum value of $1ms^{-1}$

occurs in November and then again increases in December.

The cross section analysis of the wind speed along the Palghat Gap section for different months are given in figs.(3.37 & 3.38). From the figures it is clear that the maximum wind speed of about 8-10 ms^{-1} is occurring at the 950 hPa level during the Winter season and as we go up the wind speed decreasing to 800 hPa level. But from April onwards the wind speed picks up and during the southwest monsoon months the maximum wind speed of about 18-20 ms^{-1} is occurring at the higher levels rather than the surface due to the influence of low level jet streams. The sudden increase of wind speed at the funnel mouth of the Gap at the eastern side is visible during the monsoon periods. During the Winter months of December and January this phenomena can be seen at the western exit of the Gap at 76.5°E longitude in Kerala.

3.4.1 Variation of Boundary layer Parameters along Palghat Gap

The turbulent kinetic energy of the air motion is plotted for every month through the Gap and are presented in figs.(3.39 & 3.40). In January the maximum kinetic energy transfer of about 1.6 JKg^{-1} is occurring at the western side of the Ghat at about 76°E in Kerala which is the down wind region during that season. Elsewhere in the region the the minimum value is 0.2 JKg^{-1}. During the months of southwest monsoon there is an increase of turbulent kinetic energy in the Gap and it is reaching upto 0.6 JKg^{-1} at the mouth of the Gap at 77.1°E which is about 30 km away from the Gap and at the funnel mouth opening at the down wind region in the eastern side. During the southwest monsoon months the surface wind speeds are maximum and we can see that in the entire area the turbulent kinetic energy is slightly higher than the rest of the months.

The variation of PBL height is also large in different months (figs.3.41& 3.42). The

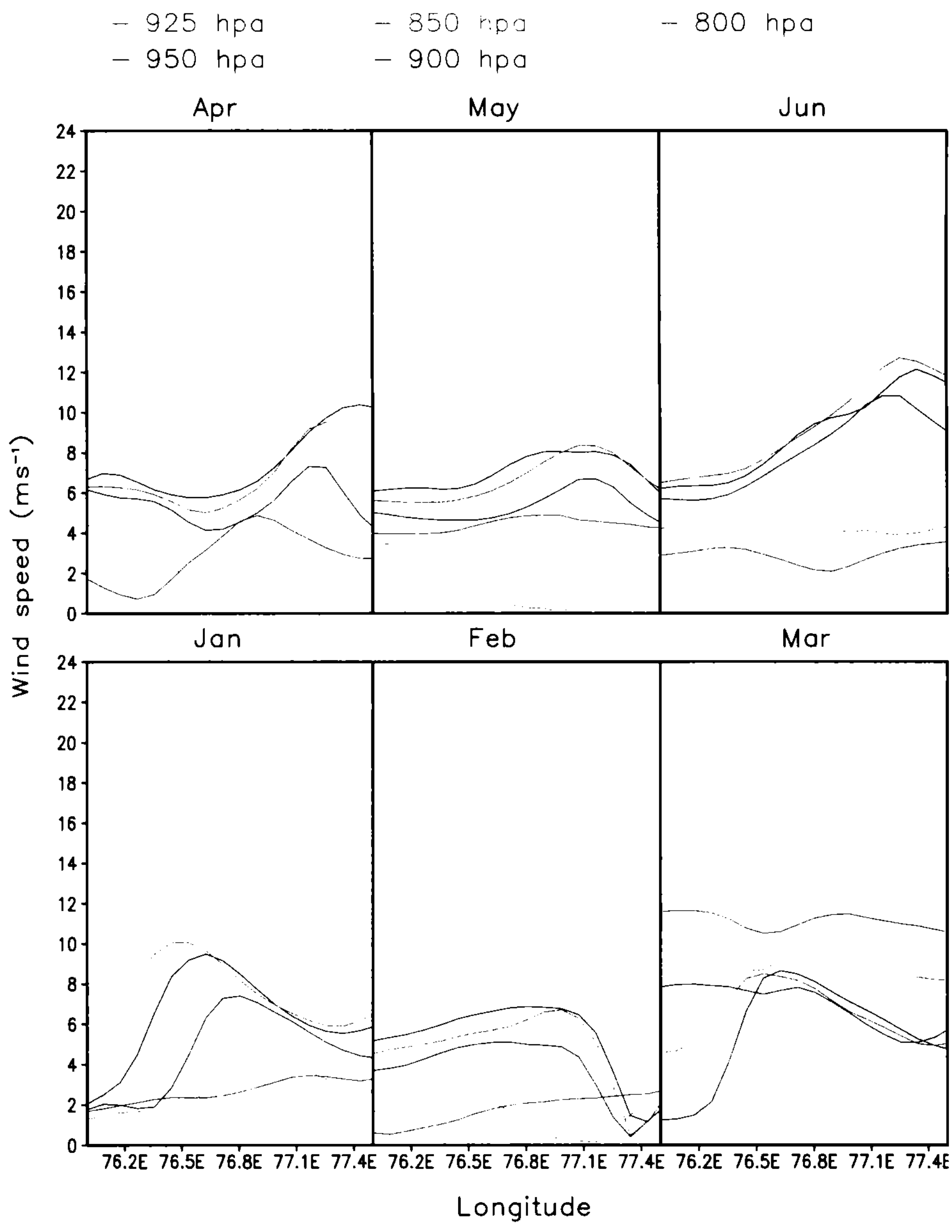


Figure 3.37: The cross section analysis of wind along the Palghat Gap for different levels from January to June

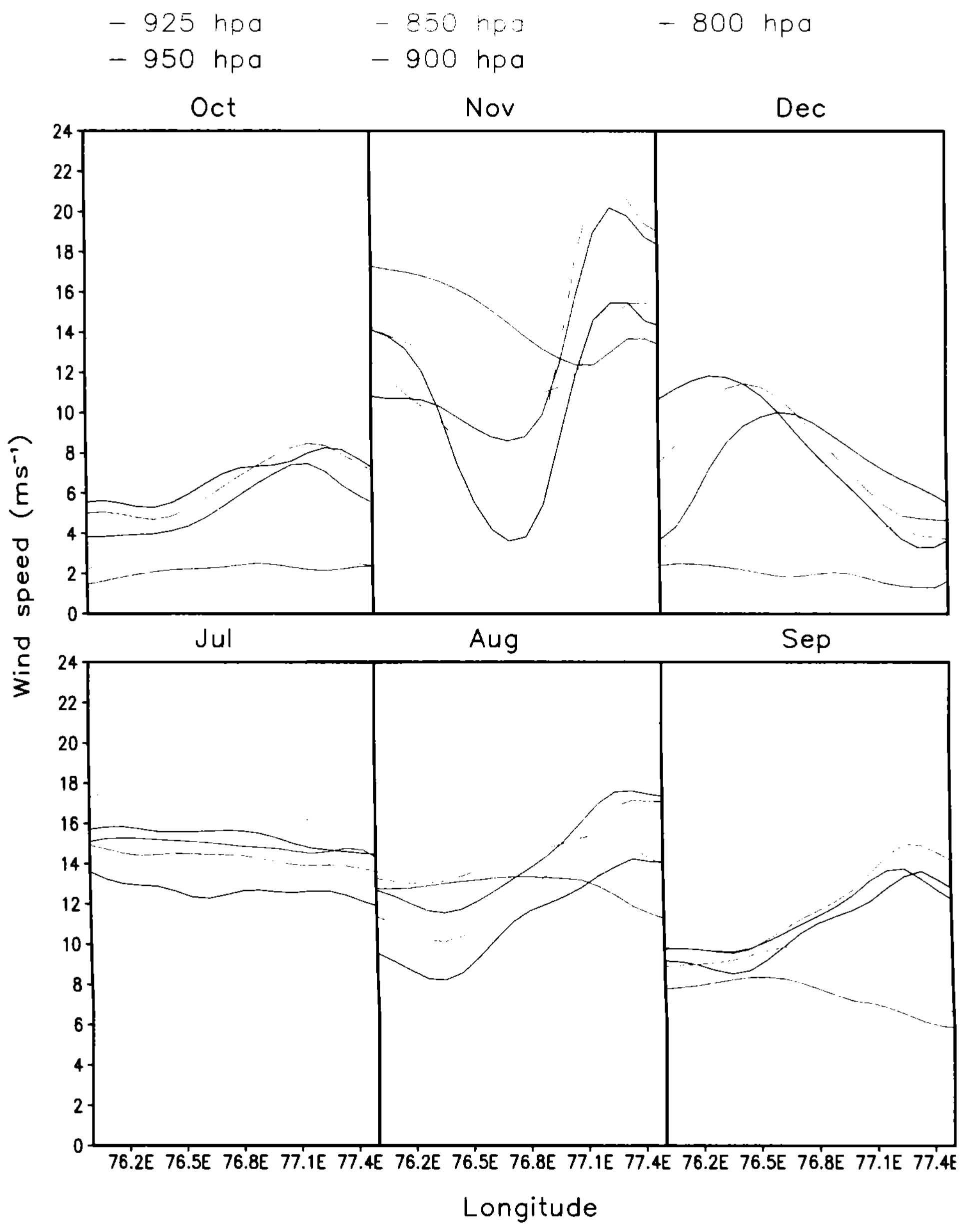


Figure 3.38: The cross section analysis of wind along the Palghat Gap for different levels from July to December

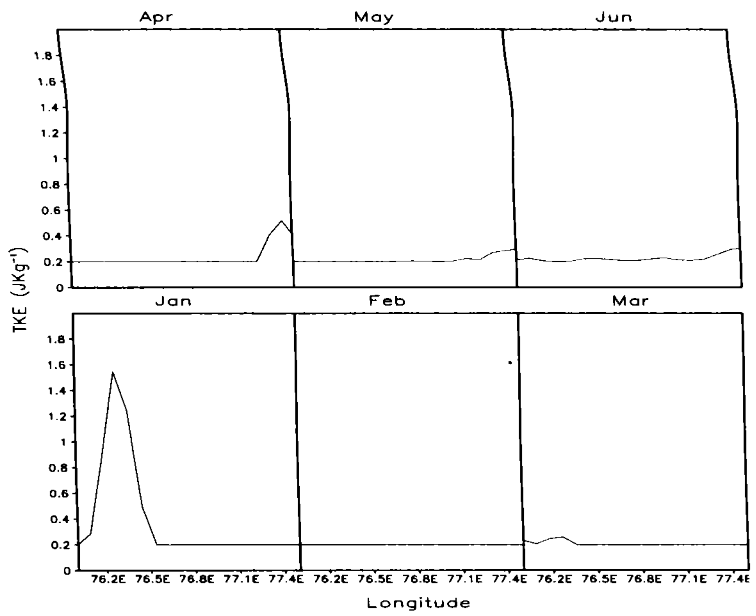


Figure 3.39: Turbulent kinetic energy transfer through Palghat Gap during the months January to June.

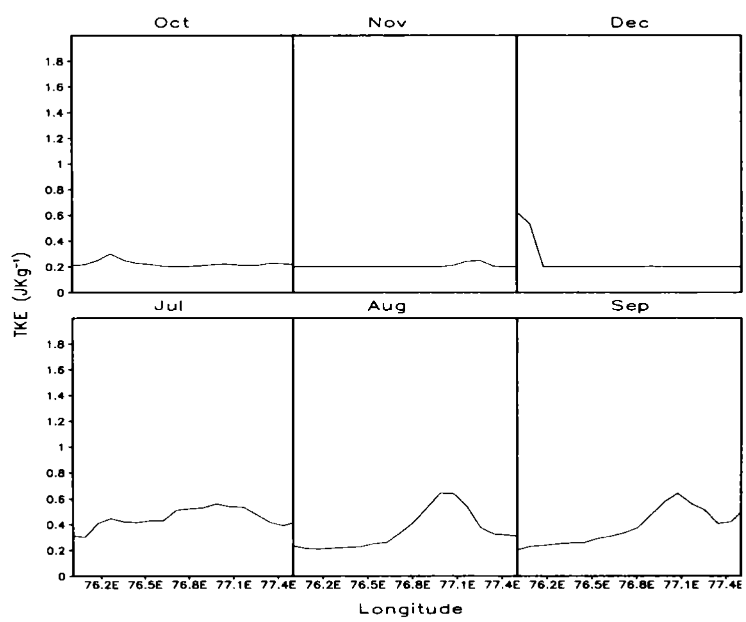


Figure 3.40: Turbulent kinetic energy transfer through Palghat Gap during the months July to December.

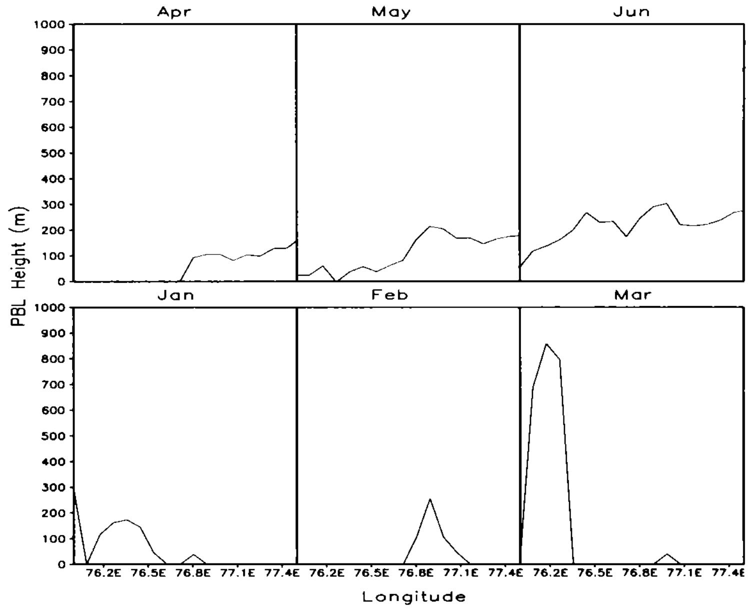


Figure 3.41: Variations of Planetary Boundary layer height through Palghat Gap during the months January to June.

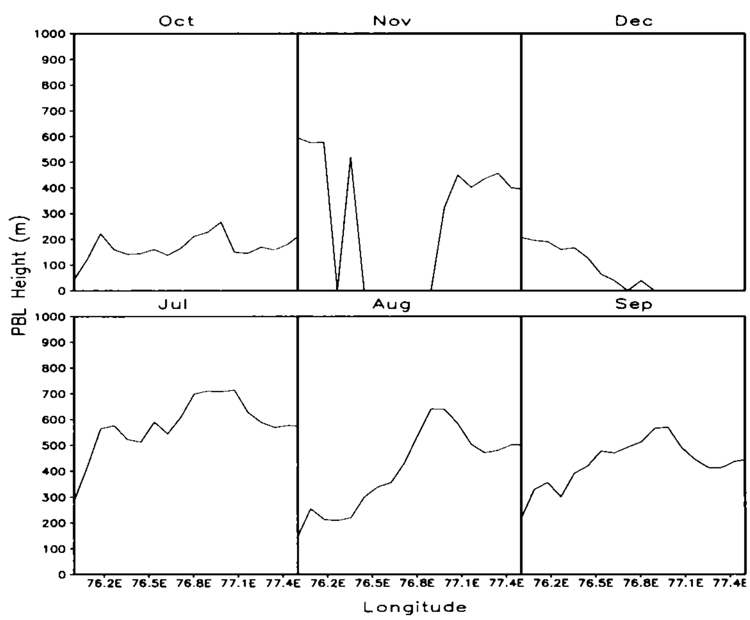


Figure 3.42: Variations of Planetary Boundary layer height through Palghat Gap during the months July to December.

maximum height of about 800 meters occur at April in the western side of the Gap. During the southwest monsoon period the PBL height is increasing from 200 to 700 meters in the region and it is maximum at the down wind regions of the Gap at 77°E, which is right at the mouth of the Gap. Hence at the funnel mouth of the Gap at the eastern side of the Ghat is the place where the maximum turbulence and mixing is occurring along the stretch during the Summer season. The stations Pollachi, Udumelpet and Coimbatore experiences the effect of these variability more than any other stations.

The analysis of the vertical wind at the region shows some interesting results (fig.3.43). The analysis have been carried out for the summer monsoon period and for a Winter

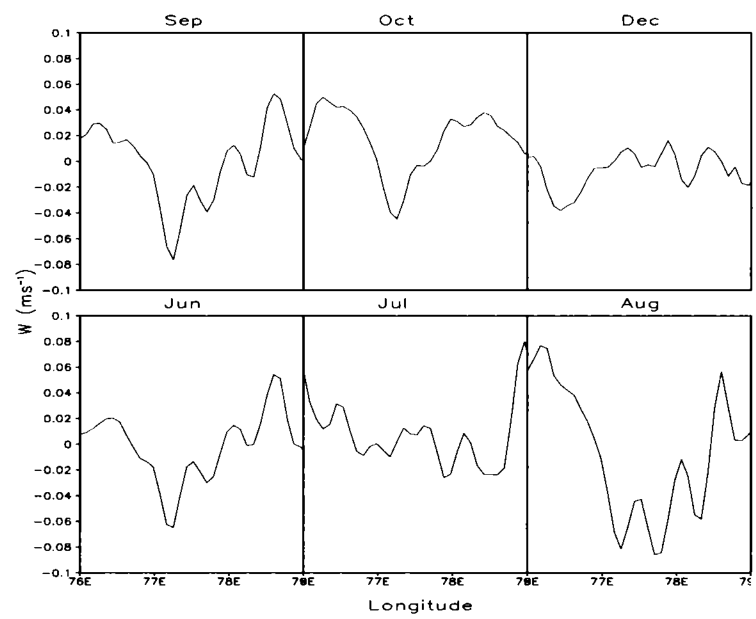


Figure 3.43: Vertical wind (W) along the Palghat Gap cross section during Summer monsoon months and a Winter month

months, in order to understand the difference in pattern existing in the vertical wind pattern. There is a negative vertical velocity value from 76.8°E to 77.5 °N with maximum of 0.08 ms^{-1} at about 77.2°E occurring. These area comes under the funnel mouth of the

Gap. Intense subsidence during this period at this region is very clear from the negative values of vertical velocity. This can be attributed to the reduction of rainfall in these region during the southwest monsoon period. During December slight subsidence can be seen in the eastern side of the Gap in Kerala while the prevailing wind will be easterlies during the time. This clearly shows the control of Palghat Gap in the wind modification.

3.4.2 Dynamic Pressure Developed at the Downwind Region of the Gap

Bernoulli's principle about the fluid flow is mainly concentrating the energy change. It explains many phenomenon like Venturi effects when the flow channel area changes. Thus we can precisely say that for a steady incompressible frictionless flow along a streamline Bernoulli's equation states

$$(\frac{V2^2 - V1^2}{2}) + (\frac{P2 - P1}{\rho}) + g(Z2 - Z1) = 0 \tag{3.7}$$

where

V2 = Velocity of the upper layer	V1 = Velocity of the lower layer
P2 = Pressure of the upper layer	P1 = Pressure of the lower layer
ρ = Mean density of the layer	g = Acceleration due to gravity
Z2 = Height of the upper layer	Z1 = Height of the lower layer

The first term denotes kinetic energy or the dynamic pressure term, the second term is the work done by the pressure force and the third term is called potential energy or the static pressure term. Dynamic pressure is the component of fluid pressure that represents fluid kinetic energy while static pressure represents hydrostatic effects. Hence

$$P_{total} = P_{dynamic} + P_{static} \tag{3.8}$$

The dynamic pressure of a fluid with density ρ and speed U is given by

$$(\frac{\rho U^2}{2}) \tag{3.9}$$

From Bernoulli's equation

$$P1 - P2 = \frac{\rho(U2^2 - U1^2)}{2} \tag{3.10}$$

From Continuity equation

$$A1V1 = A2V2 \tag{3.11}$$

From equations 3.10 & 3.11 we can take that

$A2 < A1$ & $V2 > V1$

$V2 > V1$ & $P2 < P1 \Rightarrow$

Decreasing Area = Increasing Velocity

Increasing Velocity = Decreasing Pressure

Thus when the wind is channelizing from a reduced area to a wider opening the speed increases and the dynamic pressure increases at the exit region of the Gap. This is how the fanning out of the wind at the exit mouth of the Palghat Gap occurs during the high wind regime of the southwest monsoon months. The fig.3.44 shows the variation of dynamic pressure as well as static pressure for the flow during southwest monsoon. When the static pressure decreases, dynamic pressure increases over the region.

The variation of the dynamic pressure is maximum in the lower layers at about 925 hPa than the upper levels. It varies from 20-75 Kg $m^{-1}s^2$ at 925 hPa level while it is 10-20 Kg $m^{-1}s^2$ at the 850 hPa level. The maximum dynamic pressure is developing at the longitude 77.2°E which is right at the funnel mouth in the eastern side of the Ghat and about 80 km from the entrance of the Gap at the western side. From 925 hPa onwards the

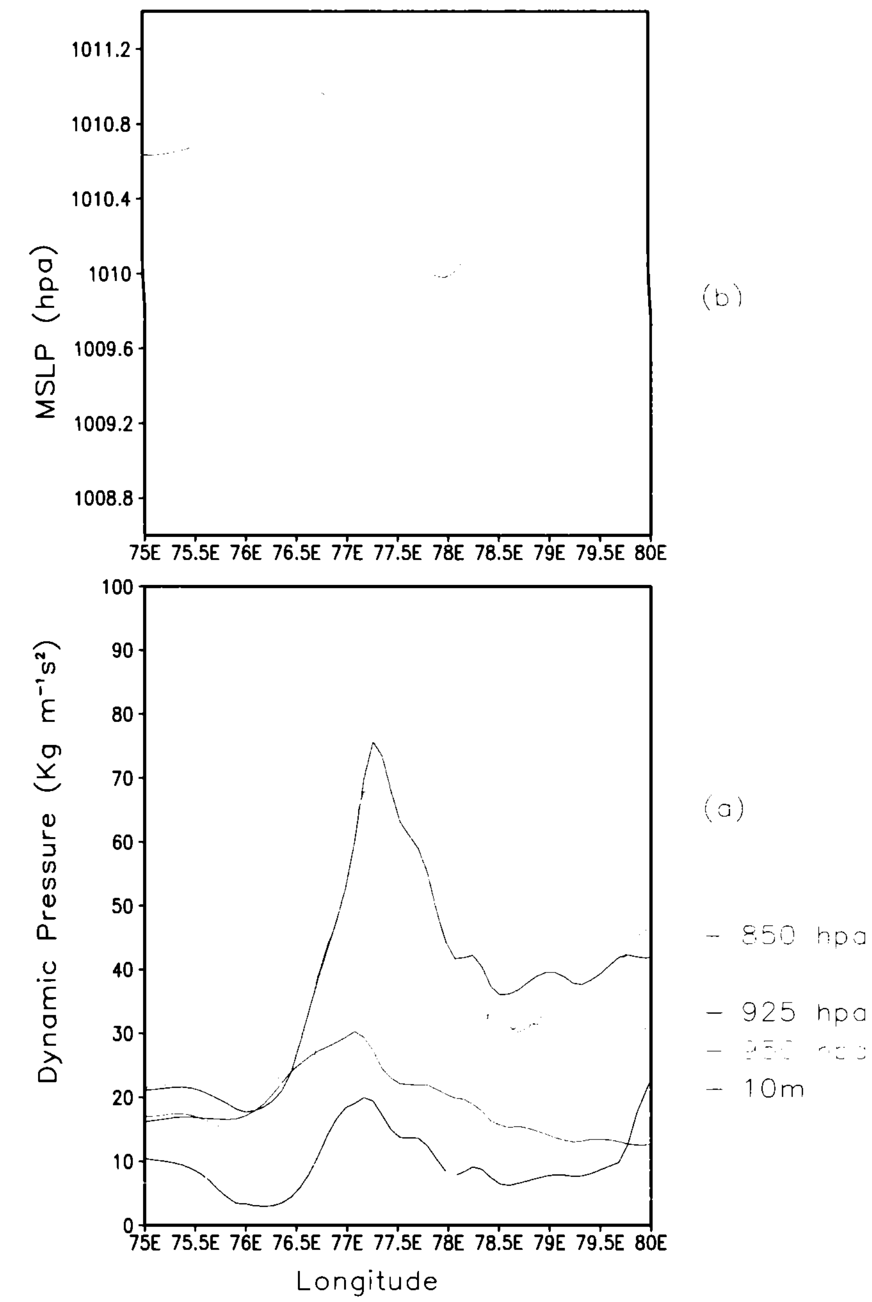


Figure 3.44: The cross section analysis of (a) Dynamic pressure at different levels (b) Static (mslp) pressure variation at the surface along the Palghat Gap during southwest monsoon period

buildup of the dynamic pressure is reducing and reaching a minimum at the 800 hPa level which is above the mountain height in that region.

The difference in the dynamic pressure development in the surface level (10m) and the upper level (925 hPa) will create a downward acceleration and hence the intense subsidence of the wind at the exit region occurs at about 77.2°E in the eastern side of the Gap. The rapid decrease of rainfall reported from Palghat Gap to a minimum of about 80 Km east of the Gap is attributed to this subsidence. This phenomena can also be seen in the western side of the Ghat during the Winter season when the easterlies prevails over the region (fig.3.45). Even-though the subsidence can be seen at around 76.2°E where the dynamic pressure build up is also very high at 950 hPa level than the eastern side, it is not building up much above that level like the eastern side. Hence the subsidence also will be less than the eastern side. Thus Palghat Gap works us a dynamic pressure building mechanism by which the precipitation of the regions on both sides of the Gap is controlled very much. Hence we can conclude that the arid conditions existing near Coimbatore and adjoining places like Pollachi in Tamilnadu and also at some parts of Palghat and Malappuram districts of Kerala are primarily due to the result of these dynamic pressure buildup by Palghat Gap.

3.5 Conclusions

The circulation system around the Western Ghats is complex as the case of any other mountain environment. The average height of the mountain in present study area is about 1200 meters and the entire mountain stretch in this area is divided by two passes like Aryankavu Pass and Palghat Gap. Even-though the Aryankavu Pass is not comparable to Palghat Gap in topographical specialties, even then it controls the weather and climate

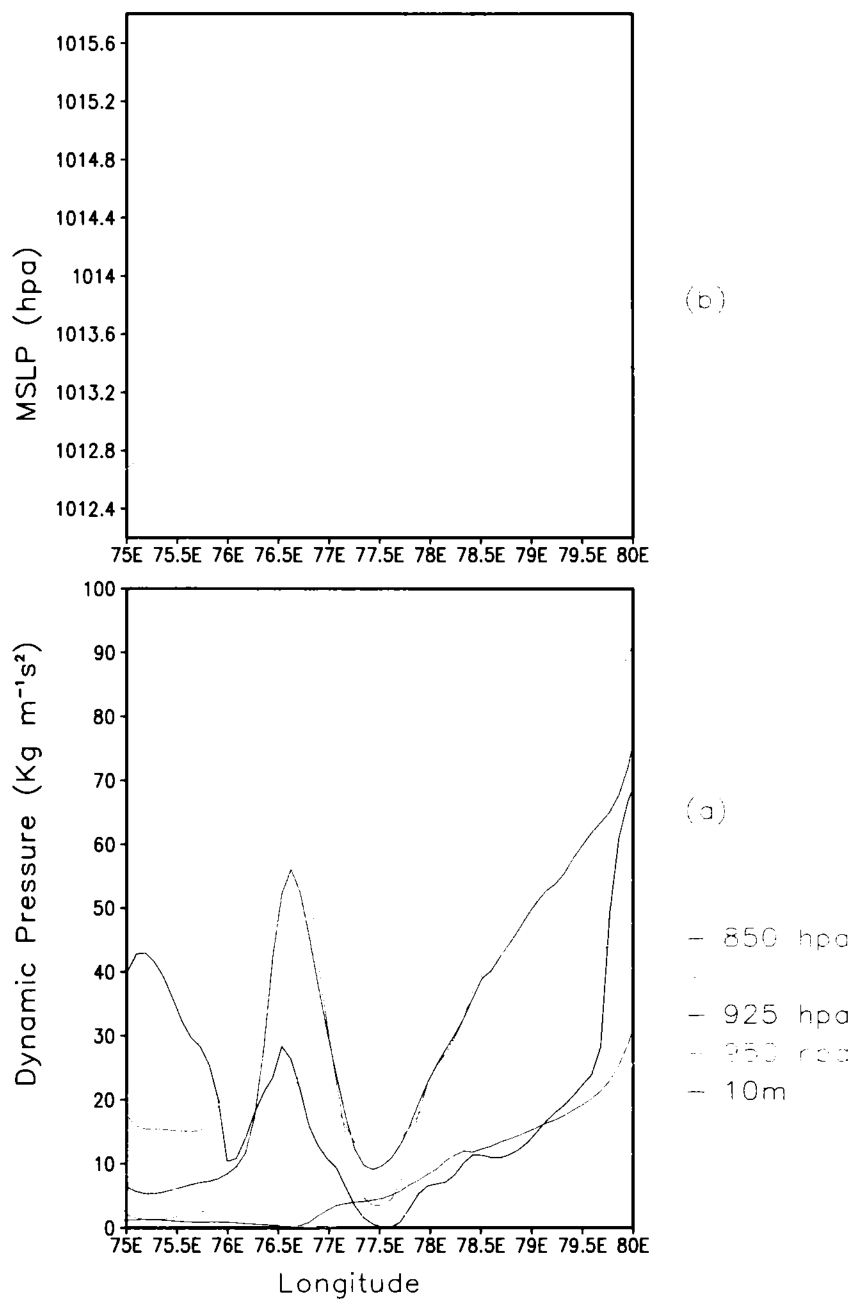


Figure 3.45: The cross section analysis of (a) Dynamic pressure at different levels (b) Static (mslp) pressure variation at the surface along the Palghat Gap during Winter season

of the adjoining areas of Aryankavu and Punalur in the western side and also the part of Madurai district in the eastern side. Similarly the places like Pollachi, Coimbatore and Udumelpet in the eastern side and Palghat and Malappuram Districts in the western side of the Western Ghats is also under the control of the major Gap of Palghat. The above analysis in this chapter shows the impact of the mountain on the wind pattern and the effect of these Gaps in controlling the local climate very clearly.

The circulation system around the mountain is controlled mainly by two factors. The Dynamical factors and the thermal factors. The dynamical modification can be classified as planetary scale, synoptic scale and the local air flow modification. The effect of conservation of absolute vorticity is making the diffluence over the mountain peaks and a curvature effect over the summit of the mountain region. But since the study area is near to the equator region the latitude effect is very small than the curvature effect which is found to be 10 times greater than the former one.

The wind approaching the Western Ghats in any direction will undergo a change in the potential vorticity due to which a part of the air streams will take an anticyclonic curvature and the remaining part will flow towards the low latitudes to compensate the vorticity changes. This is very clear in the both westerlies as well as easterlies. The value and the spatial distribution of the anticyclonic vorticity field is found to be larger than the cyclonic field. The mountain anticyclones which is forming in the lee ward side of the mountain environment may have its origin from this anticyclonic curvature effect in the area.

Like vorticity, the Turbulent kinetic energy is also varying much in the boundary layer. It varies from 0.2 to 3 Jkg^{-1} and the maximum transfer is taking place in the month of July when there is strong surface winds prevails over the region. The diurnal variation shows that the maximum is occurring between the noon hours of 1130 and 1430 hrs. It is found that the winds prevailing at the surface levels should possess some characteristics to overcome the mountain barrier effectively. From the analysis we have formulated a criteria for the hydraulic jump to occur over the Western Ghats mountain by analyzing the potential temperature, wind speed and the vertical shear of the air flow. It is found that the surface wind cross over to the other side of the Western Ghats in July when these three conditions satisfies. They are, 1) There should be a minimum wind speed of 12 ms^{-1} at 950 hPa level 2) The air should posses a minimum potential temperature of 28°C 3) There should be a positive wind shear always in the vertical upto the height of the mountain. The conditions are met in southwest monsoon months especially in the first half of the monsoon season when the surface winds are strong.

The effect of mountain can also seen in the synoptic scale like changes in the temperature pattern and relative humidity in the wind ward side of the mountain. The adiabatic ascend of the air will try to decrease the temperature on the wind ward side which is clear in the analysis. Also due to this ascend there will be condensation on the windward side which cause an increase in RH in the windward side. During the easterlies the eastern side of the Western Ghats shows this changes. Another synoptic scale change occurring in the mountain environment at the summit region is the effect of wind convergence and increase of pressure gradients at the left end of the ridge when we look from the upwind to downwind side and subsequently an anticyclonic curvature on the lee side. The convergence of this type of streamlines at that region is termed as the corner effect in mountain meteorology. This phenomenon, which was reported in the middle latitudes by Bergeron is prominent in the Western Ghats region and will be the cause of the local wind modification over the valley region of the high peaks of Anamudi and Nilgiri hills.

The Lee wave formation on the lee side is major phenomena happening due to the wind flow pattern over the mountain atmosphere. By knowing the Froude's number and the Scorer's parameters we can assess that whether the air flow is capable of making a hydraulic jump over the mountain and possible wavelengths of the lee waves can also be calculated with the help of Brunt-Vaisala frequency. It is found that the air flow over the study region is capable of making lee wave formation mainly in the Summer monsoon months. Rest of the periods, the wave formation is theoretically very difficult. More mid-tropospheric observation is needed to study the lee wave formation more precisely. Thus it is found that the wave formation in the western side of the Western Ghats in easterlies are rare. The theoretical calculation shows that the possible prominent wave length of the lee waves in the eastern side of the mountain in July is about 55 meters and lesser wave lengths also evolved during the calculations in other months.

The Fohn wind formation in the day time is very clear from the potential temperature and relative humidity analysis. Both in western and eastern side of the Western Ghats the Fohn winds are forming in the day time especially in the forenoon hours and the condition disappears within hours. The winds originated from the thermal reason such as Katabatic and Anabatic winds are very prominent in the Western Ghats region. The Katabatic winds are forming in the night time by about 2330 hrs and in the day time at about 1430 hrs, the Anabatic winds are developing with a maximum wind speed of 3 ms^{-1} at the higher slope regions. Studies in the middle latitudes shows that this winds are more stronger at above 20 meter level which cannot be verified due to the lack of the data at that level in this study. The speed of this gravity flows are calculated using the Reiher's formula as 2.6 ms^{-1} and it agrees well with the modelled value of 2.1 ms^{-1}.

Palghat Gap modifies the wind exists over the region drastically. The fanning out of the winds at the funnel mouth of the Gap at the eastern side and also in the western side is creating excess dynamical pressure over the exit regions and this helps to intensifies the subsidence over the down wind regions of the Gap. Thus the reduction of the rainfall at Pollachi, Coimbatore districts of Tamilnadu in the eastern side and the Malappuram and Palghat districts in the western side is primarily due to the intense subsidence over the region in the westerlies and easterlies respectively. Even though the magnitude of the dynamic pressure is equal on both sides of the Palghat Gap, the level upto which the dynamic pressure develops is less over western side than the eastern side. Thus the subsidence also will be intense over Tamilnadu side rather than the Kerala region. At the down wind region, the PBL height is also increasing indicating the increased mixing in the boundary layer. Along the Gap at the down wind region both at the western and eastern side, the maximum transfer of turbulent kinetic energy is occurring. Thus Palghat Gap controls the dynamics of the wind flow over the region and makes enormous changes in the planetary boundary layer of the region.

CHAPTER 4

Climatic Characteristics of Western Ghats

4.1 Introduction

The basic factors which affect the mountain climate have been discussed in earlier chapters of this thesis. In this chapter, some general climatic characteristics like energy fluxes, precipitation, evaporation, temperature pattern of the Western Ghats area are studied. The ways in which altitudinal and topographical effects interact to create orographic patterns in the spatial and temporal distribution of each climatic elements is analyzed in detail. The energy budget of the atmosphere shows that there is a surplus of solar energy exists in the tropical region and which is being transmitted to the higher latitudes according to the classical theory of general circulation of the atmosphere. Since the study area lies in the near equatorial belt the energy surplus will be high and this will be the major factor controlling the climate of that region. The difficulty in getting the actual rainfall and evaporation data of the hilly terrains makes the study more difficult and hence the role of the mesoscale models like MM5 is highly appreciable to understand the variation and relationship of these parameters with the topography of the region.

4.2 Energy Budget

Mountain environment were of special importance to early research on solar radiation, but there has been a general lack of modern radiation and energy budget studies on the mountains especially over the tropics. An adequate level of information on the spatial and temporal distribution of radiation exists only for the European Alps. From the energy budget studies the radiation surplus or deficit over a region can be assessed and by which the climate of a region can be very well be studied. The model calculated the short wave and long wave radiation fluxes in both upward and downward directions and also the sensible and latent heat fluxes. They are plotted for different months, representing different season.

Figs.(4.1 to 4.4) give the analysis of the net radiation, sensible heat and latent heat of nine stations in the study region in different months. Since the study area is located in the regime of near equatorial region the surplus energy budget is there in all season which can be seen from the positive values of the graphs in all stations and the absence of negative values in the figures. Generally the value of the net radiative flux varies in the range -800 Wm^{-2} to 1000 Wm^{-2} in the region. Except July the net radiation, the sensible and latent heat fluxes shows an increase in the noon hours between 1130 and 1430 hrs LT in all stations. But in Summer season there is a reduction of net energy in the noon hours. This is primarily due to the increased monsoon clouding during the south-west monsoon.

In April which represents Spring season, there is a marked deficiency of net radiation (-800 Wm^{-2}) over the summit regions which is seen at the stations B2 and D2. The

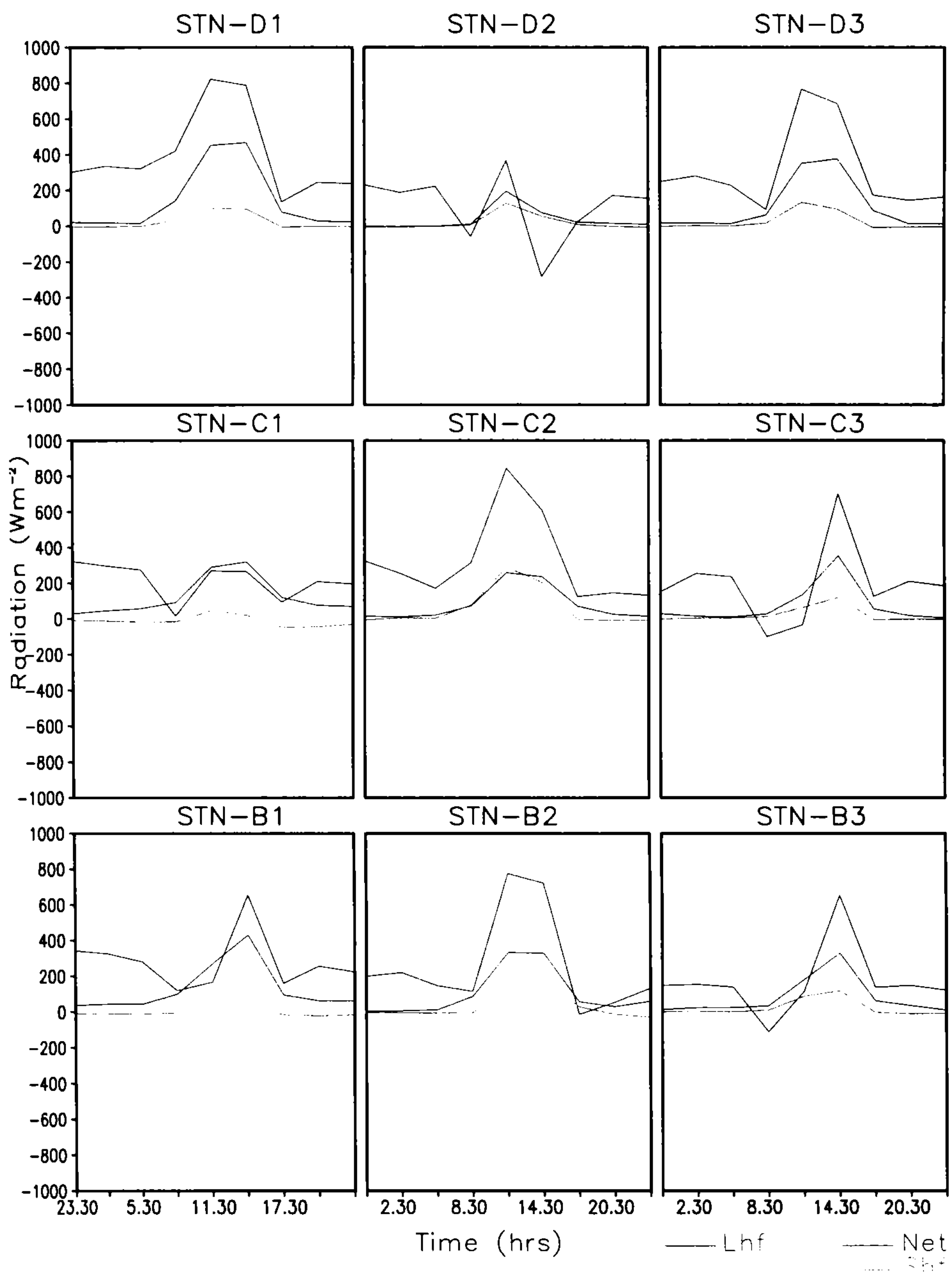


Figure 4.1: The energy budget in nine stations during a day of the month of January.

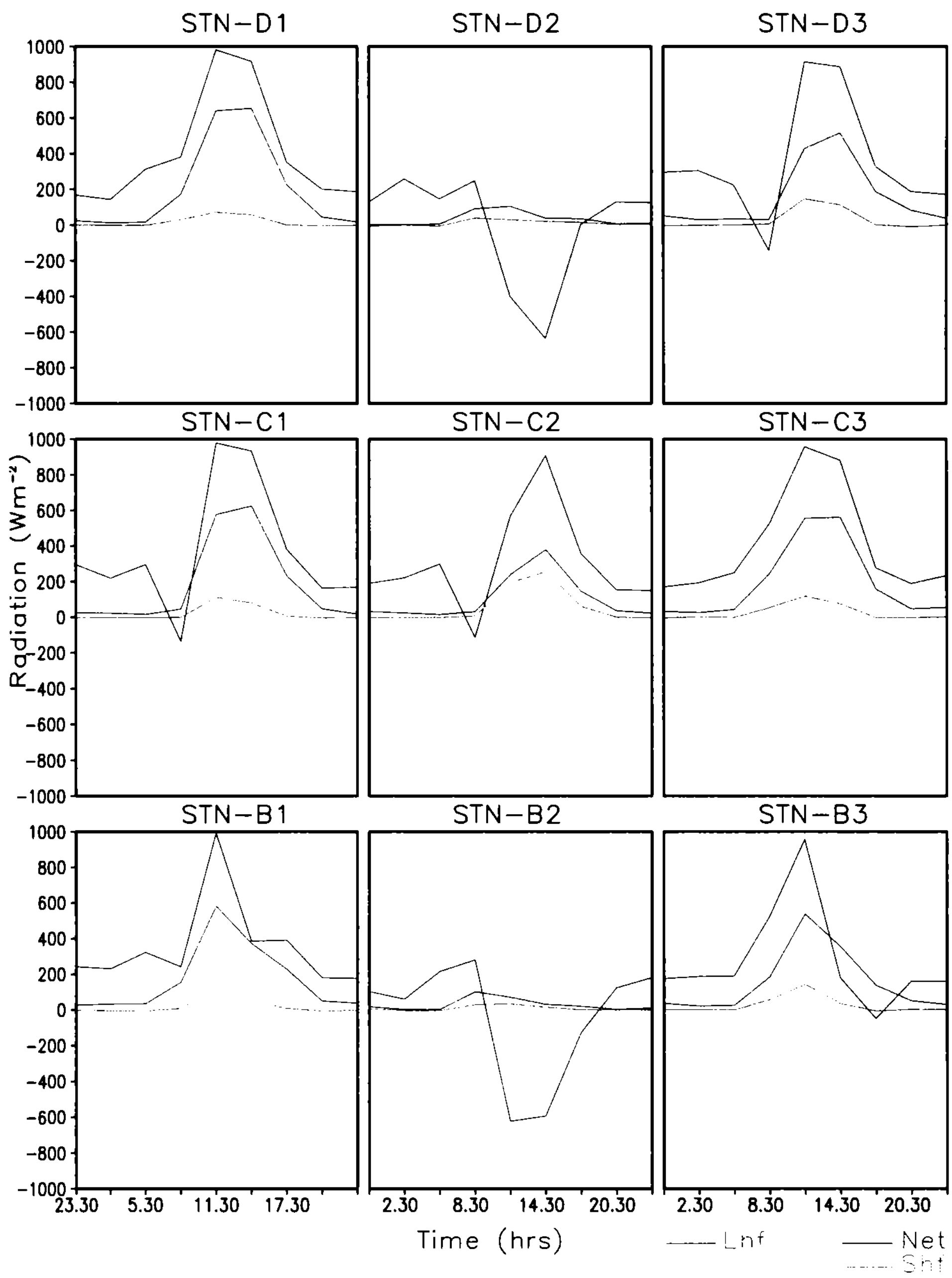


Figure 4.2: The energy budget in nine stations during a day of the month of April.

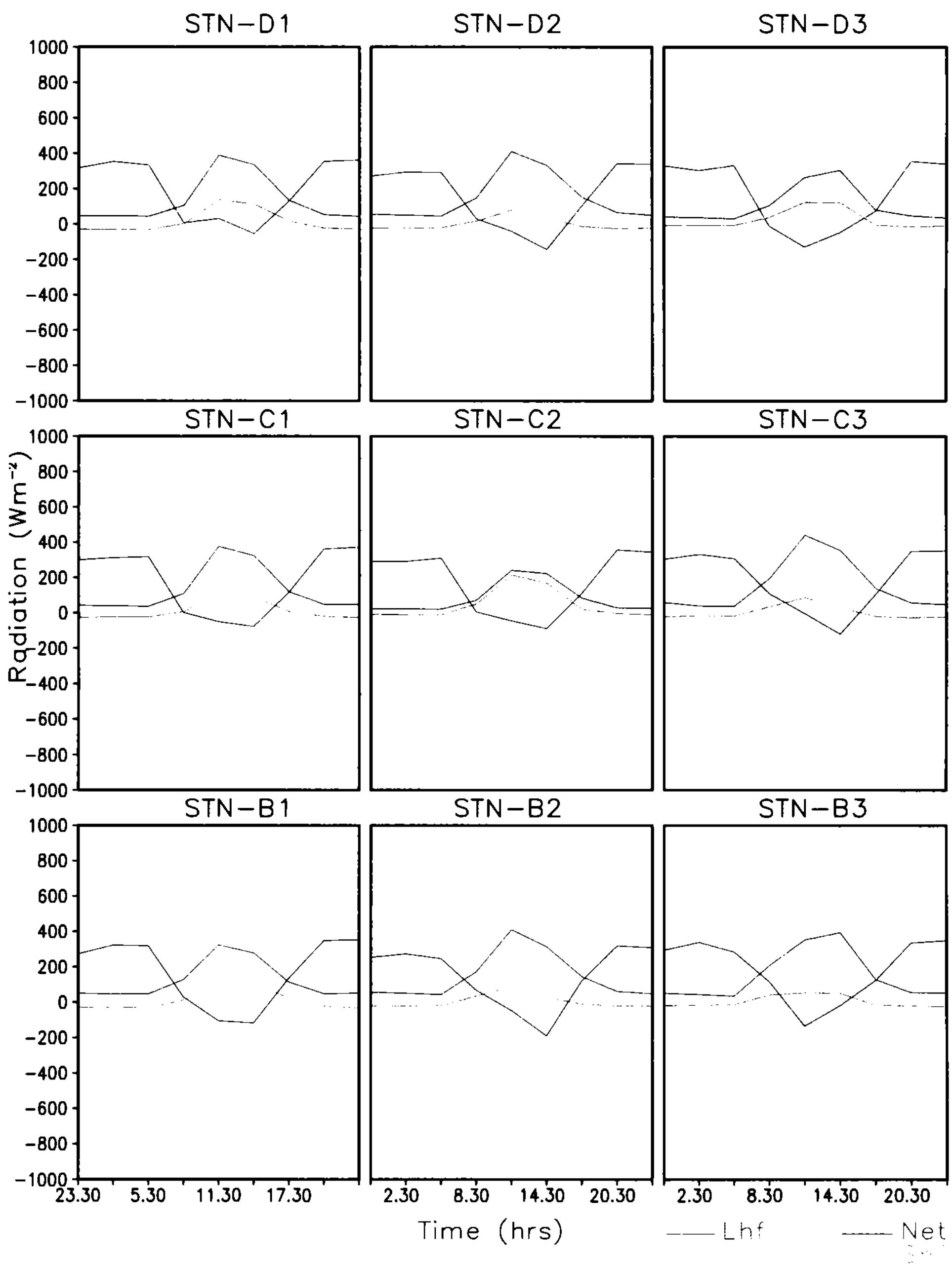


Figure 4.3: The energy budget in nine stations during a day of the month of July.

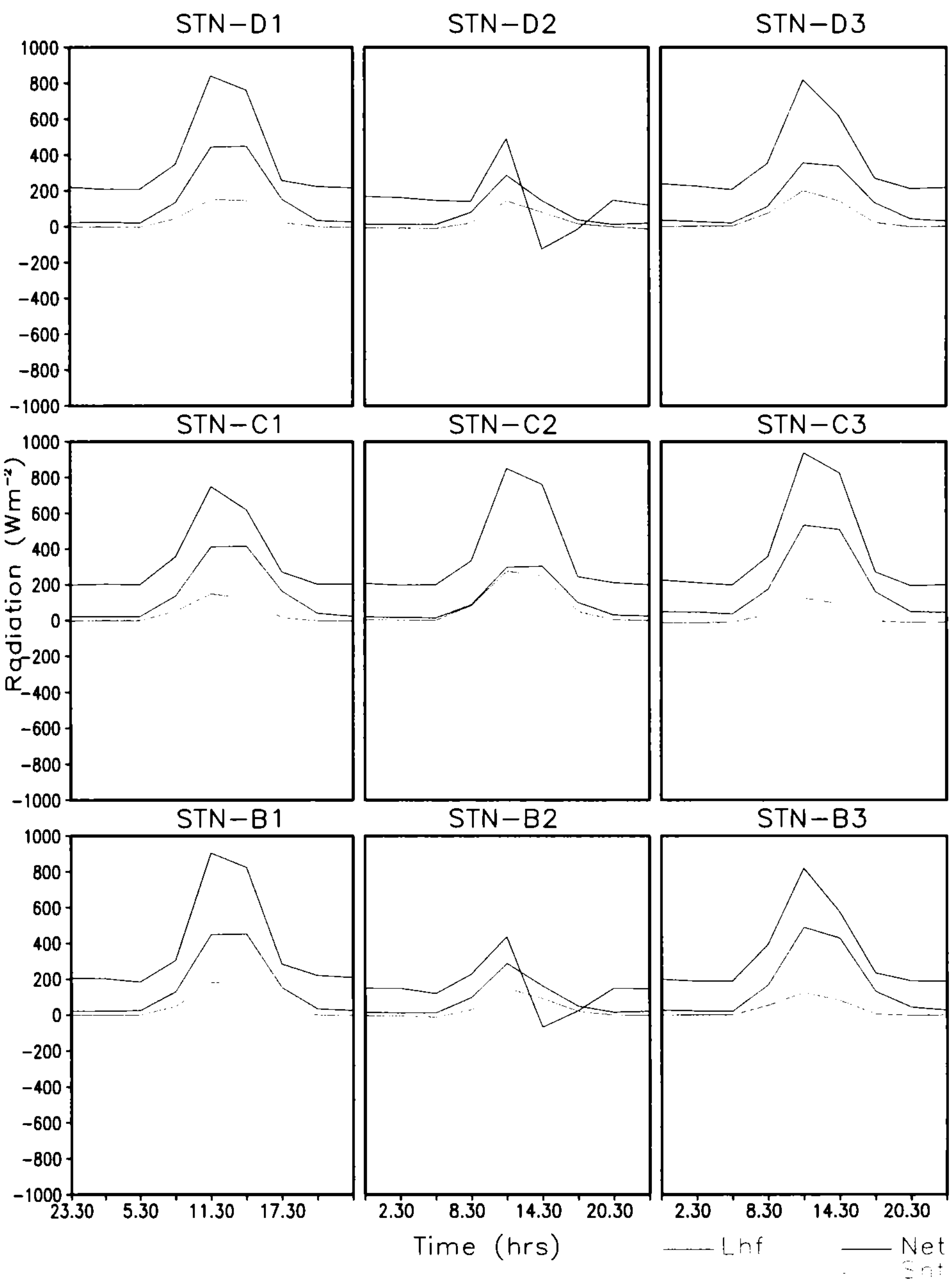


Figure 4.4: The energy budget in nine stations during a day of the month of October.

value of the latent heat flux is roughly half and sensible heat flux is quarter of the net radiation received in the noon hours of all stations throughout the season. Except in the Summer months the sensible heat is higher at the plain stations than the summit stations over the region. This may be due to the larger fraction of the available energy fluxes at the ground stations. Large scale moisture intrusion in Summer season on all lower tropospheric levels wipes out this difference in pattern of available energy existing in summit and plain stations. Palghat Gap do not show much variation from the plain stations. Only a reduction of latent heat flux and an increase in the sensible heat flux from the surrounding stations have been noticed over there.

4.3 Precipitation

The influence of mountain barriers on precipitation distribution and the amount has been a subject of long standing debate and controversy. To gain the understanding of the mountain precipitation we must consider the basic condensation processes and the ways in which mountain can affect the clouds and the precipitation regimes. Atmospheric water vapour content decreases quite rapidly with the height in the lower troposphere, so that, at 3 km, the water vapour content of the atmosphere is typically about one third of that at sea level. Precipitation amounts might also be expected likewise to decrease upward. But the vapour flux convergence, cloud water content and vertical wind profile are the other dominant influencing factors which control the precipitation regime. The amount of orographic precipitation depends on three factors operating on quite different scales. They are *(1) Air mass characteristics and synoptic scale pressure pattern (2) Local vertical motion due to the terrain and (3) Micro-physical processes in the cloud and the evaporation of falling drops.*

In the Western Ghat region the terrain is so complex and getting the accurate data is really difficult. Also the sparse network of rain gauges makes the situation more complex. India Meteorological Department is having rain gauge stations of about 80 numbers in Kerala and 140 numbers in Tamilnadu. In addition to this, rain gauge stations are maintained by the Electricity Board and the Ground Water Departments in both states. But these data points are not widely distributed but they are situated along the catchment areas of the major rivers of the study region and will not be useful much for the spatial analysis of the precipitation over the entire southern peninsular region. The data sets used for the present study is IMD's climatological data set for 82 stations in Kerala from 1901 to 1980 and 242 stations in Tamilnadu from 1901-1950. Also the monthly data of 82 stations in Kerala from 1981-1996 and 12 stations in Tamilnadu from 1966-1990 published by IMD are also used to supplement the main data set.

4.3.1 Observed precipitation in both sides of the Western Ghats

In the western side of the Western Ghats, the maximum rainfall is getting along the Konkan coast and the Eastern side becomes a rain shadow region. Thus Kerala comes under the heavy rainfall regime and Tamilnadu falls in the rain shadow region. The analysis of the observed rainfall pattern over the region has been done with the climatological data set of India Meteorological Department. In the case of Kerala rainfall, above 10°N is considered as Northern Kerala and the rest is taken as Southern Kerala. The figs.(4.5 & 4.6) give the mean monthly rainfall of Kerala and Tamilnadu.

The monthly variation of Kerala rainfall shows more rainfall in south Kerala than north Kerala except June, July and August. But in the major rain giving months of south-west monsoon periods, North Kerala dominates with the rainfall. In the month of July a maximum of 85 cms of rainfall is getting in the North Kerala while it is below

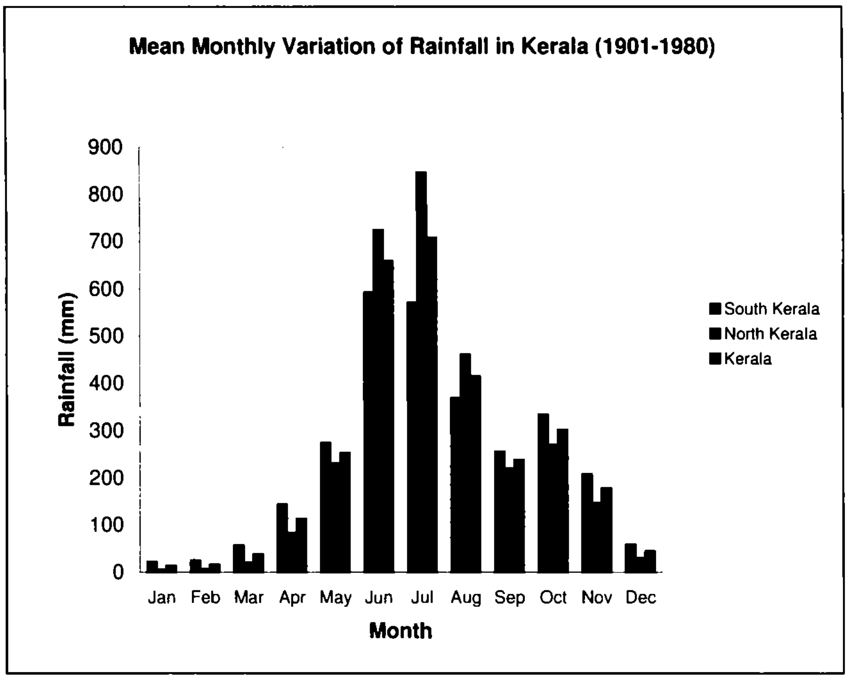


Figure 4.5: The mean monthly observed rainfall of Kerala (1901-1980).

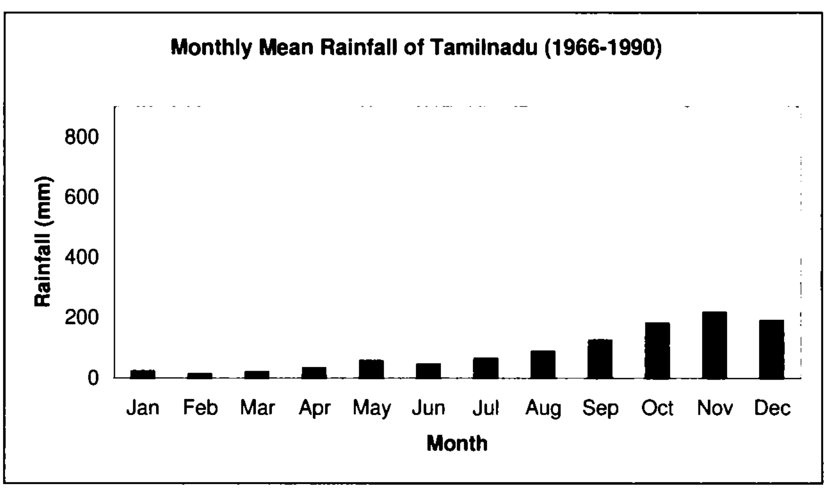


Figure 4.6: The mean monthly observed rainfall of Tamilnadu (1960-1990).

60 cms in South Kerala. Tamilnadu is getting a maximum of 20 cms of rainfall in the month of November which comes under the north-east monsoon period. Only in December Tamilnadu rainfall exceeds that of Kerala. During that month only about 5 cms rainfall is getting in Kerala while it is about to 20 cms in Tamilnadu. The rain shadow effect due to the mountain in the eastern side is very clear from the mean monthly observed rainfall pattern.

The mean seasonal analysis of rainfall shows that Kerala gets 68% of annual rainfall (202 cms) in south-west monsoon period while Tamilnadu gets 30% of their annual rainfall (32 cms) in that period (fig.4.7). In Winter season 4% is getting at Tamilnadu while it is 1% in Kerala. Even the amount of rainfall getting in Kerala is almost same as the rainfall of Tamilnadu in the other three season (Spring, Autumn and Winter). North-East monsoon do not shows any rain shadow effect in the western side of the mountain in Kerala. This is primarily due to the intrusion of easterlies through the northern end of the mountain and also the impact of Palghat and Aryankavu pass.

The annual variation of rainfall for Kerala and Tamilnadu has given in fig.(4.8). Eighty years of data is used for Kerala while 24 years for Tamilnadu according to the availability of the data set for this analysis. The inferences obtained with this data set can be used to understand the general pattern exisiting in the respective regions. The slope of the trendline in Kerala is -2.4 while at Tamilnadu it is -1.4. Thus Kerala's rainfall is decreasing with the rate of 2.4 mm/year and in Tamilnadu it is 1.4 mm/year. Also the positive and negative departure of the annual rainfall from the trend line is about 2 years for Kerala and 4 years for Tamilnadu. Hence more inter-annual variability is seen over Kerala than Tamilnadu. A maximum of 4200 mm rainfall is received in Kerala during the year 1961 and the minimum is 2500 mm in many years. In Tamilnadu the annual

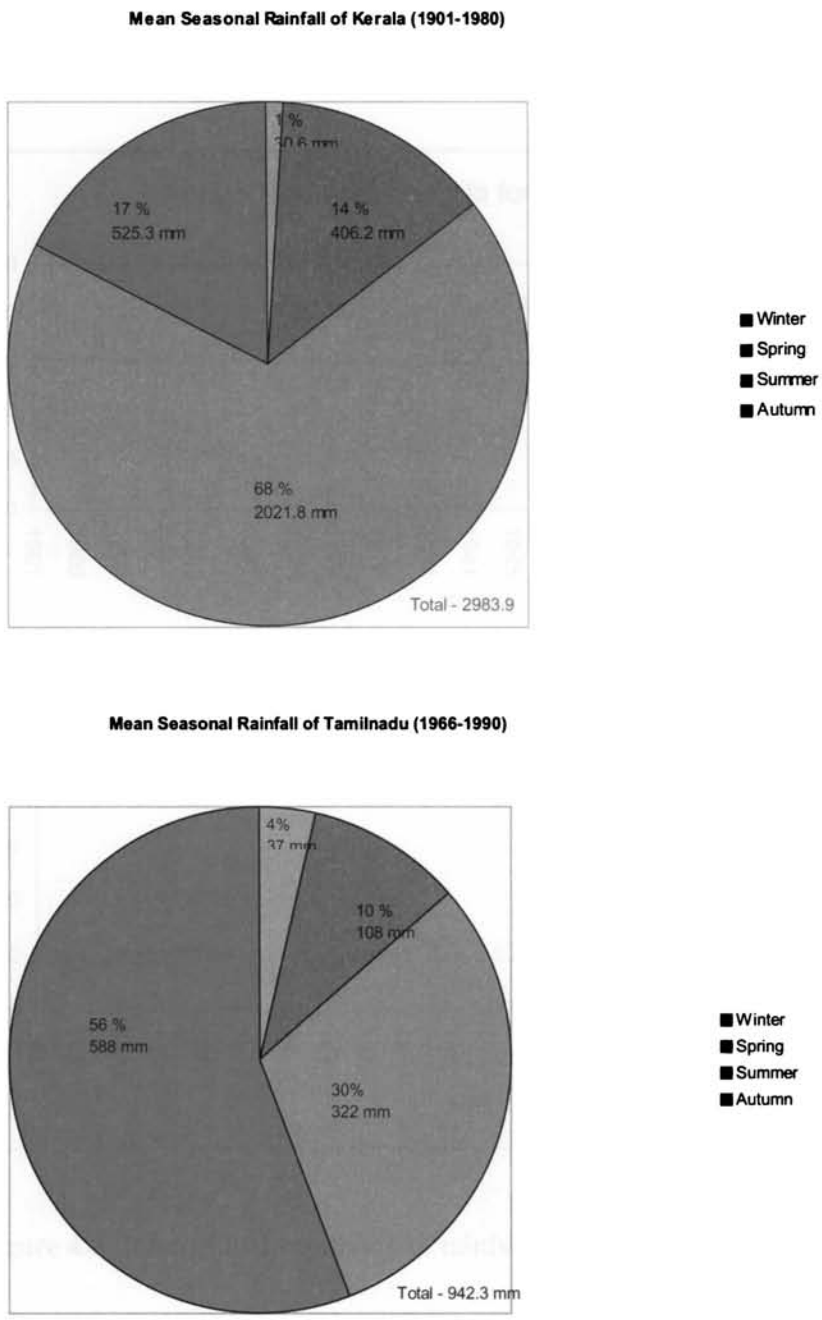


Figure 4.7: The mean seasonal rainfall of Kerala and Tamilnadu (1960-1990).

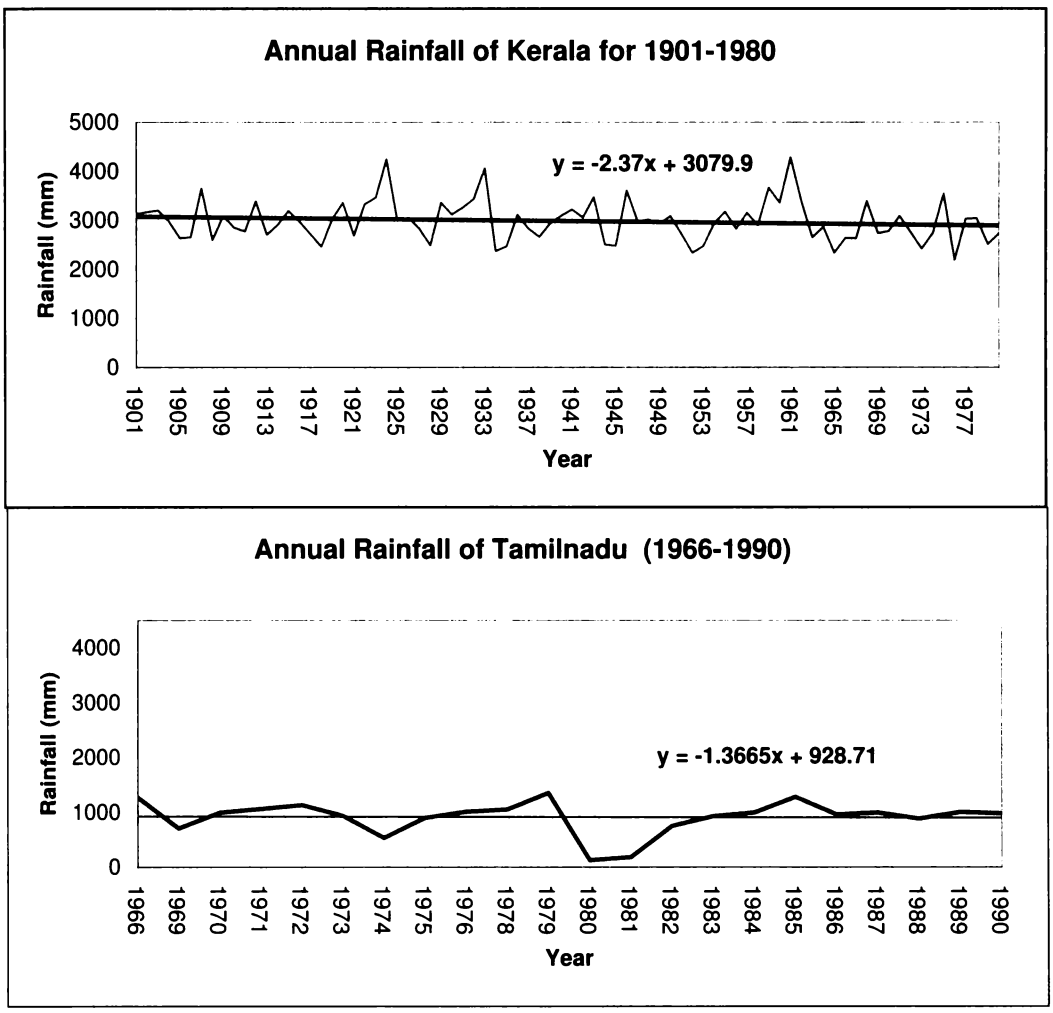


Figure 4.8: Inter-annual variability of rainfall over Kerala and Tamilnadu.

maximum is 1500 mm during 1979 and 1985 and the minimum of 100 mm is recorded in the year 1980.

Altitudinal Characteristics of the Rainfall

The slope of the terrain is quite different in the whole stretch of the Western Ghats. The maximum mean slope of 75.9°is seen at the western side of the Anamalai hill from Neriamangalam to Munnar stretch as well as the western side of the northern end of the study area near Kannur and Kasargod districts of Kerala. Eastern side of the Anamalai hill is having a slope of 56.1°and that at the northern end is 32°, which is mainly surrounded by the southern end of the Deccan plateau. The slope is 14.5°between Malayattur (138.6 m) and Neriamangalam (282.4 m) at the western side of the Ghat. But at the Nilgiri hills the maximum slope is at the eastern side (73.7°) contrary to Anamalai hills and the western side the slope is 68.4°. The average distance of the coast from the 400 meter contour is 100 km in Kerala and 200 km in Tamilnadu. Thus the steepness of the terrain near the coast and the windward side of the monsoon currents gives abundant rainfall to the western side of the mountain in Kerala.

At the Aryankavu pass the terrain attains a slope of 44.4°from Punalur to Aryankavu and then descends to Tamilnadu side. Similarly at the largest discontinuity at the Palghat, the terrain increases from Chittoor (145.7 m) of Palghat district to Dharapuram (268.5 m) of Coimbatore district. But here the slope is 36.9°, less than the Aryankavu Gap but the width of the Gap is more than double the width of Aryankavu pass. Generally a sudden decrease of rainfall can be seen at the Tamilnadu side of the Gap in south-west monsoon period but at the mouth of the Gap away from the center, the rainfall is found to be higher than rest of the places around it. The rainfall over the study region increases from south to north in both sides of the mountain. Earlier studies show that maximum rainfall is getting near to the Mangalore region and then again decreases towards north. This is primarily due to the proximity of the Western Ghat mountain to the coast and the positioning of the low level jet during the period of south-west monsoon period.

The variation of rainfall along different cross sections of latitudes in the study region has been analyzed for south-west and north-east monsoon period with the help of observed mean data of IMD (figs.4.9 & 4.10). Along the Anamalai cross section during south-west monsoon season, rainfall increases sharply from Malayattur (240.6 cm) to Neriamangalam (383.8 cm) and then decreases dramatically afterwards. In north-east monsoon season also maximum rainfall is getting at Neriamangalam and the zone of maximum rainfall reaches upto Perumbavoor which is about 35 kms down side of Neriamangalam. Thus it is evident that the characteristics of the terrain in this stretch is quite favourable for the precipitation in any season. Similarly there is a marked reduction of rainfall in south-west monsoon period from Punalur (1714.5 mm) to Shenkotai (529.3 mm) were the terrain is having a maximum slope . But during north-east monsoon period there is a slight increase of rainfall at Aryankavu and Punalur stations than the Tamilnadu stations. Along the Palghat Gap also rainfall decreases as the height increases from Chittoor to Dharapuram during south-west monsoon season.

Evaluating the Orographic Components

The variation of rainfall with terrain is investigated in this section. The terrain over the study region has been divided into 4 categories for the purpose of analysis. They are *Low (0-200 m), medium (200-600 m), High (600-1000 m) and Summit (>1000 m)* levels. The average rainfall pattern for these different categories for Kerala and Tamilnadu have been given in fig.(4.11). It is found that in Kerala, the maximum amount of rainfall is getting at the medium elevation classes while that in the Tamilnadu side is in the high terrain class. The

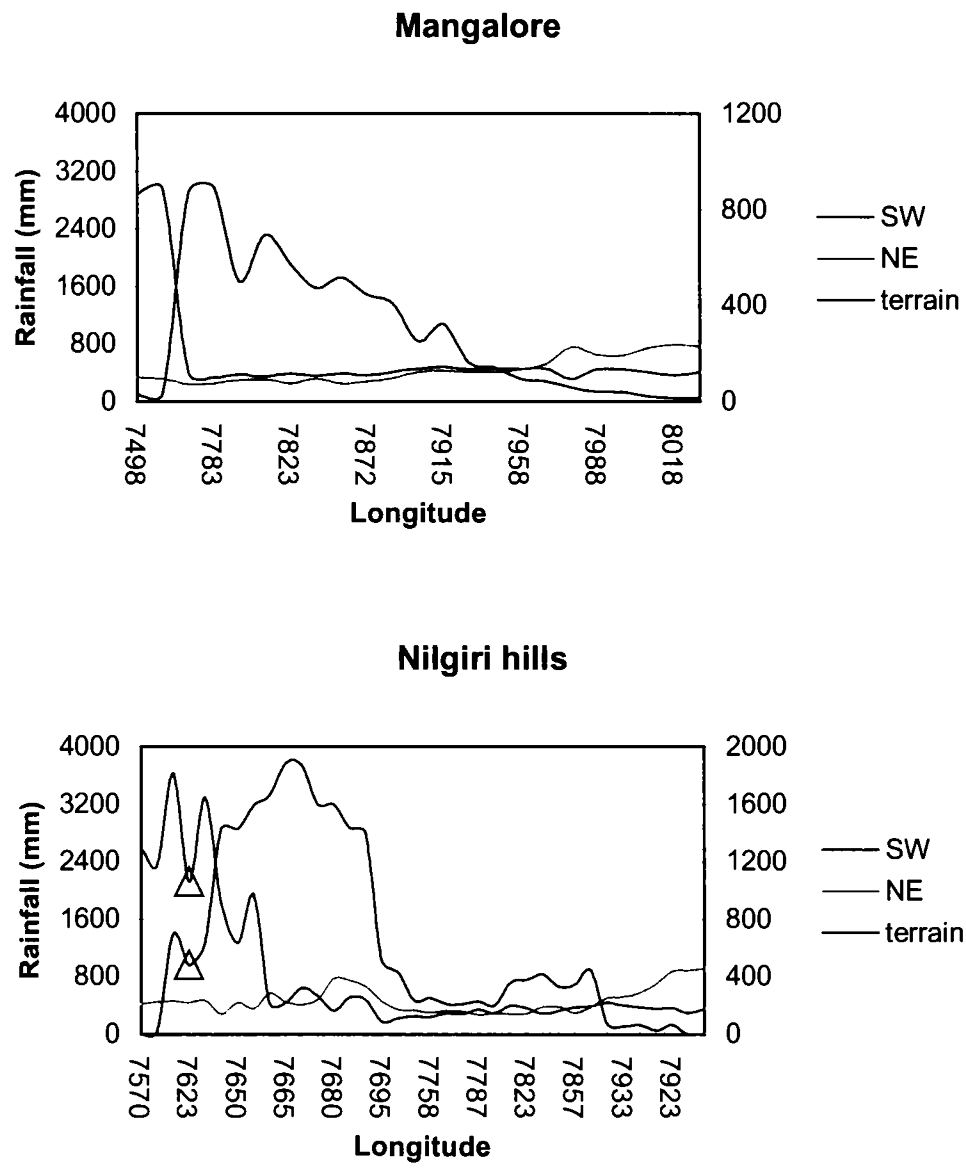


Figure 4.9: The latitudinal cross section of observed mean rainfall along the northern side of the Ghat.

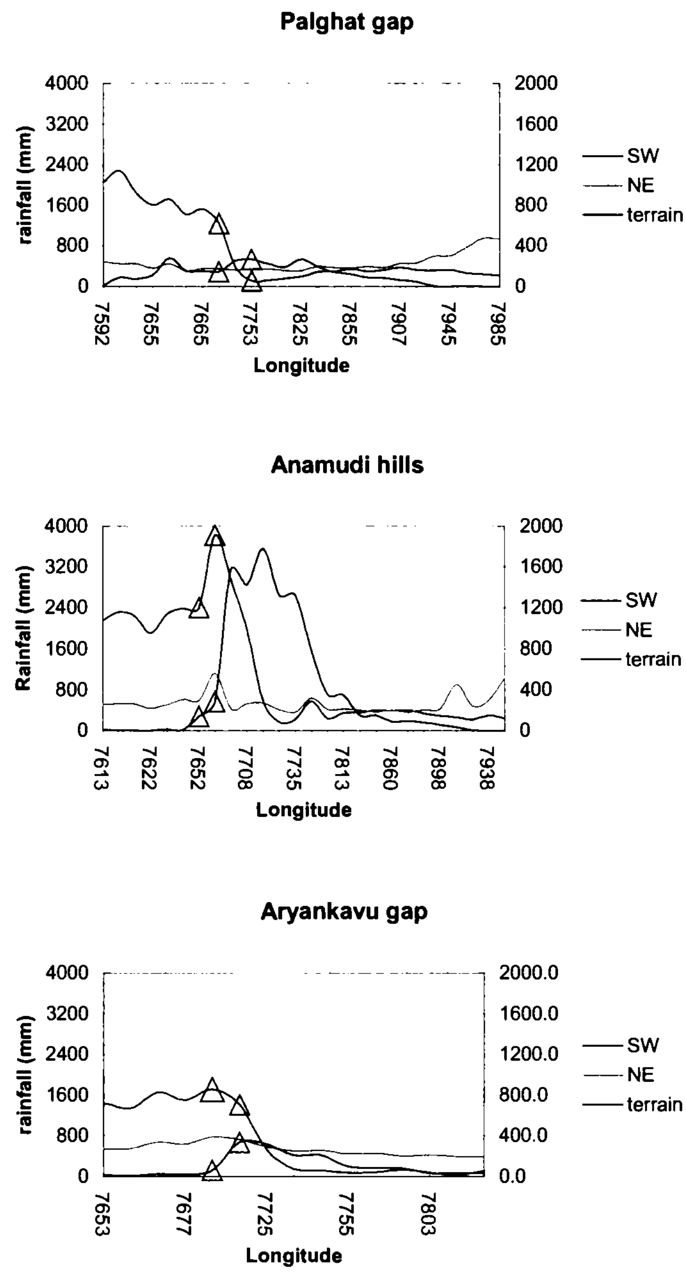
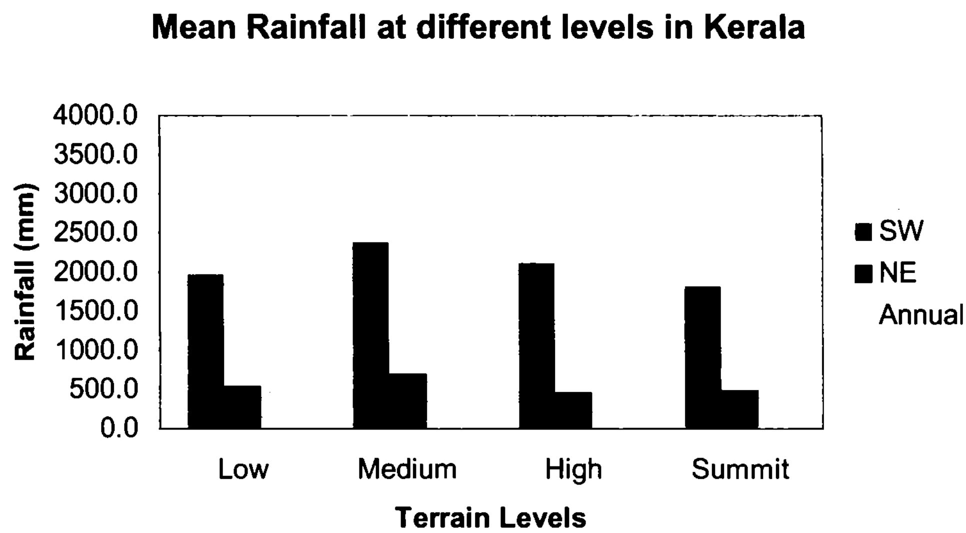


Figure 4.10: The latitudinal cross section of observed mean rainfall along the southern side of the Ghat.



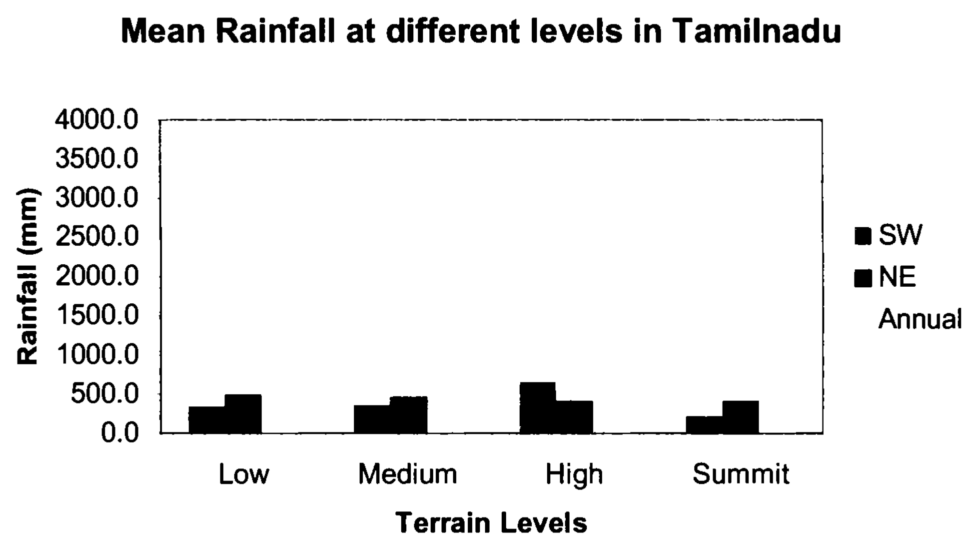


Figure 4.11: The mean observed rainfall in different classification of terrain in the study region.

correlation of the rainfall with the different class of terrain is given in table (4.1). There is a

Terrain	South-West		North-East		Annual	
	Kerala	Tamilnadu	Kerala	Tamilnadu	Kerala	Tamilnadu
Low	-0.3	0	-0.2	0.2	-0.4	0.1
Medium	-0.4	0.1	-0.6	-0.1	-0.5	0.1
High	-0.8	0.3	-0.5	0	-0.8	0.3
Summit	0.9	-0.6	-1.0	0.3	0.9	-0.3

Table 4.1: The correlation of rainfall with different levels of terrain in different season in the study area

high negative correlation of -0.8 is found in the high class and a high positive correlation of 0.9 is seen at the summit levels in the Kerala region. While there is no significant correlation is seen at the Tamilnadu stations at any levels except a negative correlation of -0.6 is found for south-west monsoon rainfall at the summit level. Hence we can conclude that in Kerala, stations located between 200-600 meter are more prone to higher rainfall occurrences and there is not much control of the terrain at the lee ward side of the mountain. In the windward side of Kerala generally a negative correlation exists between terrain height and rainfall which indicates that the rainfall activity is more concentrated at the down valley region and the plain stations than the high ranges. But at the eastern side there is not much dependence of rainfall activity to the local terrain except at summit levels in south-west monsoon period.

North-South variation of Rainfall over the study region

It is found that the rainfall pattern in both sides of the Ghats increases towards north (fig.4.12). But in north-east monsoon it decreases towards the north in Kerala. The slope of the trend line in Kerala for south-west monsoon is 270 mm deg^{-1} increase and 5 mm deg^{-1} decrease during north-east monsoon in the north-south direction in a year. For Tamilnadu it is 12 mm deg^{-1} increase in south-west monsoon and 1 mm deg^{-1} increase for north-east monsoon. Intrusion of the easterlies at the southern end of the peninsular region through the

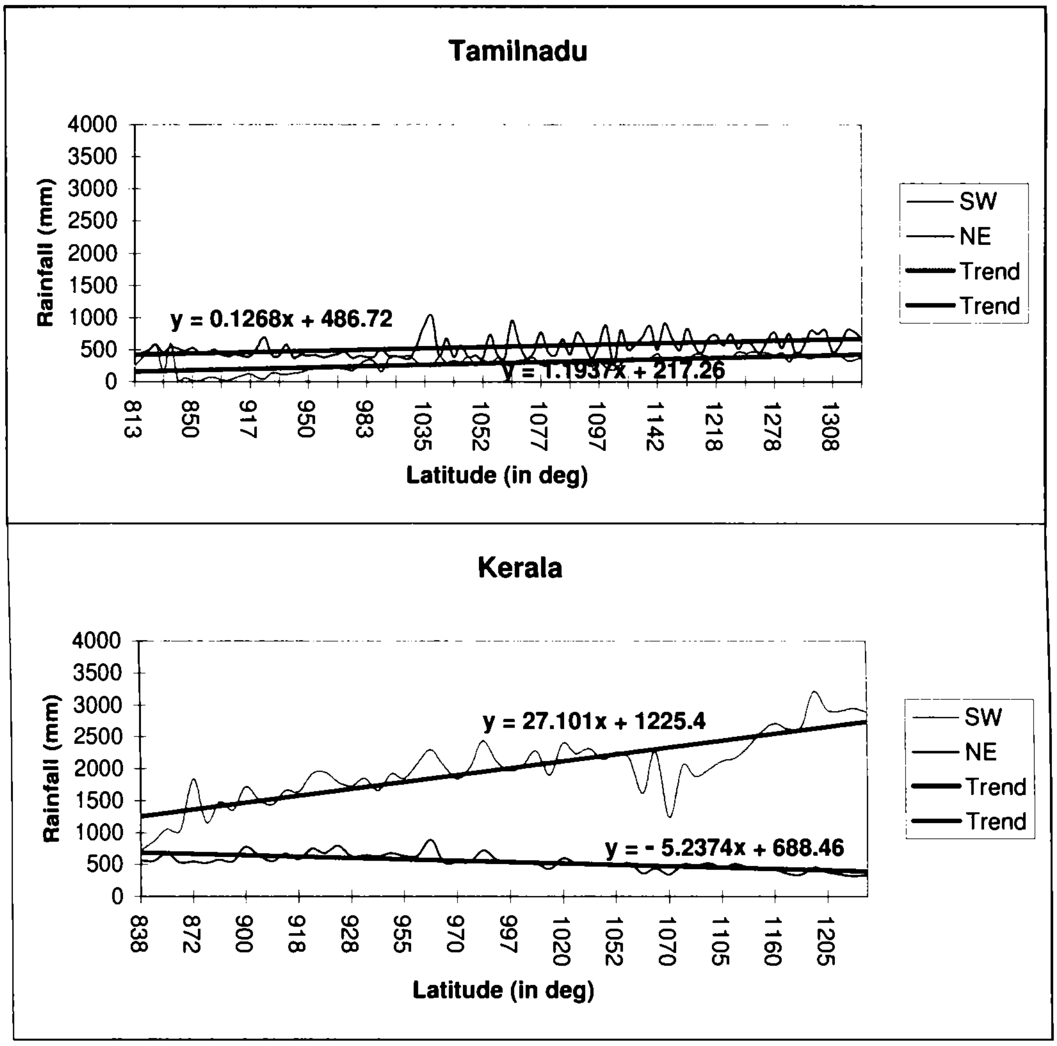


Figure 4.12: The mean observed rainfall of stations below 500 m in the north-south direction both in eastern and western side of the mountain.

Aryankavu pass and through the low level mountains of the region is enhancing the rainfall activity in those region (fig.4.13). The correlation study of annual coastal rainfall and the

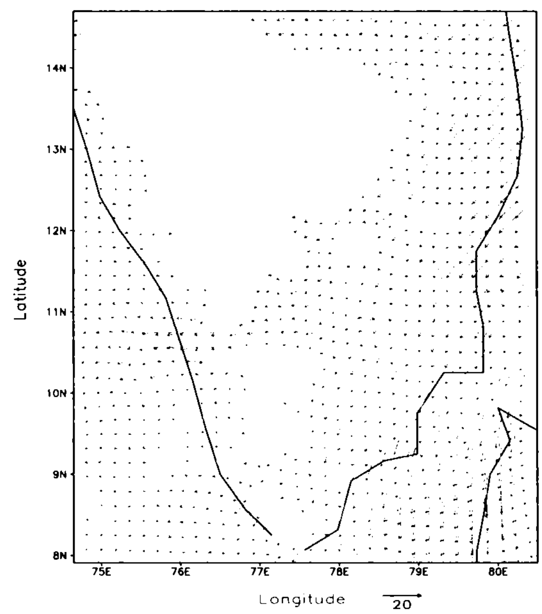


Figure 4.13: The wind pattern at 950 hPa level in December over the study region.

angle of incidence of the monsoon wind at different levels assuming the winds are purely zonal is carried out. But a significant correlation is not seen (only 0.2) at any level. Also the correlations between the coastal rainfall and the distance between coast and different levels of the terrain is found out. A high value of negative correlation (-0.8) is found with levels greater than or equal to 1000 m in Kerala. That shows as the distance of the coast increases from 1000 m terrain, the rainfall decreases in Kerala. This is same for Tamilnadu also, but the negative correlation coefficient is 0.5 only. Thus one of the reason for the increase of rainfall towards the north in the study region is due to the proximity of the high mountain terrain of above 1000 m height to the coast.

Spatial variation of maximum and minimum rainfall

The maximum rainfall at any season in the study region is not getting at the exact peak of the mountain, but some distance away from the summit. During south-west monsoon period around the Anamudi hills the maximum rainfall is getting at Neriamangalam which is 32.2 km air distance away from the maximum peak and at Nilgiri hills it is 27.8 kms away from the peak in the western side of the mountain (see fig.4.10). While north-east monsoon period this value is 40.1 km air distance away from the peak in the eastern side of the mountain in the Anamalai cross section and 16.7 km east of Nilgiri hills.

The top ten maximum and minimum rainfall getting places over the study region are given in tables (4.2 to 4.5). The maximum annual rainfall in Kerala is getting at Neriamangalam of Idukki district (5883.5 mm) and minimum at Chinnar (649.2 mm) of Idukki district. It is seen that Neriamangalam gets maximum rainfall in every season. High range places like Vyttiri, Kutyadi and Peerumedu also get more rainfall during south-west monsoon. Stations in the north Kerala is getting more rainfall in south-west monsoon. But the effect of Aryankavu pass is very clear in the north-east monsoon period. Places like Punalur, Aryankavu, Pathanamthitta and Konni is getting more rain mainly due to the effect of this pass. The station Kanjirappally in Kottayam district is distinct for its excess rainfall in north-east monsoon period. The convective rain in the non-monsoon months also will be maximum at these regions.

Reduction of rainfall towards the south of Kerala during south-west monsoon period is very clear in the analysis. Five places in Trivandrum district come in the first ten places where minimum rainfall is reported in Kerala during the south-west monsoon. Reduction of rainfall is seen in the high-ranges of Kumali and Santhanpara, which are categorized as the plain land of high ranges. The wind in those regions is experiencing high surface

Station	**Latitude**	**Longitude**	**District**	**Annual (mm)**	**HT (m)**
Neriamangalam	10°.03′	76°.47′	Idukki	5883.5	282.4
Kuttyadi	11°.40′	75°.45′	Malappuram	4504.3	275.4
Peerumedu	9°.34′	76°.59′	Kottayam	4471.3	601
Vyttiri	11°.33′	76°.02′	Wayanadu	4435.7	693.7
Kanjirappilly	9°.34′	76°.47′	Kottayam	4156.5	263.8
Pala	9°.36′	76°.45′	Kottayam	3985.3	122
Irikkur	11°.58′	75°.33′	Cannore	3978.2	48.6
Munnar	10°.06′	77°.04′	Idukki	3815.9	1573.9
Karikode	9°.50′	76°.40′	Ernakulam	3806.4	50.2
Hosdurg	12°.18′	75°.06′	Kasarkode	3562.2	31.2
Station	**Latitude**	**Longitude**	**District**	**SW (mm)**	**HT (m)**
Neriamangalam	10°.03′	76°.47′	Idukki	3828.3	282.4
Vyttiri	11°.33′	76°.2′	Wayanadu	3624.1	693.7
kuttyyadi	11°.40′	75°.45′	Malappuram	3361.1	275.4
Irikkur	11°.58′	75°.33′	Cannoore	3216.9	48.6
Peerumedu	9°.34′	76°.59′	Kottayam	3159.9	601
Hosdurg	12°.18′	75°.6′	Kasarkode	2955.6	31.2
Munnar	10°.06′	77°.4′	Idukki	2951.3	1573.9
Taliparamba	12°.03′	75°.21′	Cannoore	2929.4	74.5
Payyannur	12°.06′	75°.12′	Cannoore	2903.5	0.9
Kasarkode	12°.31′	74°.59′	Kasarkode	2886.7	30.9
Station	**Latitude**	**Longitude**	**District**	**NE (mm)**	**HT (m)**
Neriamangalam	10°.03′	76°.47′	Idukki	1113.8	282.4
Kanjirappilly	9°.34′	76°.47′	Kottayam	927.1	263.8
Pala	9°.36′	76°.45′	Kottayam	886.2	122
Pathanamthitta	9°.16′	76°.46′	Pathanamthitta	790.0	15.2
Punalur	9°.0′	76°.55′	Kollam	772.6	62.1
Peerumedu	9°.34′	76°.59′	Kottayam	759.7	601
Konni	9°.13′	76°.51′	Pathanamthitta	745.3	15.2
Aryankavu	8°.59′	77°.10′	Kollam	732.3	334.2
Karikode	9°.50′	76°.40′	Ernakulam	721.8	50.2
Mavelikkara	9°.15′	76°.32′	Pathanamthitta	681.2	17.3
Station	**Latitude**	**Longitude**	**District**	**Others (mm)**	**HT (m)**
Neriamangalam	10°.03′	76°.47′	Idukki	941.4	282.4
Kanjirappilly	9°.34′	76°.47′	Kottayam	933.2	263.8
Konni	9°.13′	76°.51′	Pathanamthitta	799.3	15.2
Pala	9°.36′	76°.45′	Kottayam	797.2	122
Pathanamthitta	9°.16′	76°.46′	Pathanamthitta	730.5	15.2
Punalur	9°.0′	76°.55′	Kollam	672.3	62.1
Karikode	9°.50′	76°.40′	Ernakulam	647.7	50.2
Alleppey	9°.33′	76°.25′	Kottayam	612.6	0.8
Adur	9°.09′	76°.44′	Kollam	607.8	22.4
Changanassery	9°.27′	76°.33′	Pathanamthitta	591.3	13

Table 4.2: Top 10 maximum rainfall receiving stations in Kerala in different season

Station	**Latitude**	**Longitude**	**District**	**Annual (mm)**	**HT (m)**
Annamalai	10°.35′	76°.55′	Coimbatore	4242.0	367.1
Sinnakallore	11°.15′	77°.11′	Coimbatore	4143.4	289.5
Devala	11°.28′	76°.24′	Nilgiri	4045.8	637.1
Naduvattom	11°.28′	76°.33′	Nilgiri	2578.7	1590.1
Gudallore	11°.30′	76°.30′	Nilgiri	2333.5	1426.9
Pechipara	8°.26′	77°.19′	Kanyakumari	2262.2	595.9
Kulasekharam	8°.22′	77°.18′	Kanyakumari	2052.9	225
Puthen Dam	8°.22′	77°.20′	Kanyakumari	2051.4	347.6
Glenmorgan	11°.35′	76°.30′	Nilgiri	2040.6	1426.9
Kaliyal	8°.23′	77°.16′	Kanyakumari	1947.8	225
Station	**Latitude**	**Longitude**	**District**	**SW (mm)**	**HT (m)**
Sinnakallore	11°.15′	77°.11′	Coimbatore	3412.5	289.5
Devala	11°.28′	76°.24′	Nilgiri	3286.8	637.1
Annamalai	10°.35′	76°.55′	Coimbatore	3149.1	367.1
Naduvattom	11°.28′	76°.33′	Nilgiri	1930.9	1590.1
Gudallore	11°.30′	76°.30′	Nilgiri	1828.8	1426.9
Glenmorgan	11°.35′	76°.30′	Nilgiri	1273.1	1426.9
Pechipara	8°.26′	77°.19′	Kanyakumari	928.3	595.9
yercaud	11°.47′	78°.13′	Salem	833.3	569.6
Puthen Dam	8°.22′	77°.20′	Kanyakumari	798.5	347.6
Kulasekharam	8°.22′	77°.18′	Kanyakumari	767.5	225
Station	**Latitude**	**Longitude**	**District**	**NE (mm)**	**HT (m)**
Vedaranyam	10°.22′	79°.50′	Tanjaore	1027.7	0
Tirupoondi	10°.37′	79°.49′	Tanjaore	955.0	0
NaGapatanam	10°.46′	79°.51′	Tanjaore	934.2	0
Portonovo	11°.30′	79°.45′	South Arcot	911.8	4.6
Nedivasal	10°.21′	79°.09′	Tanjaore	896.7	33.5
Sirkali	11°.15′	79°.44′	Tanjaore	892.5	1.3
Tranqubar	11°.02′	79°.52′	Tanjaore	875.8	0
Chidambaram	11°.24′	79°.42′	South Arcot	874.8	3.5
Cuddallore	11°.46′	79°.46′	South Arcot	829.4	8.6
Mayuram	11°.06′	79°.06′	Tanjaore	806.2	2.8
Station	**Latitude**	**Longitude**	**District**	**Others (mm)**	**HT (m)**
Pechipara	8°.26′	77°.19′	Kanyakumari	588.8	595.9
Kulasekharam	8°.22′	77°.18′	Kanyakumari	547.8	225
Puthen Dam	8°.22′	77°.20′	Kanyakumari	523	347.6
Annamalai	10°.35′	76°.55′	Coimbatore	509.8	367.1
Kotagiri	11°.26′	76°.52′	Nilgiri	499.7	1432.5
Kaliyal	8°.23′	77°.16′	Kanyakumari	498.8	225
Coonoor	11°.21′	76°.48′	Nilgiri	460.7	1597.2
Kodaikanal	10°.14′	77°.31′	Madurai	453.9	782.8
Chorlakode	8°.25′	77°.25′	Kanyakumari	428	654.4
Thadikarankonam	89°.20′	77°.26′	Kanyakumari	422.1	370.5

Table 4.3: Top 10 maximum rainfall receiving stations in Tamilnadu in different season

Station	Latitude	Longitude	District	Annual (mm)	HT (m)
Chinnar	9°.52′	77°.06′	Idukki	649.2	817.4
Marayur	10°.16′	77°.09′	Idukki	1348.9	1378.9
Parasala	8°.20′	77°.09′	Trivandrum	1479.1	140.3
Neyyattinkara	8°.23′	77°.05′	Trivandrum	1653.9	70.5
Kumali	9°.32′	77°.10′	Kottayam	1720.7	905.1
Chittur	10°.45′	76°.44′	Palghat	1794.1	145.7
Trivandrum	8°.29′	76°.57′	Trivandrum	1812.1	34
Santhanpara	9°.58′	77°.13′	Kottayam	1861.1	1018.6
Attingal	8°.42′	76°.49′	Trivandrum	1955.6	0
Palghat	10°.46′	76°.39′	Palghat	2019.4	31.2
Station	**Latitude**	**Longitude**	**District**	**SW (mm)**	**HT (m)**
Chinnar	9°.52′	77°.06′	Idukki	162.9	817.4
Marayur	10°.16′	77°.09′	Idukki	555.7	1378.9
Parasala	8°.20′	77°.09′	Trivandrum	618.2	140.3
Neyyattinkara	8°.23′	77°.05′	Trivandrum	721.9	70.5
Santhanpara	9°.58′	77°.13′	Kottayam	836.9	1018.6
Trivandrum	8°.29′	76°.57′	Trivandrum	862.8	34
Kumali	9°.32′	77°.10′	Kottayam	1720.7	905.8
Attingal	8°.42′	76°.49′	Trivandrum	1027.6	0
Nedumangad	8°.36′	77°.00′	Trivandrum	1058.2	70.5
Paravur	8°.47′	76°.40′	Kollam	1155.4	0
Station	**Latitude**	**Longitude**	**District**	**NE (mm)**	**HT (m)**
Manathavadi	11°.48′	76°.01′	Wayandu	256.8	282.4
Hosdurg	12°.18′	75°.06′	Kasarkode	317.2	263.8
Kasarkode	12°.31′	74°.59′	Kasarkode	331.8	122
Payyannur	12°.06′	75°.12′	Cannoore	339.3	15.2
Canannore	11°.52′	75°.22′	Cannoore	343.4	62.1
Chittur	10°.42′	76°.44′	Palghat	345.3	601
Telicherry	11°.45′	75°.30′	Cannoore	351.8	15.2
Chinnar	9°.52′	77°.06′	Idukki	162.9	354.5
Palghat	10°.47′	76°.39′	Palghat	2019.4	355.5
Alattur	10°.38′	76°.33′	Palghat	681.2	364.0
Station	**Latitude**	**Longitude**	**District**	**Others (mm)**	**HT (m)**
Chinnar	9°.52′	77°.06′	Idukki	131.8	817.4
Chittur	10°.42′	76°.44′	Palghat	209.4	145.7
Palghat	10°.47′	76°.39′	Palghat	237.4	155.6
Nilambur	11°.17′	76°.14′	Malappuram	245.1	480.8
Marayur	10°.16′	77°.09′	Idukki	251.9	1378.9
Taliparamba	12°.03′	75°.21′	Cannoore	251.9	74.5
Kasarkode	12°.31′	74°.59′	Kasarkode	259.3	30.9
Manathavadi	11°.48′	76°.01′	Wayandu	263.4	702.3
Payyannur	12°.06′	75°.12′	Cannoore	270.4	0.9
Alathur	10°.38′	76°.33′	Palghat	278.1	113.2

Table 4.4: Top 10 minimum rainfall receiving stations in Kerala in different season

Station	Latitude	Longitude	District	Annual(mm)	HT (m)
Siruganur	11°.02′	78°.48′	Tiruchirapalli	476.3	112.3
Sulur	11°.02′	77°.08′	Coimbatore	541.4	343.8
Arasadi	8°.52′	78°.06′	Tirunelveli	585.0	34
Palladam	10°.59′	77°.18′	Coimbatore	593.8	329.5
Tuticorin	8°.48′	78°.09′	Tirunelveli	602.1	10.4
Dharmapuram	10°.44′	77°.32′	Coimbatore	605.3	268.5
Kodumudi	11°.05′	77°.52′	Coimbatore	608.4	147.6
Coimbatore	11°.00′	76°.58′	Coimbatore	614.2	359.9
Kiranur	8°.33′	78°.06′	Tirunelveli	623.5	24.8
Kangayam	11°.00′	77°.34′	Coimbatore	624.6	269.1
Station	**Latitude**	**Longitude**	**District**	**SW (mm)**	**HT (m)**
Tiruchandur	8°.30′	78°.07′	Tirunelveli	20.8	4.7
Kiranur	8°.33′	78°.06′	Tirunelveli	21.5	24.8
Kulasekharapatanam	8°.25′	78°.03′	Tirunelveli	29.8	18.6
Arasadi	8°.52′	78°.06′	Tirunelveli	29.8	34
Tuticorin	8°.48′	78°.09′	Tirunelveli	30.5	10.4
Pamban	9°.16′	79°.18′	Ramanathapuram	53.8	1.7
Sattankulam	8°.27′	77°.55′	Tirunelveli	58.7	17.1
Morekulam	9°.15′	78°.48′	Ramanathapuram	59.7	5.5
Srivaikuntam	8°.38′	77°.55′	Tirunelveli	61.3	23.5
Palyamkottai	8°.44′	77°.45′	Tirunelveli	63.6	53.3
Station	**Latitude**	**Longitude**	**District**	**NE (mm)**	**HT (m)**
Thally	12°.35′	77°.39′	Salem	246.9	872.2
Hosur	12°.43′	77°.50′	Salem	248.6	894.1
Vaniyampadi	12°.41′	78°.38′	North Arcot	252.3	516.8
Tiruppattur	12°.29′	78°.35′	North Arcot	254.8	499.6
Krishnagiri	12°.32′	78°.14′	Salem	255.4	575.3
Kodumudi	11°.05′	77°.52′	Coimbatore	258.6	147.6
Talavadi	11°.47′	77°.01′	Coimbatore	266.0	826.1
Sankari	11°.28′	77°.52′	Salem	271.3	227.1
Rasipuram	11°.27′	78°.11′	Salem	276.9	358.5
Ambur	12°.48′	78°.43′	North Arcot	278.9	444.7
Station	**Latitude**	**Longitude**	**District**	**Others (mm)**	**HT (m)**
Siruganur	11°.02′	78°.48′	Tiruchirapalli	42.0	112.3
Vayalur(Kattur)	12°.55′	79°.50′	Chinglepet	94.3	58.2
Attippat	13°.16′	80°.17′	Chinglepet	98.3	4.9
Sriperumbudur	12°.58′	79°.58′	Chinglepet	111.5	46.8
Ponneri	13°.19′	80°.12′	Chinglepet	116.8	12.9
Chingelput	12°.42′	79°.59′	Chinglepet	120.0	40.2
Wallajah(Walatpet)	12°.56′	79°.22′	North Arcot	123.2	144
Gudiyattam	12°.58′	78°.52′	North Arcot	123.7	408.6
Meenambakkom	13°.00′	80°.11′	Chinglepet	123.6	15.7
Covelong	12°.47′	80°.15′	Chinglepet	127.0	14.7

Table 4.5: Top 10 minimum rainfall receiving stations in Tamilnadu in different season

friction and a descend of air over that stations may be the reason for the reduction of rainfall activity. Stations like Marayur and Chinnar are on the leewards side of the Western Ghats and thus experience less rainfall.

In the eastern side of the Western Ghats at Tamilnadu, the maximum annual rainfall is getting at Annamalai (4242 mm) of Coimbatore district. The districts of Coimbatore and Nilgiri is getting the benefit of south-west monsoon maximum due to the influence of Palghat Gap and also the reduced steepness of the terrain of Nilgiri hills at the eastern side respectively. The fanning out of the monsoon wind through the mouth of the Palghat Gap is enhancing the rainfall of the northern stations of Coimbatore district. The down wind stations at the mouth of eastern side of the Gap is suffering a reduction of rainfall due to the increased subsidence over that region. Some stations in Kanyakumari district also is getting maximum rainfall due to the influence of north-east monsoon. Even though the districts of Tanjaore and South Arcot are more beneficiaries for the north-east monsoon rainfall, the maximum rainfall is about 900 mm compared with the rainfall of above 2000 mm at the northern districts of Nilgiri and Coimbatore during south-west monsoon season. It is noteworthy that most of the stations getting maximum rainfall during the north-east monsoon period is located at the coastal regions. It shows that synoptic systems forming over the Bay of Bengal during the Autumn season is playing a major role in the coastal rainfall of the central part of Tamilnadu coast. Convective rainfall is also higher at Kanyakumari district.

The minimum rainfall is reported at Siruganur (476.3 mm) in Tiruchirappilly district. Tirunelvelli and Coimbatore districts dominates with stations having less rainfall. The off season rainfall is minimum at almost all stations in Chingalpet district. In general the central and western districts of Tamilnadu state gets deficient rainfall compared to the south, north and eastern coast of the state.

It is seen the elevation of the hilly stations in Kerala and Tamilnadu has only a lesser impact over the rainfall activity over those regions. In the present study we tried to correlate the coastal rainfall with the angle of incidence of wind at the terrain of 800 m and found no significant correlation. Thus the angle of incidence of the winds over the high terrains do not make much difference in the rainfall of the windward side of the stations. It is evident that the proximity of the Western Ghats to the coast, slope of the terrain, windward and leewardness of the place and geological discontinuity of the Western Ghats makes the over all changes in the rainfall pattern of a region in the study area.

4.3.2 Analysis with model predicted rainfall

The MM5 model has been used to simulate the rainfall pattern of the study area. Betts-Miller-Eta scheme combination has been used for the model run which is taken after a number of experimental runs conducted with different combinations of schemes. For the rainfall study we have taken the year 1984 and the model run has been given for 48 hours starting from the first day of every month. The data set used for the model is from the FNL data of 1984. The analysis is done with the accumulated rainfall of last hour (2330 hrs) of the integration.

Dominance of convective and non-convective rainfall in total rainfall of the region

In the MM5 modelling system we are calculating the accumulated rainfall for both convective and non-convective cases. The analysis has been carried out with the single day accumulated rainfall for a station in each season. The convective and the non-convective rainfall of the nine stations of the study region for various months representing different season are illustrated in the figs.(4.14 & 4.15). In all season Palghat Gap show a deficit

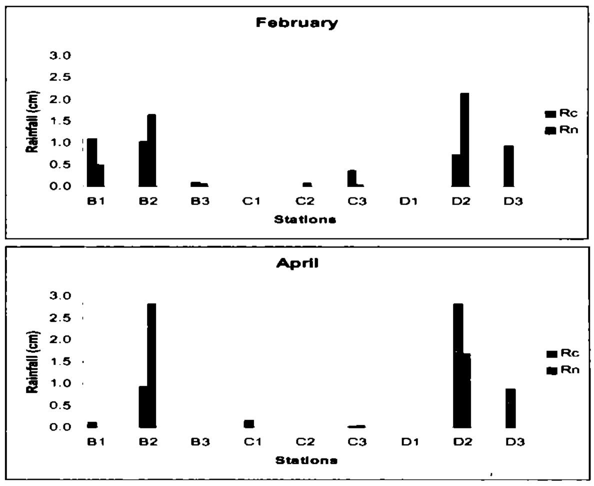


Figure 4.14: The convective and non-convective accumulated rainfall calculated by the model for a single day in the month of February and April for nine stations in the study area .

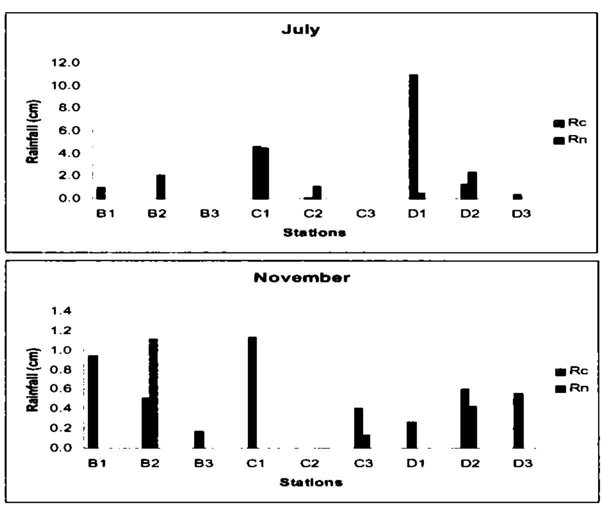


Figure 4.15: The convective and non-convective accumulated rainfall calculated by the model for a single day in the month of July and November for nine stations in the study area.

rainfall and the east and west side of the Gap also will be in the rainfall deficit regime in February and April representing Winter and Spring respectively. The non-convective rainfall like orographic lifting produces more rainfall over the summit stations than the convective rainfall which is evident from the pattern of the stations like B2 and D2 in February and April. Convective type of rainfall is more dominant in the western side of the Western Ghats (stations B1,C1 and D1) throughout the year and it is clear even in the south-west and north-east monsoon months. During north-east monsoon period the plains of the Tamilnadu (stations B3,C3 and D3) is also getting more convective rainfall.

The percentage of convective and non-convective rainfall input to the total rainfall of the study area in different months are given in fig.(4.16). During the two main monsoon

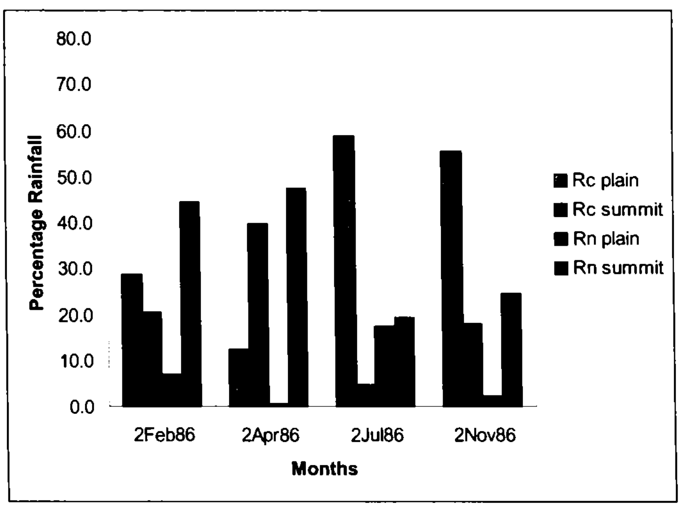


Figure 4.16: The convective and non-convective accumulated rainfall percentage for plain and summit stations in the study area calculated by the model for a single day in different months in 1984.

season, above 50% of the rainfall received in the study area are mainly from convective rains from the plain stations. The orographic rain from the summit stations follows with the non-convetive rain from the plain stations during south-west monsoon period. Non-convective rainfall over plain stations is negligible (2%) during the north-east monsoon period. Thus the total rainfall of the study area in south-west monsoon rainfall is decided by the plain stations whereas the north-east monsoon rainfall is decided by the combination of plain as well as summit stations. Orographic lifting in the plain and summit stations in the south-west monsoon period shows almost equal contribution in the overall rainfall pattern.

During the Spring season, summit stations contribute 90% of the total rainfall getting in the study area, and the non-convetive rainfall in plains is quite less. Orographic as well as the convetive activities contributes to the total rainfall during Winter. Thus modelled results shows that the influence of the orographic rainfall in the summit region is a deciding factor for the total rainfall pattern of the study area during the off-monsoon season and its influence is less in the monsoon months.

Influence terrain characteristics on the rainfall over the region

The slope, orientation and the surface canopy of the terrain influences the precipitation characteristics of a place especially if it is in the mountain region. If the station is in the upslope of a trough of an elevated mountain terrain, then there will be a decrease of rainfall at the station. Example is the Nilambur station (11.28°N, 76.23°E) at the Nilgiri cross section (see fig.4.9). It is situated at the upslope of the gully region of the terrain. But the station Vyttiri which is near to it but situated at the downslope of the inner valley region is receiving maximum rainfall. Similarly the frictional characteristics of the surface layer will be a deciding factor for the smooth flow of the wind and it affects the precipitation characteristics of the place.

The wind direction in the PBL changes with height in response to the Coriolis force due to the earth's rotation. In the surface layer the wind flow will be modified by the surface drag considerably. Surface roughness, horizontal pressure gradient and the PBL height is fully accounted for in the surface drag parameter (τ). From that we can calculate the frictional velocity (U*) which is an indication of the surface frictional characteristics.

$$U^* = (\frac{\tau}{\rho})^{\frac{1}{2}} \tag{4.1}$$

where

U^*=Frictional velocity

τ = Surface drag parameter

ρ = Density

It is found that there is a negative correlation between the frictional velocity and the rainfall calculated by the model (fig.4.17). There exists a high negative correlation (-0.75) in Winter months and south-west monsoon period over Kerala. In September and October the correlation changes slightly. During the Summer season over Tamilnadu the relation shows a small positive correlation while during winter a maximum of 0.5 negative correlation can be seen. Thus it is clear from this analysis that surface roughness controls very much the precipitation pattern over the Western Ghat region.

In the Kerala region maximum rainfall is getting at Neriamangalam (10.05°N, 76.78°E) and Vyttiri (11.55°N, 76.03°E) stations which are two different stations in the valley of Western Ghats in the windward side. Analysis along this cross sections (fig.4.18) shows that the frictional velocity is minimum (0.2 $ms^{-}1$) at Neriamangalam during the south-west monsoon and north-east monsoon months. The frictional velocity is maximum (1.6 $ms^{-}1$) at the summit region, where the rainfall is very less. The decrease of frictional velocity is also seen at Vyttiri in both monsoon months. This indicates that the increased rainfall of these stations can be attributed to the reduced surface drag of the terrain and

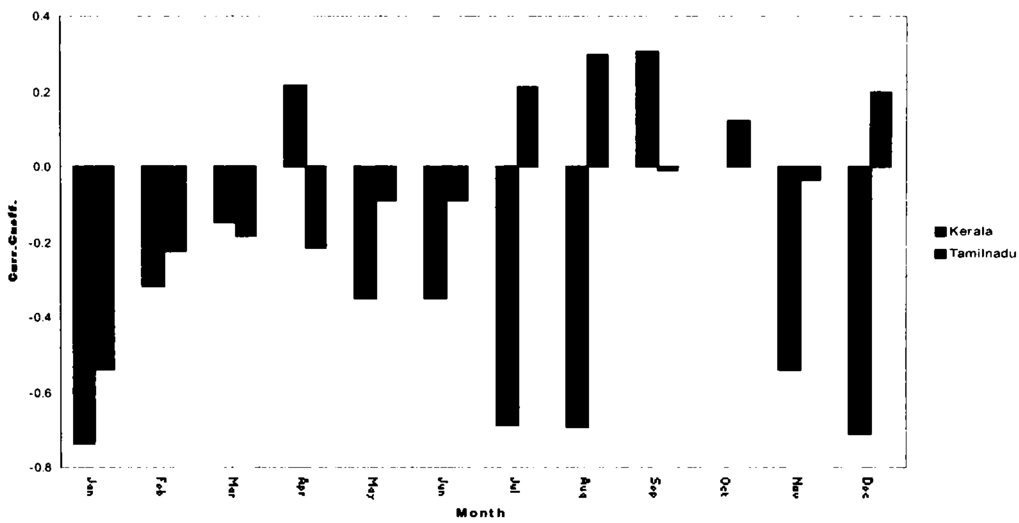


Figure 4.17: The correlation of frictional velocity and the rainfall along 10.05°latitude cross section in the study area calculated by the model for a single day in different months in the year 1984.

also the geographical position of the wind ward side of the Ghat.

The maximum annual rainfall regions like Gudallore, Glenmorgan of Nilgiri district of Tamilnadu is getting the advantages of the windward slope of the Western Ghats. Also we can see a reduction of frictional velocity at both coastal lines at 76.2°E and 79.2°E in fig.(4.17) and 75.6°E and 79.8°E in fig.(4.18). In these regions also the rainfall activity is maximum as we have seen from the observed rainfall analysis of the previous sections. Thus reduction of the frictional velocity also may have its own influence over the enhancement of the coastal rainfall activity over the region.

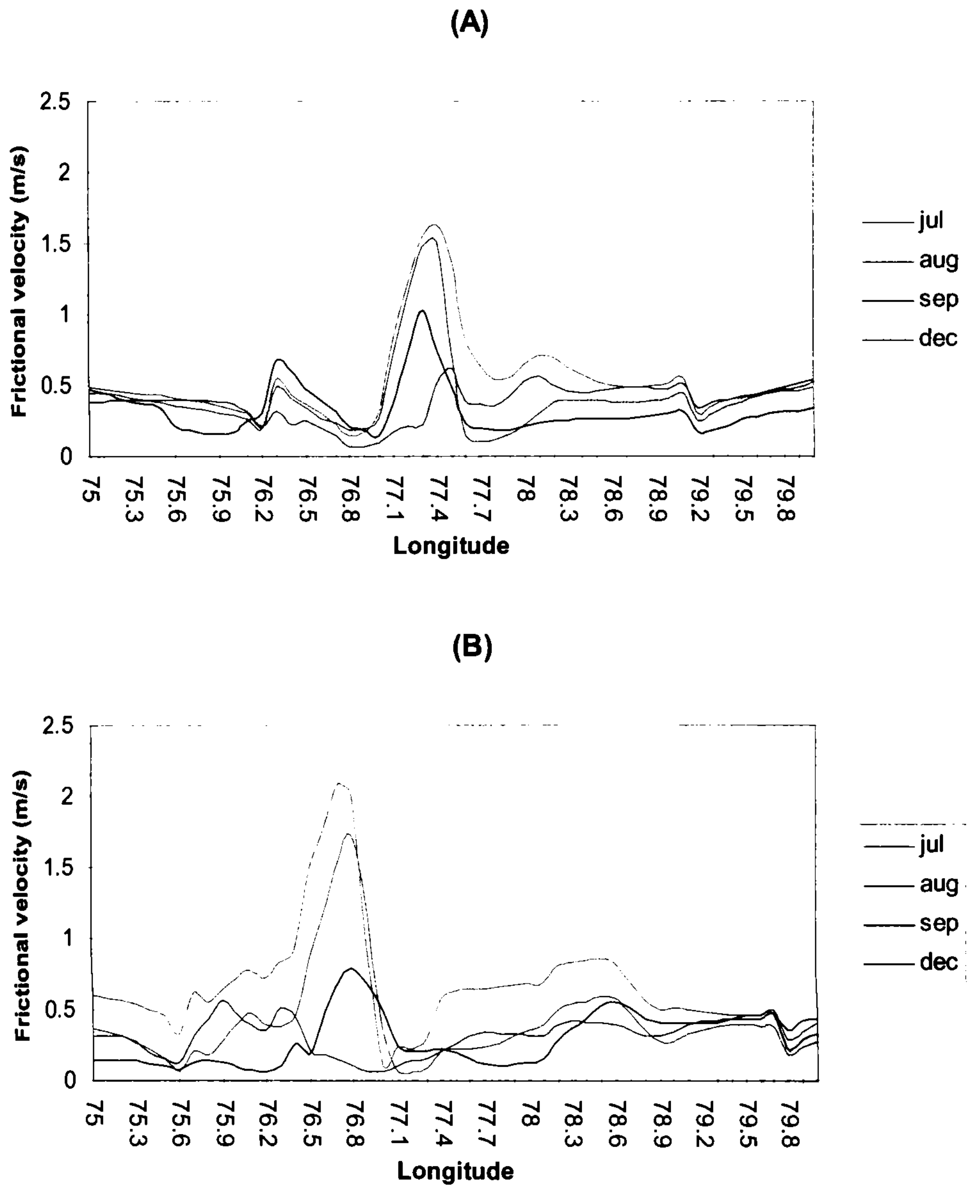


Figure 4.18: Variation of frictional velocity (A) along 10.05°N cross section (B) along 11.55°N cross section in the study area calculated by the model for a single day in different *months in the year 1984.*

Variability of precipitation rate with terrain height in Western Ghats

The mean rate of precipitation and the terrain height is found to be well correlated in the Western Ghats region. Analysis has been carried out along the Anamudi cross section for a day in the month of July is given in the fig.(4.19). A high correlation of 0.8 is found

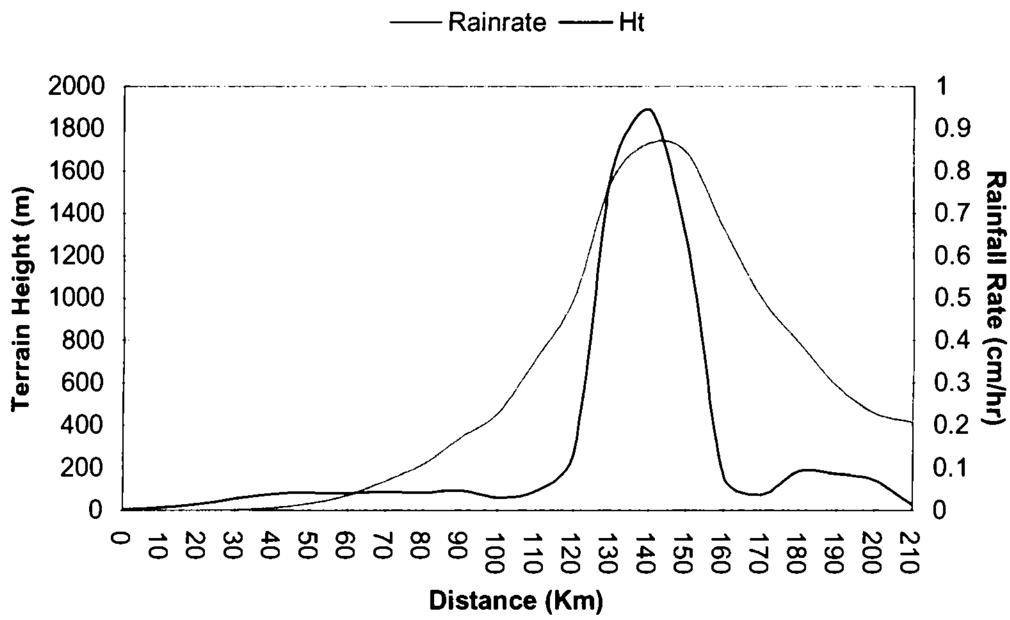


Figure 4.19: The mean precipitation rate of the study region with altitude along the latitude belt of Anamudi range for a day in the month of June (x=0 is at the west coast).

between the precipitation rate and the terrain height during the monsoon months. As the terrain height increases from surface to 1800 meter the precipitation rate also increases from 0.1 to 0.8 cm hr^{-1}. It has to keep in mind that as the total rainfall amount receiving at the summit stations is also depending upon some other factors like the geographical position of the station, slope of the terrain, surface drag, moisture availability in the air and the orographic cloud amount.

Relation between cloud amount and the precipitation

The model calculated the cloud amount separately for the low, medium and the high clouds and the value ranges from 0 to 1. These values of cloud amount has been correlated with the total precipitation calculated at each station and given in fig.(4.20). The correlation between the cloud amount and the rainfall for each month and a season as a whole has been analyzed. Medium clouds are having maximum correlation of 0.92 during the south-west monsoon period follows the high clouds with 0.7 and low clouds with 0.38 in the study area. During the north-east monsoon, the medium clouds show perfect correlation over the region. The influence of high and low clouds are meager during these period. During the off monsoon months influence of high clouds are much more than compared to the medium and low clouds. The huge Cumulonimbus (Cb) clouds over the region can be attributed to this variability of high clouds in the model. Thus the influence of the medium clouds like Nimbostartus (Ns) is very much affecting the rainfall pattern of the region during the monsoon months. The effect of large Cb clouds in the Spring season is clearly distinct in the present study.

Observational problems for point rainfall measurements in high terrains

It has been assumed upto now that precipitation amounts can be reliably measured in the mountainous areas. In the real case it is not true. The errors involved in precipitation measurements are illustrated in the flow chart of fig.(4.21). The rain catch in a standard gauge mounted on the ground with a rim at 25 cm height is systematically 6-8 percent less than that caught by a ground level (sunken) gauge. In mountain areas, gauge catch is strongly affected by local and micro scale wind effects. The effect of slope aspect on precipitation has been the subject of various investigations with rather differing conclusions.

Rain is collected in the rain gauge and the catch is taken for the estimation of rain-

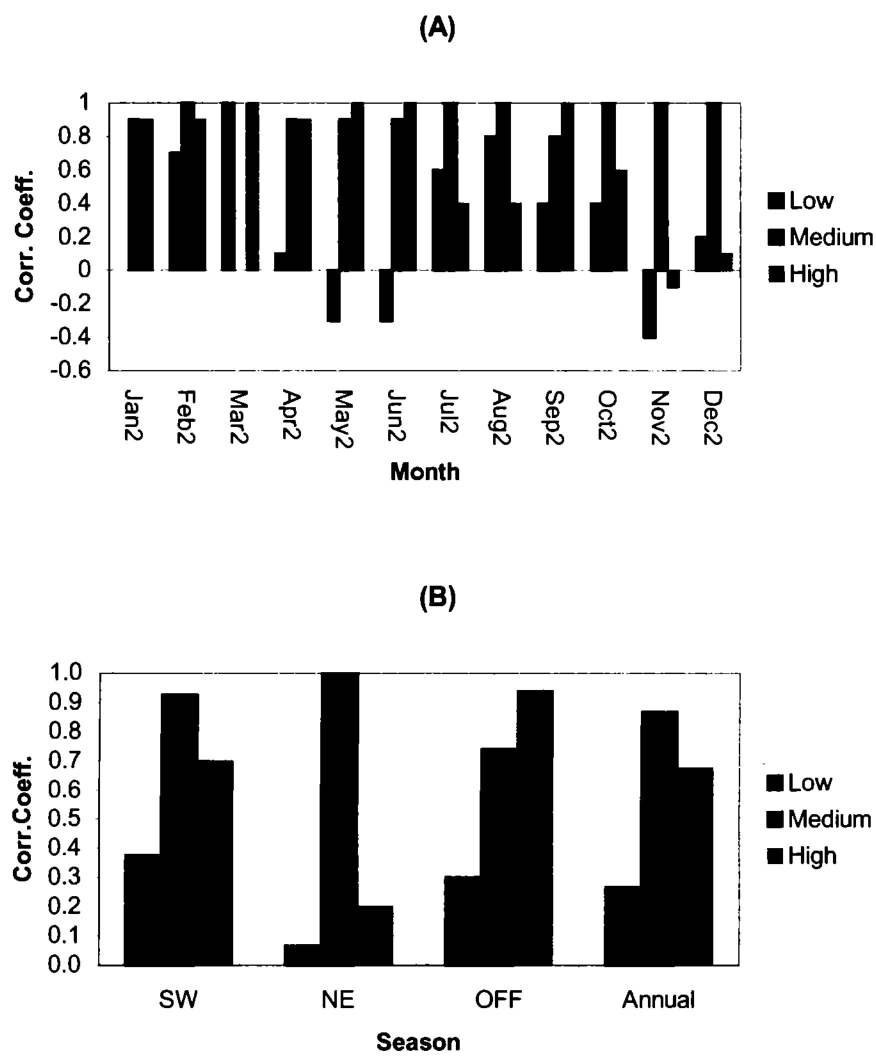


Figure 4.20: Correlation of (A) rainfall with cloud amount calculated by the model for a day of every month in 1984 (B) representative seasonal rainfall with cloud amount calculated by the model for a season in 1984

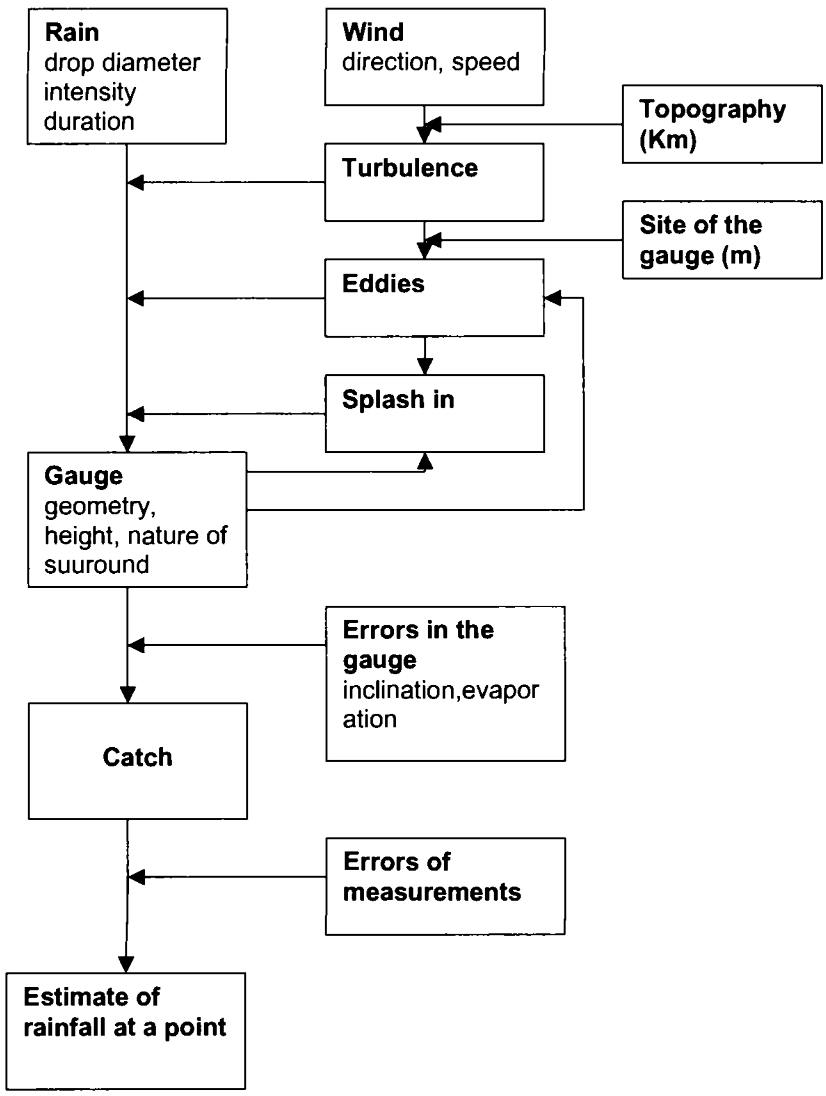


Figure 4.21: Schematic summary of processes and problems involved in the determination of rain gauge catch.

fall at a point. Wind and the terrain features are the main obstacles for measuring the rainfall correctly with a rain gauge. Wind creates turbulence and the result is the formation of eddies, which in-turn causes splash in the fall of rainfall to the gauge. Nature of the surroundings of the gauge, like the thick forests and green canopy, itself will help to create the eddies in the atmosphere and it affects the rain collection again. Topography of the area, for example valleys or gullies of the high ranges, will create the turbulence in the wind. Also the site of the gauge plays a major role in the formation of eddies by the way convection triggers over the region.

These above factors will create errors in the catch and again the errors generated manually and mechanically during measurements also will be affecting the estimation of the rainfall at a point. In view of the many problems associated with the point measurements, experiments have been conducted to test the use of radar determinations of precipitation volume over extensive mountain watersheds found, in the middle latitudes, as good as could be obtained with a gauge network density of 1 per 25 km^2, and is far better than with regular network at 1 per 500 km^2.

4.4 Evaporation and condensation of the study region

The transfer of water vapour from a water surface or from a bare soil (evaporation) depends on both the properties of the ambient air and the energy supply to the surface. A number of meteorological factors are involved in this processes like surface-air difference in vapour pressure, temperatures of air and of the evaporating surfaces, the rate of air movement on the evaporating surfaces and the energy supply via absorbed radiation, warm air advection and heat storage beneath the air-surface interface. Lower atmospheric pressure, which leads to a higher evaporation rate is also a factor but the pressure reduction due to high altitude is more than compensated by the decrease in air temperature.

Evaporation is calculated for the study region from the Swedrup's equation.

$$E(cms^{-1}) = (\frac{K^2\rho(q2 - q1)(u2 - u1)}{ln(z2/z1)^2}) \tag{4.2}$$

where

K=Von karman's constants (≈ 0.37)

ρ= Air density (gm cm^{-3})

q= Specific humidity

u= Wind speed (cm s^{-1})

z= height

Monthly evaporation-condensation chart shows that the condensation dominates evaporation in the south-west monsoon period over the study region (fig.4.22). Then the condensation will be at the rate of 0.02 cm s^{-1} on an average in both sides of the Ghats. At the ground, the rate of condensation in the lee side of the mountain is slightly higher in the south-west monsoon months than the windward side. But in Kerala the condensation starts during the Spring season itself. Evaporation rate is more in Kerala during the north-east monsoon months (0.07cm s^{-1}) and during the Winter, eastern side of the Western Ghats again picks up the evaporation rate ($\approx$ 0.03 cm s^{-1}). Thus eventhough the total evaporation and condensation is more in Kerala, the number of months showing increased evaporation is more (7 months) in Tamilnadu than Kerala (5 months). This is clearly an indication of the high temporal variability of the latent heat flux input to the atmosphere from the ground in the eastern side of the mountain than the western side.

The percentage weighted average of the total evaporation and condensation is calcu-

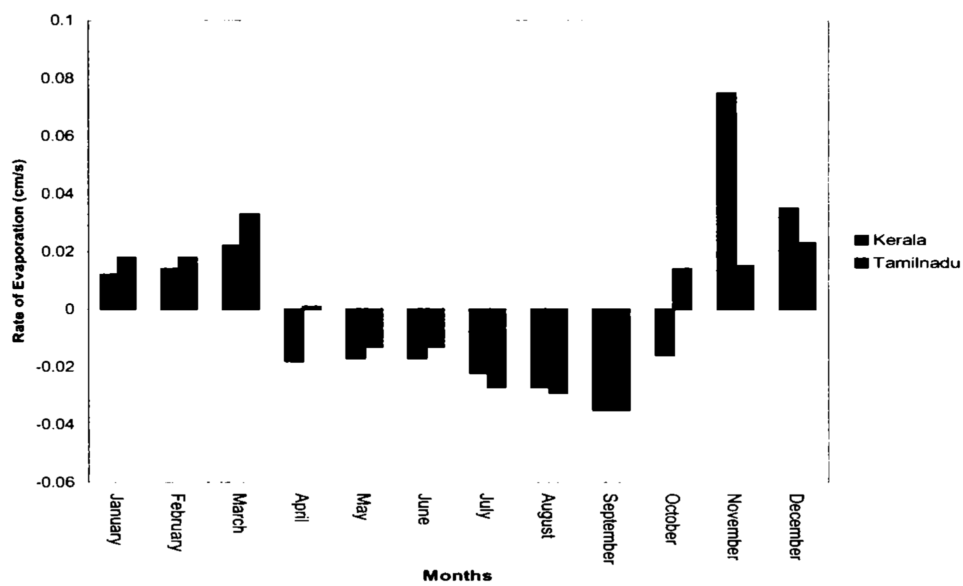


Figure 4.22: The mean rate of evaporation and condensation in different months of the year in the study area.

lated for the eastern and the western side of the mountain separately and its contribution to the total system is shown in fig.(4.23). From the figure we can asses the contribution of each component of evaporation and condensation of both sides of the Western Ghats to the total study area. The evaporation of the Kerala region shows 44% whereas Tamilnadu's contribution is only 28%. In the case of condensation, the average rate is 17% for Kerala and 11% for Tamilnadu. Thus Kerala leads the contribution of the input in both evapoartion and condensation to the total study area than that of Tamilnadu.

4.5 Effect of heat fluxes on temperature

The type of air mass present in the study area is uniform in nature as we have seen from our earlier analysis. It is found that some stations of the study area (eg. Punalur and Palghat) shows abnormal temperature pattern during the Spring and Summer season. These stations

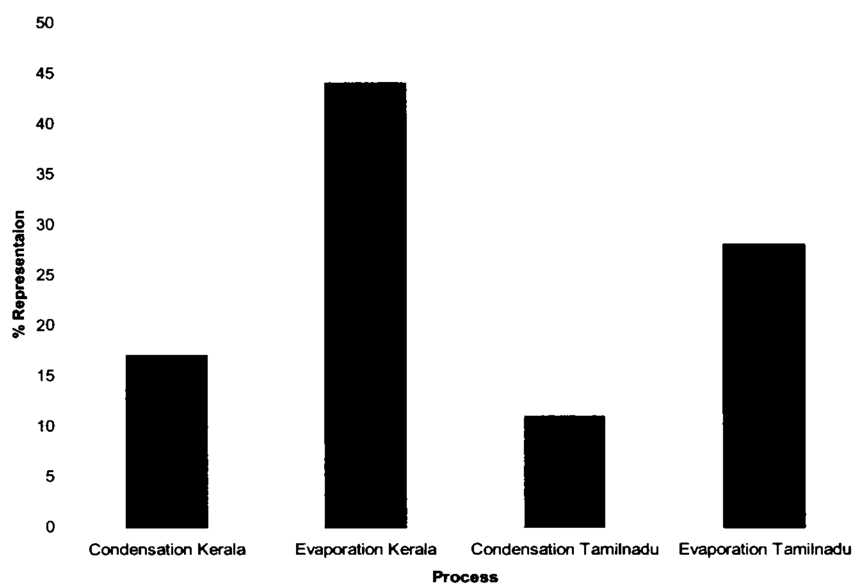


Figure 4.23: The percentage weighted mean of the rate of evaporation and condensation in Kerala and Tamilnadu for the year

are situated near the mouth of the Gap which cuts the Western Ghats mountain ranges. Temperature of the atmosphere is primarily controlled by the type of air mass and the heat fluxes that attains from the clouds or from the ground itself. Mean heat balance of the atmosphere shows that about 18.5% of the latent heat flux and 11% of sensible heat flux is transferred from the ground to the lower layers of the atmosphere. Primarily the moisture is pumped to the atmosphere from the ground due to evaporation or evapotranspiration. Similarly the sensible heat highly depends on the type of soil present and the elevation characteristics of the terrain over the region.

4.5.1 Seasonal variation of Sensible heat flux over the region

The convergence or divergence of sensible heat flux leads to warming or cooling of air, similar to that due to net radiative flux divergence or convergence. Thus a gradient of 1 W m^{-3} in sensible heat flux will produce a change in air temperature at the rate of about 3°C h^{-1} (*Arya*). The analysis of the latent and sensible heat fluxes calculated by the model along different cross sections of the latitude belt of Aryankavu Gap, Palghat Gap and Anamalai hills is illustrated in the fig.(4.24). As a representation of the season, the analysis is done for three months, ie. April for Spring, June for Summer and December for Winter season. In all these season except during some peak south-west monsoon months Tamilnadu is getting maximum sensible heat fluxes from the ground to the lower layers of the atmosphere than that of Kerala. This may be the reason for the excess air temperature usually seen over Tamilnadu than Kerala. Also from the earlier analysis of the present study shows that the air mass present in the region is homogeneous and the net radiative fluxes are same for both eastern as well as the western side of the mountain. Hence the deciding parameter for air temperature at the surface is primarily the heat fluxes from the ground.

In April the mean maximum sensible heat flux at Kerala is 40 Wm^{-2} while it is 60 Wm^{-2} over Tamilnadu. At 76.7°E near Aryankavu, the heat flux goes upto 110 Wm^{-2} and at the same time near Palghat (76.9°E) it goes upto 100 Wm^{-2}. In June it rises further to 118 Wm^{-2} in Aryankavu and a maximum of 140 Wm^{-2} in Palghat. Correspondingly there is an increase in sensible heat flux at the western side of the mountain (70 Wm^{-2}) and attains a steady value (60 Wm^{-2}) in the eastern side of the Gap. During Winter the heat flux go down to 20 Wm^{-2} in the western side of the mountain and 40 Wm^{-2} in the eastern side. One noteworthy point is that in Winter there is a remarkable reduction of the fluxes at the mountain region (100 Wm^{-2}) and also at the Gap (80 Wm^{-2}). The Gap region attains a value of 60 and 90 Wm^{-2} near Aryankavu and Palghat Gap respectively during this season. This clearly gives an indication that the effect of surrounding valleys over the Gap region is playing major role in controlling the sensible heat fluxes. Thus this type of valley effect cannot be discarded in the variation of temperature at a station near to the mouth of the Gap in the Western Ghats. Hence the excess input of sensible heat to the

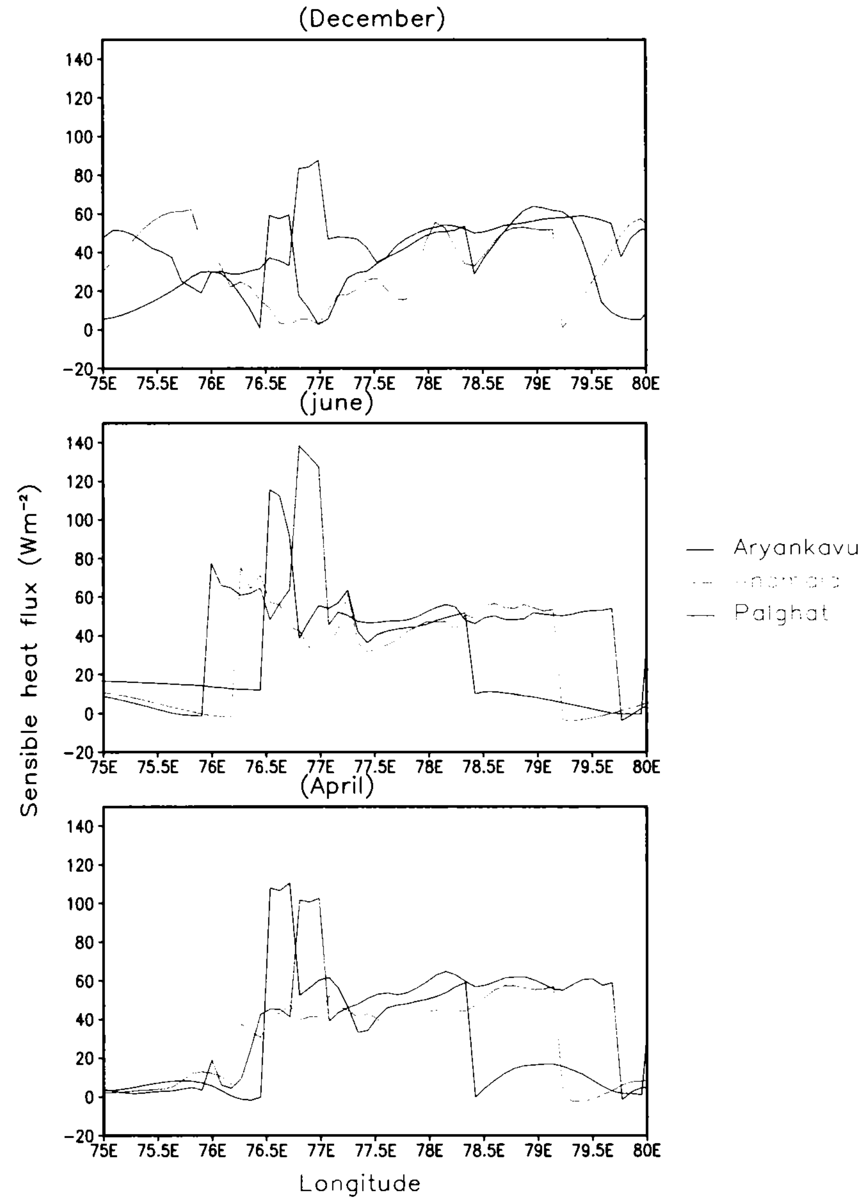


Figure 4.24: Sensible heat flux along the cross sections of 8.98°N (Aryankavu Gap), 10.2°N (Anamalai) & 10.7°N (Palghat Gap) during different months in an year

atmosphere is causing the unusual increase of air temperature over the places like Punalur and Palghat which is situated near the mouth of the Gap regions.

4.5.2 Variability of latent heat flux

The heat fluxes pumped into the atmosphere by evaporation from open water bodies or transpiration from the green canopy can be considered as the latent heat fluxes. Thus the latent heat fluxes are mainly controlled by the local atmospheric conditions and the surface characteristics. The variation of the latent heat flux over the region are given in fig.(4.25). In the study area the latent heat flux generally varies from 0 to 400 Wm^{-2}. The maximum value of the latent heat flux is in Winter season over plain stations in the study region. In the mountainous terrain the flux is found to be decreasing than the plain stations in both sides of the Western Ghat.

The mean latent heat flux in Tamilnadu is 200 Wm^{-2} whereas in Kerala it is only 150 Wm^{-2}. Thus Tamilnadu attains 50 Wm^{-2} higher latent heat flux than Kerala in almost all the months except Winter season where it is same as western side of the mountain. There is a dip of 100 Wm^{-2} in latent heat flux is found at the mouth of both the Gap regions in all season. As we have seen from our earlier analysis that the number of months contributing evaporation is more in Tamilnadu than Kerala region. This causes more variability in latent heat flux over Tamilnadu than Kerala region.

4.5.3 Bowen's Ratio and Moisture stress of the region

When the water level reduces to less than the normal levels moisture stress will occur over the region. The moisture stress can be quantify comfortably in Bowen's ratio and the value varies from negative to positive in a region. Bowen's ratio (B) can be calculated by dividing the sensible heat flux with latent heat flux. The value of 'B' varies according to the surface

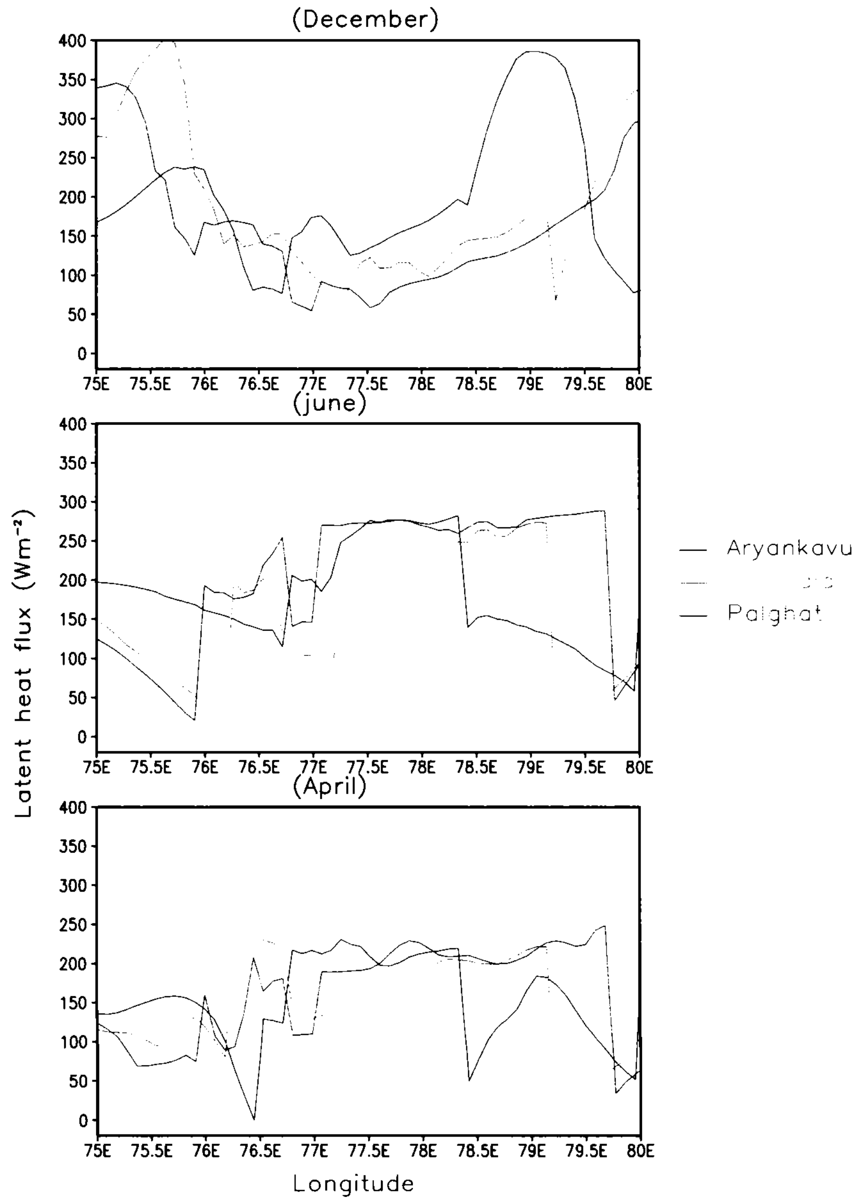


Figure 4.25: Latent heat flux along the cross sections of 8.98°N (Aryankavu Gap), 10.2°N (Anamalai) & 10.7°N (Palghat Gap) during different months in an year

characteristics. A vegetated surface will have a value of 0.77 and for water surface it will be 0.1. if the value is between 2 to 10 then the area will be a dry or desert type. In our study area the value of 'B' varies from 0 to 1.8 (fig.4.26). In Kerala the value is near to zero and

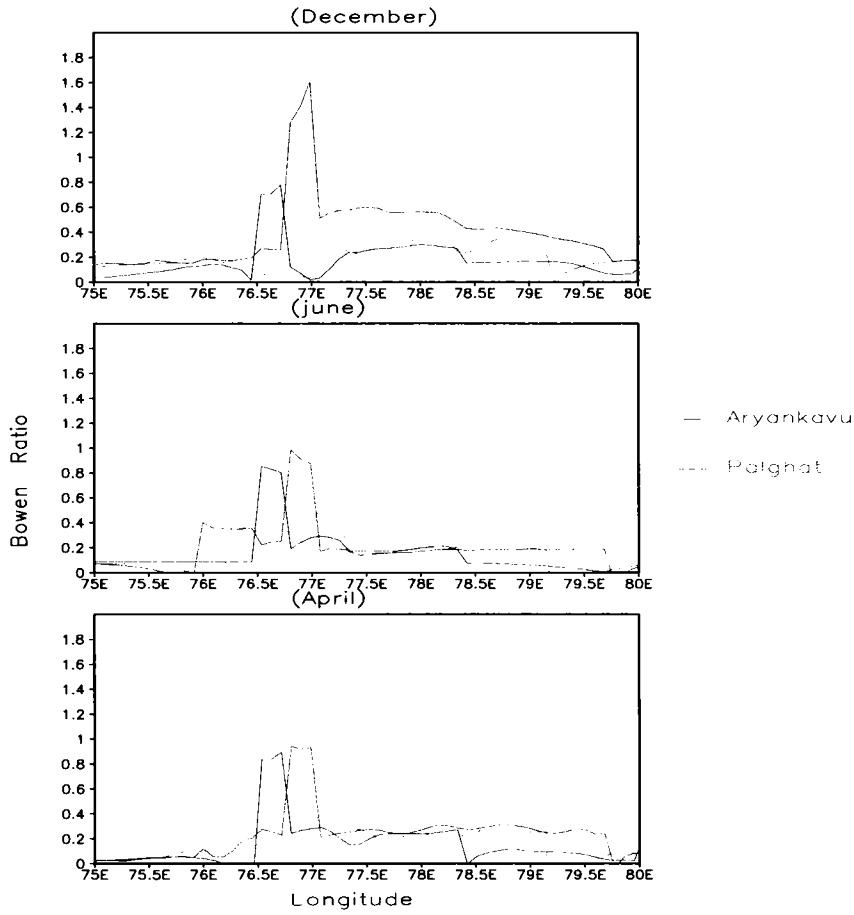


Figure 4.26: Bowen's ratio along the cross sections of 8.98°N (Aryankavu Gap), 10.2°N (Anamalai) & 10.7°N (Palghat Gap) during different months in an year

it increase to 0.2 in Winter season. But in Tamilnadu it is minimum at 0.2 in Spring and reaches 0.6 in Winter. Thus Tamilnadu is having higher moisture stress in all season and in Winter the stress becomes maximum due to the presence of dry air and frequent inversions in the study area. Near to Palghat and Aryankavu Gaps the ratio goes upto 1.8 in Winter which is very near to arid conditions. In Winter there is a marked difference of variation in Palghat Gap from Aryankavu Gap. Thus maximum moisture stress is happening at the Gap region and causing the increased temperature pattern over the region than the rest of the study area.

4.6 Conclusions

The variation in basic meteorological parameters affects the elements such as energy budget, precipitation, evaporation and the temperature, which in turn decide the climatic characteristics of a region. There is a surplus energy available in the region in Winter, Spring and Autumn season except over the summit regions during the Spring season, when the net radiative flux will be going to negative value of 700 Wm^{-2}. A reduction in the latent and sensible heat flux is also noted during this season at the summit region. Thus the summit stations will be cooler when compared to the valley and plain stations in Spring.

The variation of precipitation and the effect of the topography on the rainfall characteristics of a place is analyzed with the actual rainfall received from the IMD climatological mean data set. During the south-west monsoon period, North Kerala receives more rainfall, whereas in the other months, South Kerala gets more rainfall. South-west monsoon contributes 68% of rainfall to Kerala's annual rainfall while Tamilnadu gets only 30% of its annual rainfall during this months. The long-term annual rainfall trend shows that there is a decrease of rainfall in Kerala as well as in Tamilnadu. Kerala looses 2.4 mm per year while it is 1.4 mm per year for Tamilnadu.

The altitudinal characteristics such as the slope of the terrain, orientation of the terrain to the wind, gullies and valleys control the rainfall pattern of a place. The slope of the terrain is maximum at the western side of the Ghats at Anamalai hills (75.9 °). The eastern side is only 56.1 °. At Nilgiri hill the maximum slope is at the eastern side of the mountain (73.7 °) whereas western side is around 68.4 °. The slope is 14.5 °at the Neraimangalam stretch which is distinct as far as the rainfall pattern is considered.

By classifying the terrain in four different classes like low (0-200 m), medium (200-600 m), high (600-1000 m) and the summit (above 1000 m) it is easy for the analysis to find whether there is any link between the terrain height and the rainfall received at a place. *It is found that in Kerala, the maximum amount of rainfall is getting at the medium* elevation class and in Tamilnadu side it is in the high terrains. Eventhough the correlation is maximum at the high elevation class in Kerala the maximum amount of rainfall is getting at the medium elevated stations.

Generally, rainfall increases from south to north during the south-west monsoon periods. It is found to be maximum at about 14°N and then again decreases. There is an increase of 270 mm deg^{-1} and a decrease of 5 mm deg^{-1} in the rainfall during south-west and north-east monsoon periods respectively over Kerala from south to north. In Tamilnadu it is 12 mm deg^{-1} and 1 mm deg^{-1} increase in both south-west and north-east monsoon respectively. Coastal stations of both sides gets heavy rainfall during different months and only in Kerala significant correlation of -0.8 can be seen between the distance of terrain above 1000 m and the coastal rainfall. Thus one reason for the rainfall increase towards the northern side of Kerala is the proximity of the high terrain towards the coast.

Spatial variation of maximum and minimum rainfall over the study region shows some interesting results. As pointed out in some early stuidies in the western side of the Ghats, the rainfall peak is getting not exactly at the summit region but some distance away from the peak. As the areal distance makes larger difference in the terrain heights, the maximum rainfall will be at the downhills of the mountain mostly. In Kerala the maximum rainfall is geting at Neraimangalam in Idukki district (5883.5 mm) and minimum is at Chinnar in Idukki district which is at the lee side of the mountain. In Tamilnadu the maximum is getting at Annamalai (4242 mm) in Coimbatore district and minimum at the Siruganur (476.3 mm) in Tiruchirappilly district.

The analysis of the modelled rainfall shows the importance of the convective and non-convective rainfall over the study region. Convective rainfall is more dominant in Kerala as well as in Tamilnadu in all season and non-convective rainfall is giving more rainfall in the summit region. Thus the total rainfall in the study area is decided by the convective rainfall from the plain stations whereas the north-east monsoon rainfall is decided by the the combination of plain as well as the summit stations. During the Spring season the 90% of the rainfall is getting from the summit stations, shows the orographic lifting and the convection from the high lands.

Terrain characteristics is playing a major role in the rainfall pattern over a region. This can be incorporated in the surface roghness parameter and the firctional velocity which gives an idea of the behaviour of the terrain towards the wind. It is found that there is a negative correlation of -0.75 exisist between the frictional velocity and the rainfall received over Kerala region. Frictional velocity is found to be very low over the Neraimangalam and Vyttiri stations as well as the coastal areas. The increase of rainfall pattern in these places is due to the fovourable condition of low surfce drag due to the terrain slope and the surface canopy pattern.

The precipitation rate is found to have a high correlation of 0.8 with the altitude in the study region. Thus the rate of rainfall production is more in the upper terrain. Other important factors like geographical postion of the station, slope of the terrain etc also will be controlling the precipitation over the region. Also the correlation between the rainfall and the medium clouds are found to be 0.92 during the south-west monsoon months and nearly perfect correlation during the north-east monsoon months. Influence of medium and high clouds are more than the low clouds in the entire area in all season.

During the south-west monsoon period, the evaporation rate is very low in the study area, whereas the rate of condensation is of the order of 0.02 $cms^{-}1$. During Autumn season the evapoartion is more in both Kerala and Tamilnadu. Larger variability of latent heat flux is seen in the eastern side of the Ghat than the western side. Both in evapoartion and condensation, the Kerala side dominates in its contibution to the total study area. The temperature of region is mainly controlled by the sensible heat flux and the latent heat flux transfer to the lower layers of the atmopshere. An increase of sensible heat flux in the mouth of the Gap at the western side of Aryankavu and the Palghat leads to the increae of temeprature at Punalur, Kottarakkara region near Aryankavu pass and Chittur, Palghat near Palghat Gap. The exchange of latent heat and sensible heat fluxes are more in Tamilnadu than Kerala and that may be the reason for the general increase of temperature pattern of the eastern side of the Ghat in all season than the westeren side.

The analysis of the moisture stress over the region in different season reveals that the moisture stress is maximum in Winter than any other season and Tamilnadu is always ahead of Kerala in the higher value. The Gap regions exert tremendous moisture stress to the exit regions especially to the western side of the Gap in Kerala and an arid type of condition is existing near to the Gap regions around the Western Ghats.

CHAPTER 5

Analysis With Modified Orography

5.1 Introduction

The impact of the Western Ghats orography over the study region has been analyzed in detail in the earlier chapters. But the control of the mountain over the study region can be fully appreciated in the absence of the orography. Similarly the filled Palghat Gap gives the importance of the Gap in changing the surface meteorological pattern over those local areas. Thus these hypothetical modelling study of the terrain gives a great insight into the mountain meteorology of the region. The removed orography has been integrated with 90-30-10 km domain and the filled orographic run is done with 45-15-5 km domain in MM5. The averaging for 17 years of the out put is done and the data is used for the present analysis in this chapter.

5.2 Modification of Meteorological Elements without Orography

Western Ghats control the spatial distribution of the surface meteorological parameters in the study area which is evident from our analysis in the previous chapters. The distribution of these parameters in the east-west direction is controlled very much by the north-south oriented mountain in the study area. The modelling study by this modified orographic run enable us to distinguish the difference in the pattern of these parameters in the presence and absence of the Western Ghats and from which we can asses the impact of the mountain to a great extent.

5.2.1 Mean Sea Level Pressure

Spatial variation

It is found that there is very little spatial variation of mean sea level pressure over the study region in all season. In general the orientation of the isobars are parallel to the orography in the meridional direction. The variation of the mean sea level pressure with and without orography has analyzed in the following section. The pressure in the north-south direction varies without orography in Winter (fig.5.1). The value varies from 1013.7 hPa to 1015.5 hPa in the north-south direction instead of 1014 to 1019 from plain to summit region in the normal case. Isobars are parallel with a clear trough over Tamilnadu. The overall pressure reduces by about 1.5 hPa throughout the study region. As we reach the southern end of the study area the isobars become more parallel to latitude. Obviously the variation of pressure distribution is minimum in Kerala and maximum in Tamilnadu without orography.

During Spring Tamilnadu shows more isobars in east-west direction than Kerala even

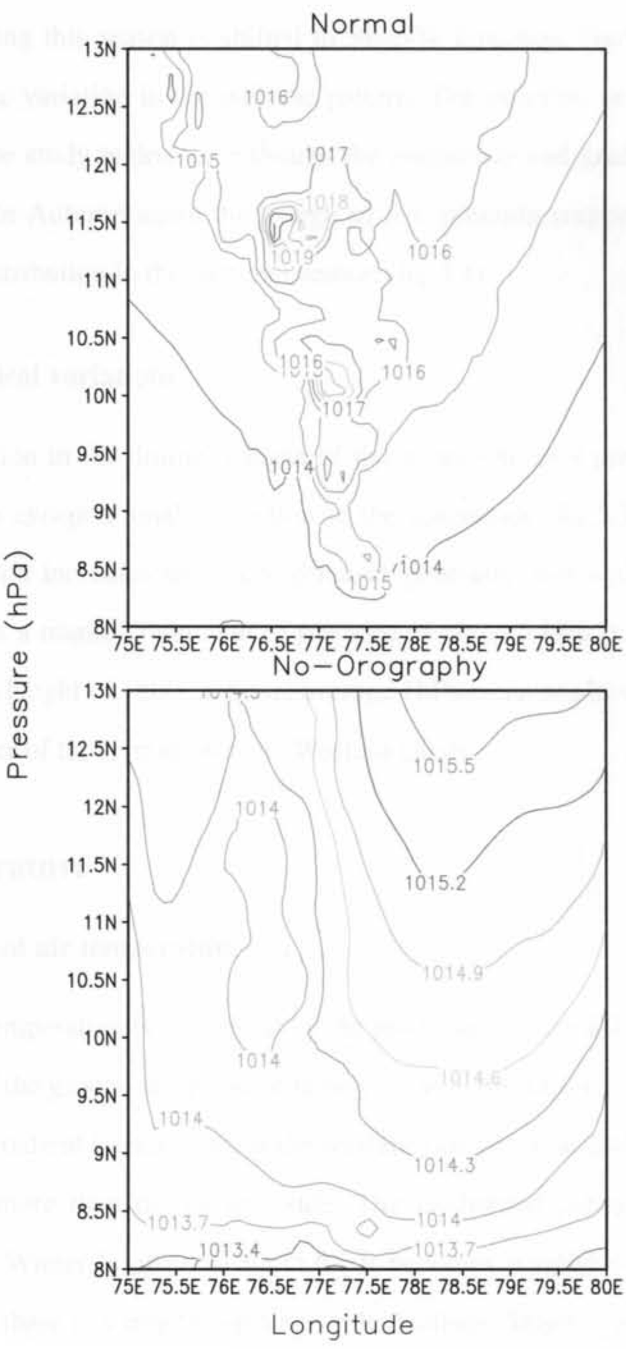


Figure 5.1: Variation of Mean sea level pressure in the study area with and without orography in Winter.

though the magnitude and gradient is less than the normal condition (fig.5.2). Orientation of the trough during this season is shifted to SE-NW direction. During Summer season there is a dramatic variation in the isobaric pattern. The pressure uniformly varies from SW to NE over the study region even though the magnitude and gradient is less than the normal (fig.5.3). In Autumn again the trough of low pressure reappears over Tamilnadu after a uniform distribution in the Summer season (fig.5.4).

Diurnal and vertical variations

There is no variation in the diurnal pattern of the mean sea level pressure (mslp) in any station in the area except a small reduction in the magnitude (fig.5.5). In vertical as the height of the station increases the mslp increases generally. But without orography that region experiences a marked reduction of pressure of about 5 hPa at the longitude of the mountain with the height of 1800 m. So an average 1hPa mean sea level pressure increases for every 360 meter of the terrain over the Western Ghats.

5.2.2 Temperature

Spatial variation of air temperature

The variation of temperature is controlled by the mountain to a great extent. The increased mean deviation of the ground temperature is very clear in the eastern side of the mountain. The temperature gradient is maximum at the western side of the mountain where steepness of the terrain is more than the eastern side. The isothermal pattern with and without orography during Winter is given in fig.(5.6). It becomes parallel to both coasts and at the central region there is a trough forming in the isolines. Magnitude of the temperature reduces a little in the plain stations at the surface without orography than the normal condition.

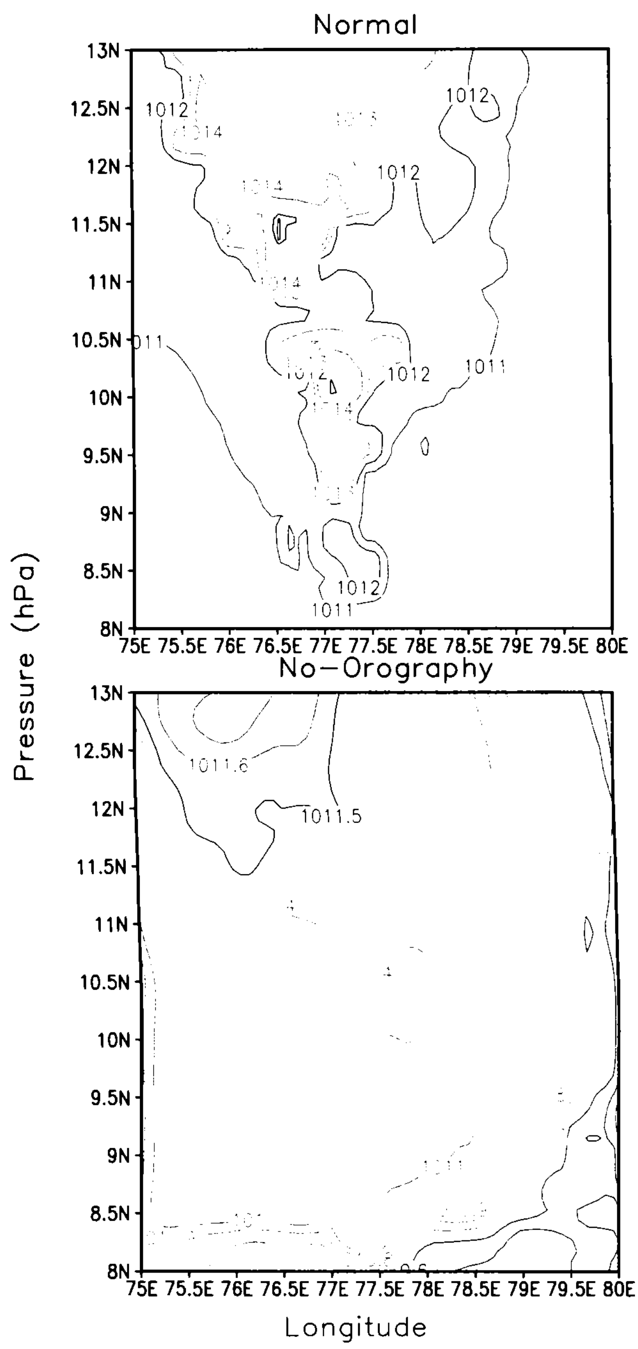


Figure 5.2: Variation of Mean sea level pressure in the study area with and without orography in Spring.

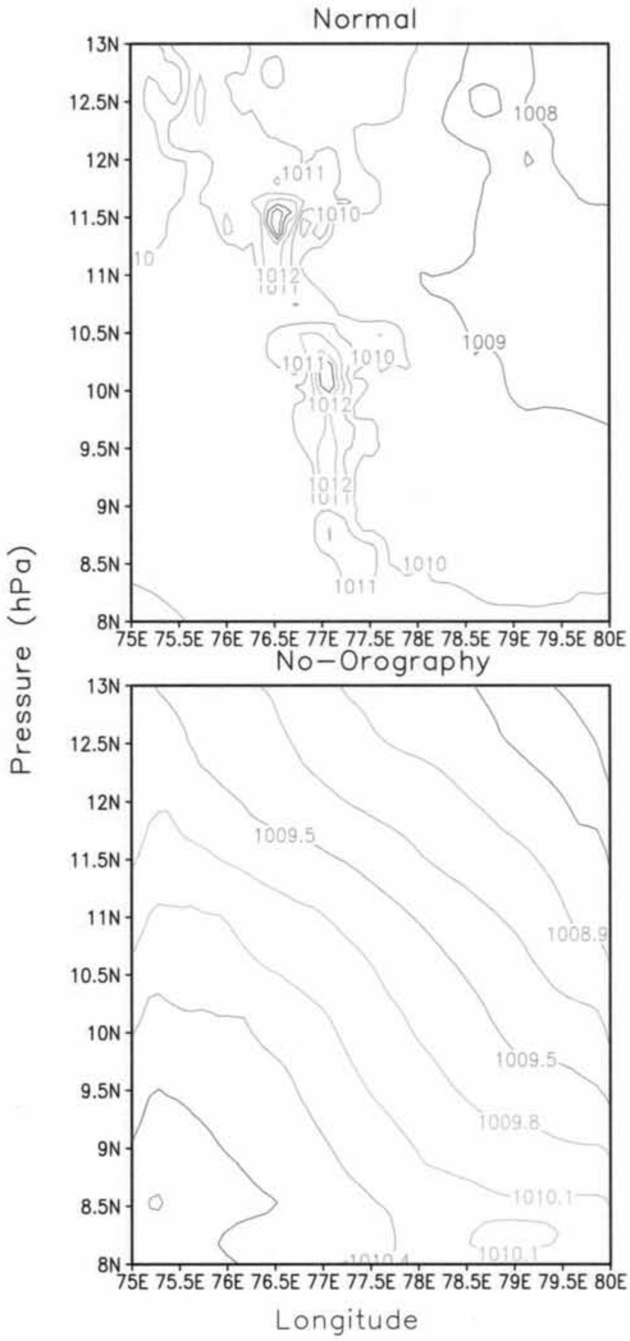


Figure 5.3: Variation of Mean sea level pressure in the study area with and without orography in Summer.

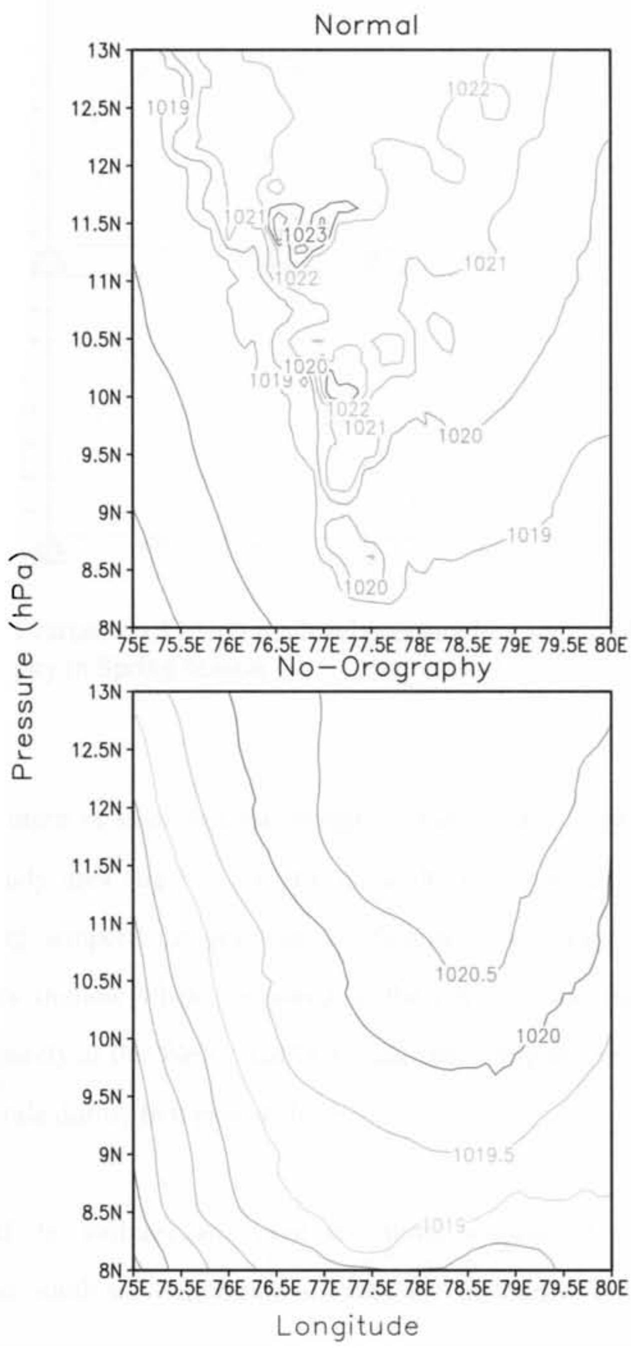


Figure 5.4: Variation of Mean sea level pressure in the study area with and without orography in Autumn.

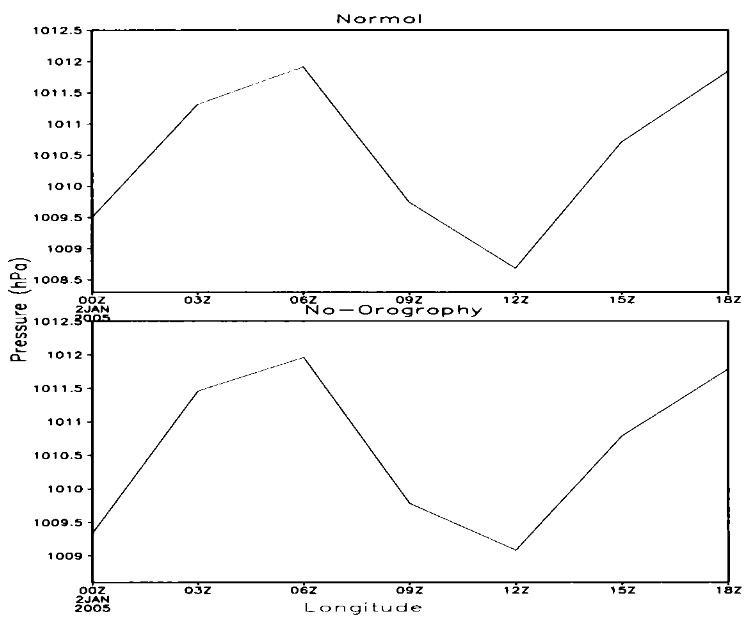


Figure 5.5: Diurnal variation of Mean sea level pressure in a station of the study area with and without orography in Spring season.

In Summer the pattern is same but the trough in the isolines shifts towards the western side of the study area (fig.5.7). At the coast the isotherms are parallel and closer indicating a strong temperature gradient. In Summer the temperature gradient over the study region is shallow when compared to the other season and the trough of the isolines are seen purely at the West coast in Kerala indicating the variation in the coastal temperature of Kerala during that period (fig.5.8).

At 900 hPa level the isolines are more structured without orographic pattern than the normal and in south-west monsoon months the isotherms are purely north-south oriented over the study region. Thus the mountain modifies the meridional pattern of the isotherm in all season and makes it more complicated pattern over the summit regions (fig.5.9). Also the effect of mountain on the pattern of mid-tropospheric temperature is

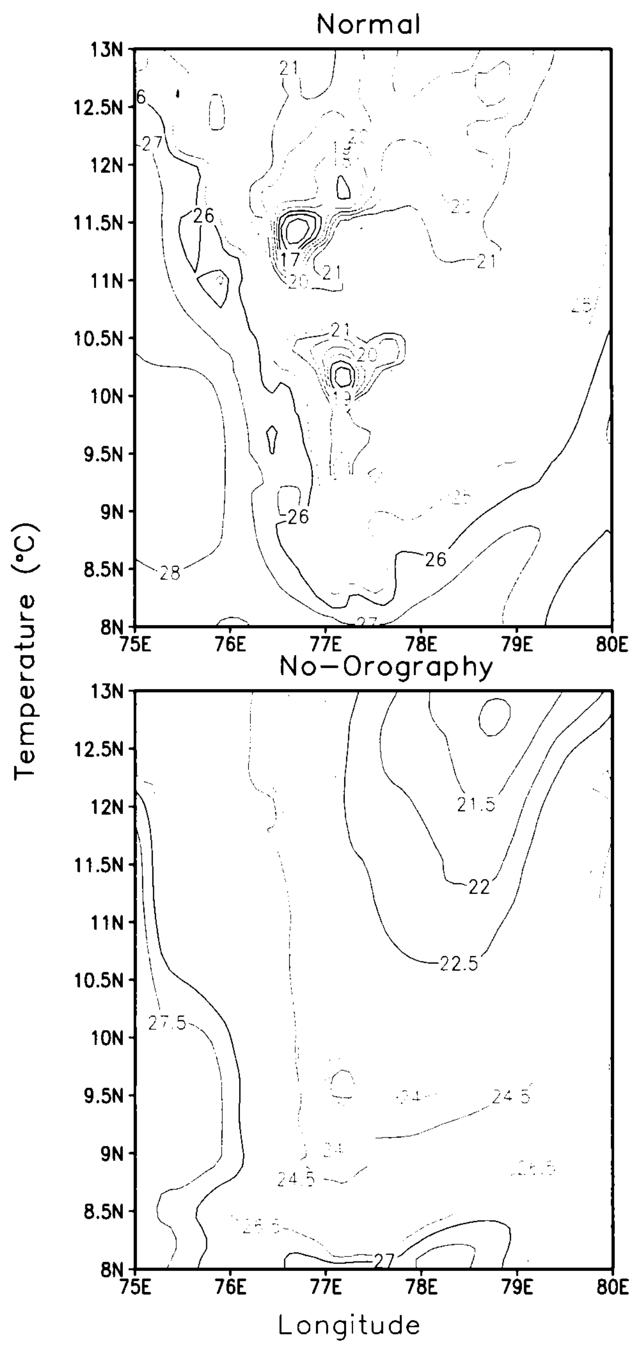


Figure 5.6: Variation of surface air temperature in the study area with and without orography during Winter.

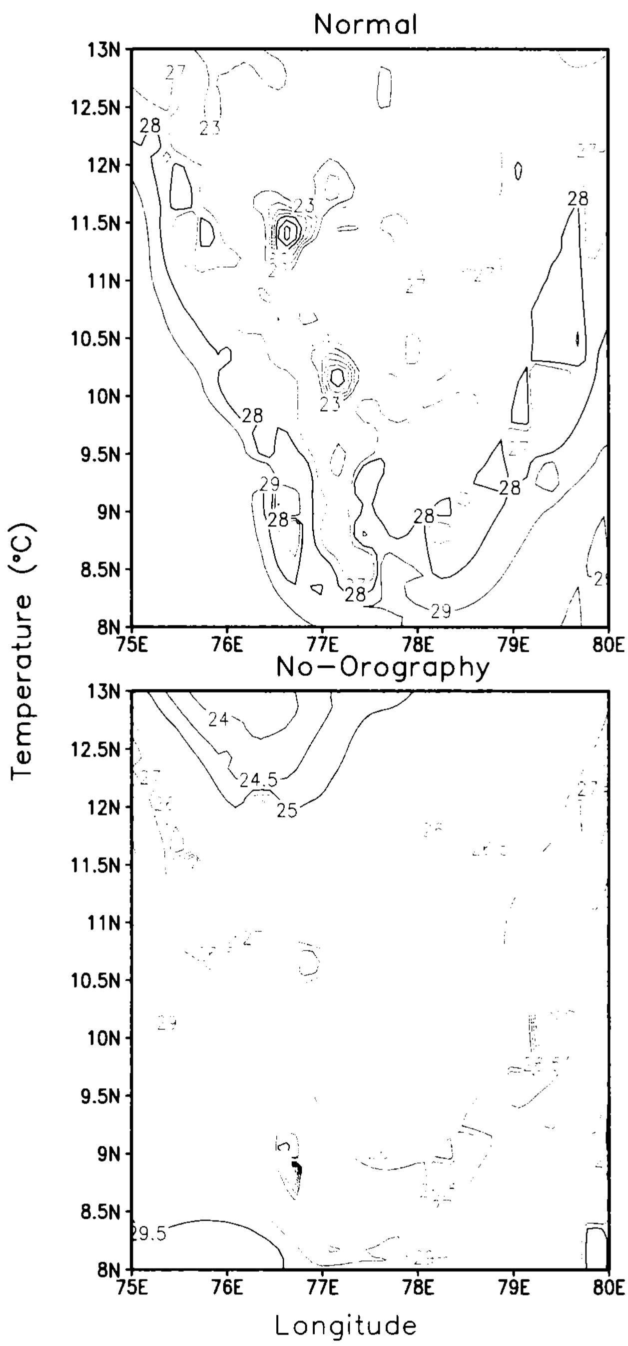


Figure 5.7: Variation of surface air temperature in the study area with and without orography during Spring.

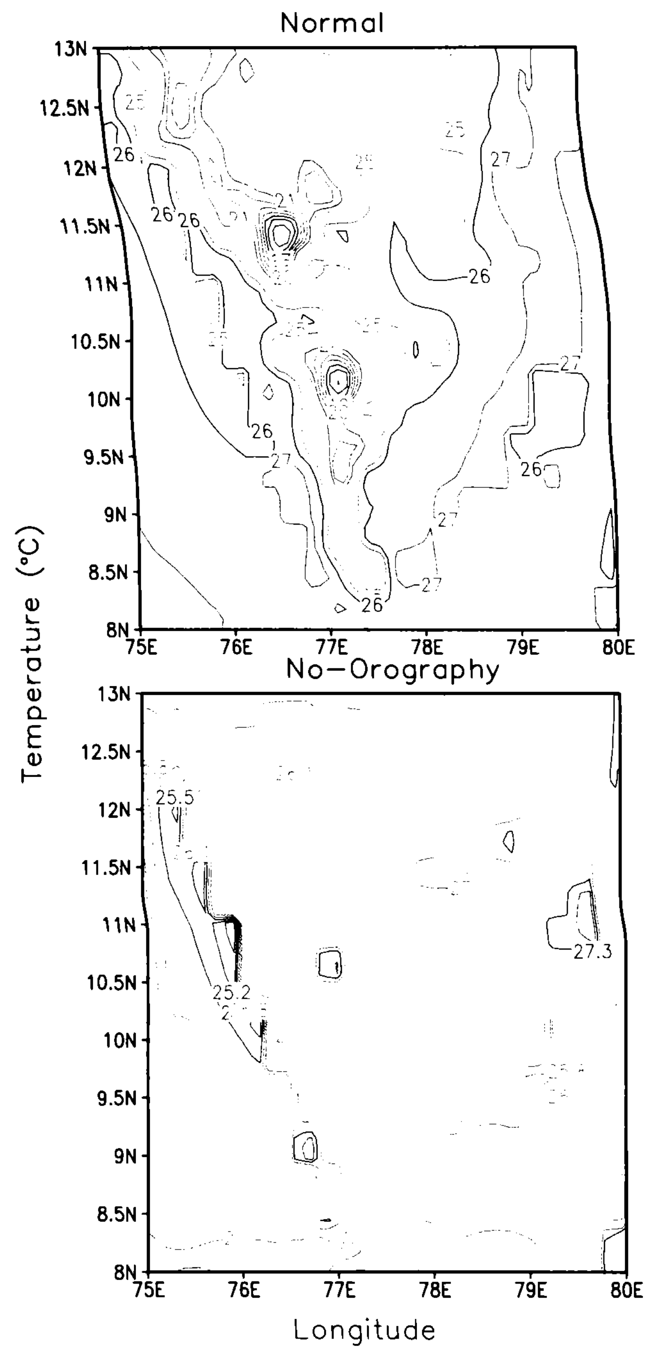


Figure 5.8: Variation of surface air temperature in the study area with and without orography during Summer.

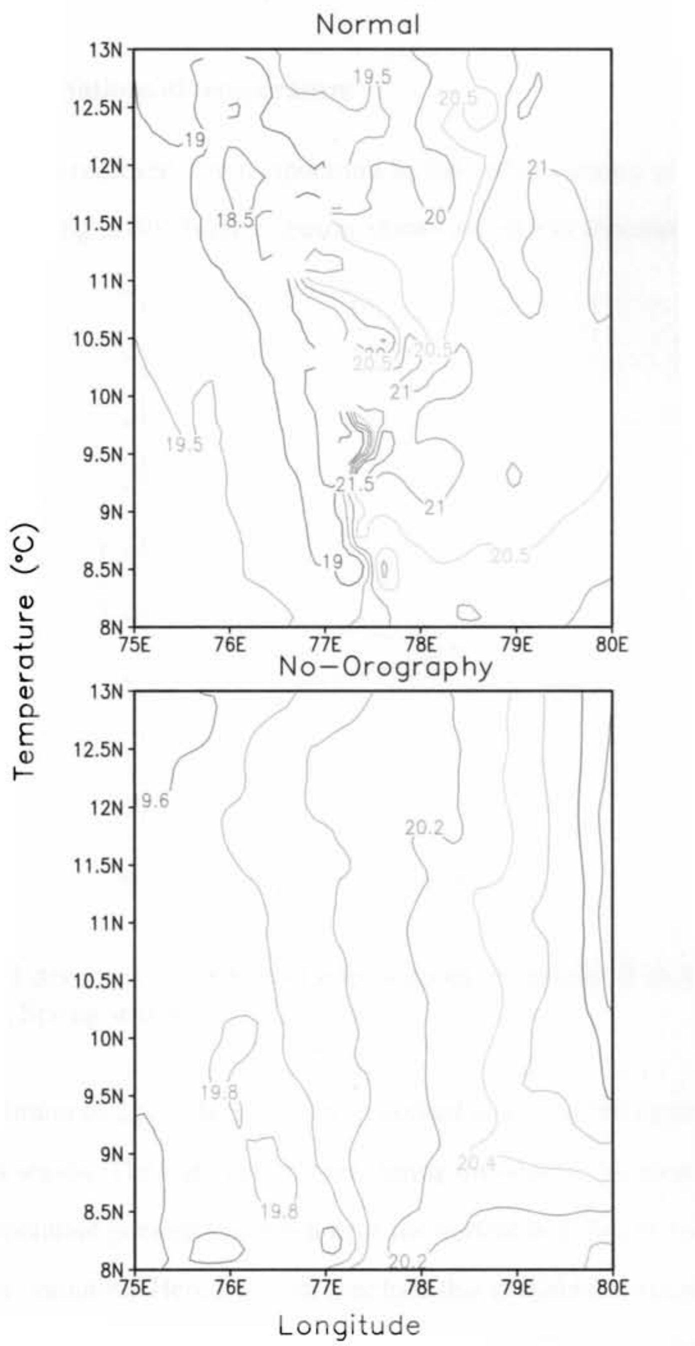


Figure 5.9: Variation of 900 hPa air temperature in the study area with and without orography during Summer.

highly noticeable in the eastern coast compared to western coast.

Diurnal and vertical variations of temperature

When the orography was removed, the temperature in the vertical shows some deviations from the normal value (fig.5.10). Winter season shows maximum fluctuations than any

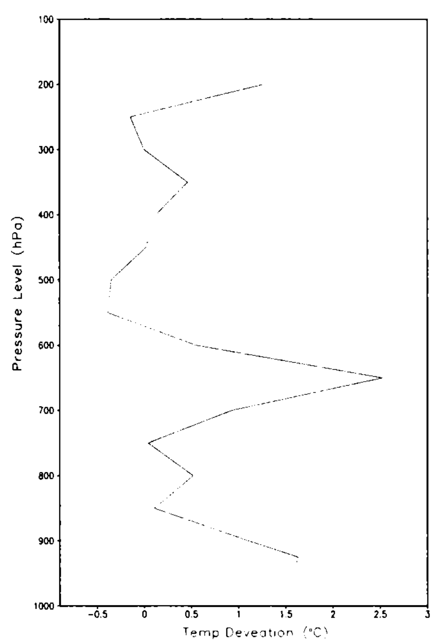


Figure 5.10: Vertical deviation of air temperature without orography from the normal in the study area during Spring season.

other season. A maximum of 2.5°C departure from normal is seen at the eastern side of the mountain during this season. The minimum is seen during the south-west monsoon months. The value of the temperature goes up and down from the normal at different levels. No fixed pattern is seen for this variation. Hence we can conclude that mountain is imparting its own influence in the temperature pattern of the air surrounding it. But quantification of this variability is difficult because it depends directly on so many other factors like circulation pattern, boundary layer characteristics and the cloud micro-physics of the region.

Mean deviation of temperature during Spring and Winter season

Mountain imparts its role in controlling the range of temperature of the surrounding region in different ways. The deviation of the Spring and Winter temperature from annual mean temperature along the latitude belt of 10.2°N with and without orography is given in fig.(5.11). The deviation of temperature in Spring and Winter over Anamudi hills is about 12°C while it is about 3°C over other regions when the orography was removed. When the orography is removed, the deviation reduces over the central region and almost a uniform pattern in the rest of the region. This increased deviation of temperature at the eastern side of mountain is purely due to the influence of the Western Ghats.

Soil temperature variations

The analysis of the variation of soil temperature at 5 cm level along the latitude belt of 10.2°N during Spring is given in fig.(5.12). The study shows that the influence of Western Ghats on the soil temperature of the plain land of both western and eastern side of it is nominal. Normally at the peak of the mountain a reduction of about 14°C from the coasts is seen in all season. The variations over plain land and valley stations on both sides are controlled by the mountain in such a fashion that there is a successive reduction of the temperature towards the peak of the mountain. When the orography was removed a uniform pattern of soil temperature distribution is seen over the entire area and not much variation from the normal is seen at the plain stations. Only in Winter there is more reduction (about 2°C) in the soil temperature over the eastern side of the region than the western side (fig.5.13). Generally it is seen that air temperature at 2 m height in Tamilnadu plains shows a reduction of about 2°C than the Kerala and this is reflecting in the soil temperature also in the Winter months. During south-west monsoon period also the change is similar to other months.

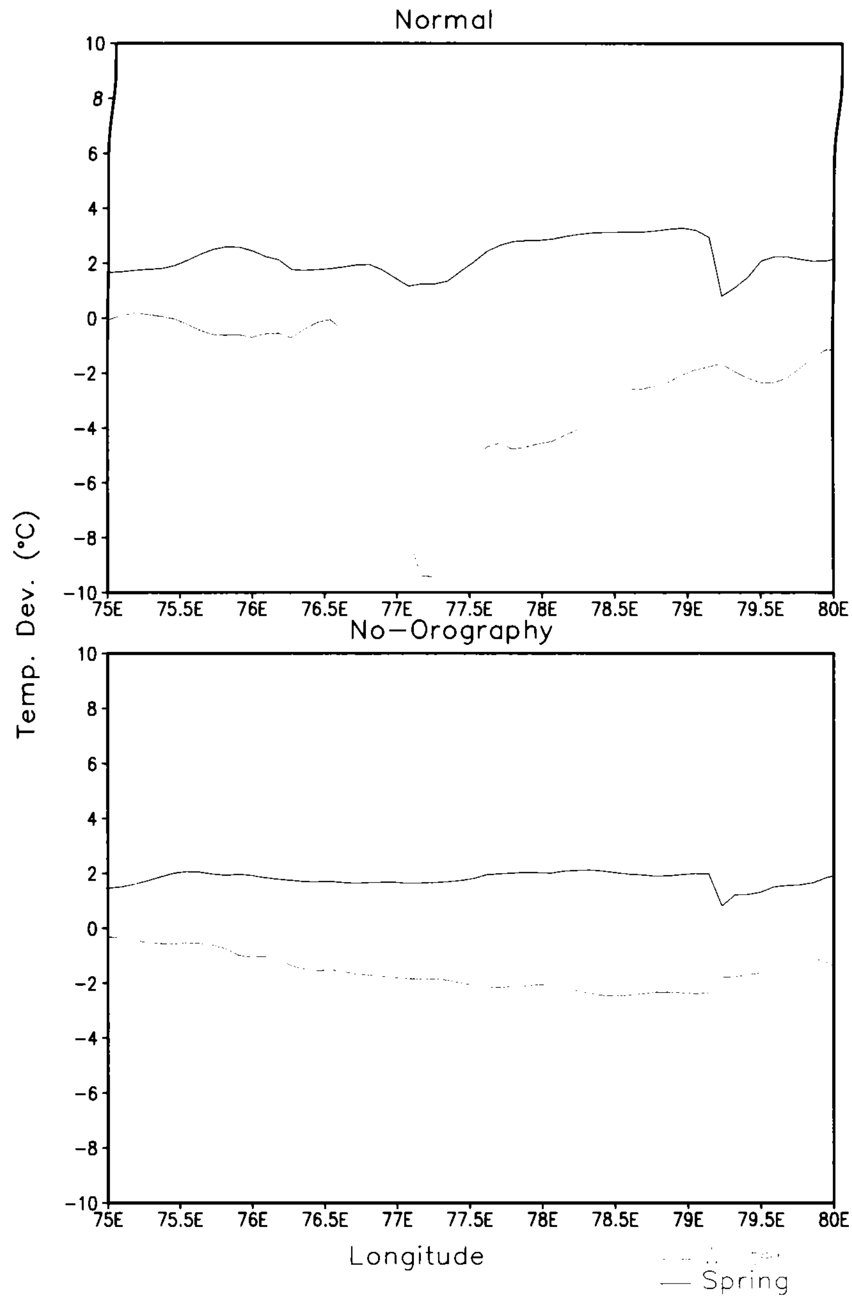


Figure 5.11: Mean deviation of air temperature with and without orography in the study area during Spring and Winter.

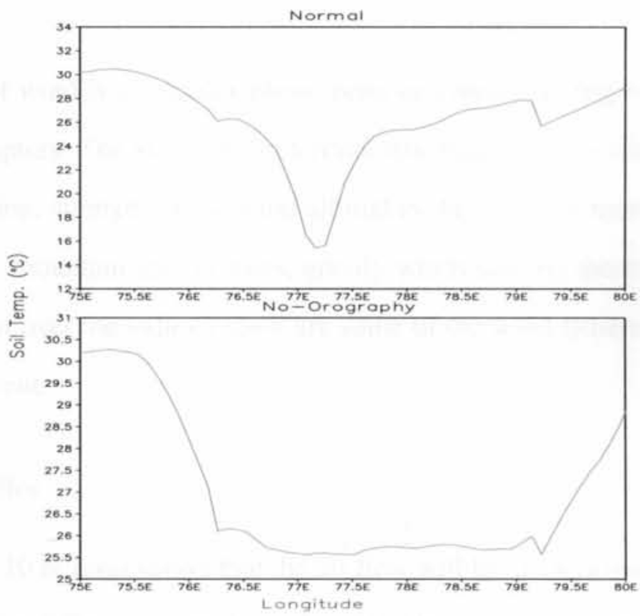


Figure 5.12: Variation of 5 cm soil temperature along 10.2°N latitude with and without orography in the study area during Spring.

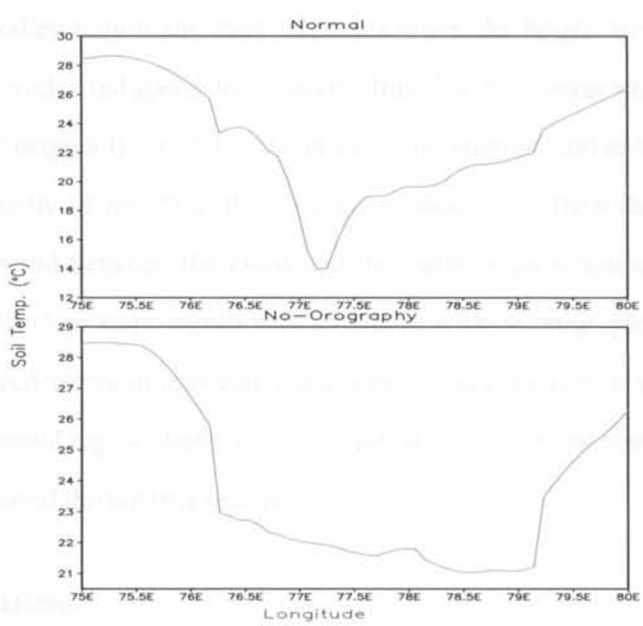


Figure 5.13: Variation of 5 cm soil temperature along 10.2°N latitude with and without orography in the study area during Winter.

5.2.3 Wind

The modification of wind is a complex phenomena in a mountain region as we have seen in the previous chapters. The slope of the terrain, orientation of the ridges, geographical position of the station, strength of the wind all makes the situation more difficult. Corner effects of the wind, mountain anticyclones, gravity winds and the thermally driven winds in the day and night over the valley region are some of the wind pattern existing over the mountain environment.

Surface wind profiles

The vector wind at 10 m level shows that the air flow will be smooth over the region in all season (fig.5.14). The diffluence pattern produced by the mountain peaks will be converted into a streamlined flow. During the Summer season the winds will be purely westerlies and parallel to latitude and flows without any interruption. Normally the surface wind reduces from the coast to valley region and then increases when the height increases. When the orography was removed, wind speed decreases by $4ms^{-1}$ at the central longitudes where the mountain was there originally (fig.5.15). Over the plain stations and at the coast the wind speed increases slightly (1 ms^{-1}) in the absence of mountain. Then there is a reduction of the gradient of wind between the coast and the valley region when the orography is removed. Both coasts show same variation in all season without orography. During Autumn season the wind speed varies in between 3 and 4 ms^{-1} over the region without orography (fig.5.16). At the coastal region there is an increase of 1 ms^{-1} in the wind speed when the orography was removed during that season.

Vertical wind variations

The winds will be smoothened vertically and the increase of the wind speed is seen in the PBL of all the stations. During Spring between 850-900 hPa level, a minimum wind speed

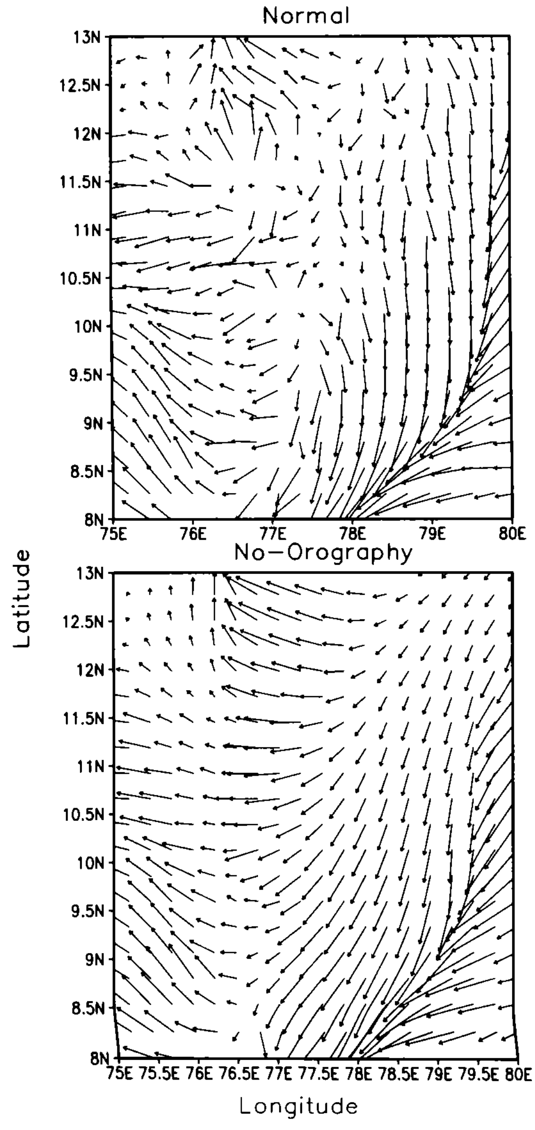


Figure 5.14: The surface winds over the study region during Winter with and without orography.

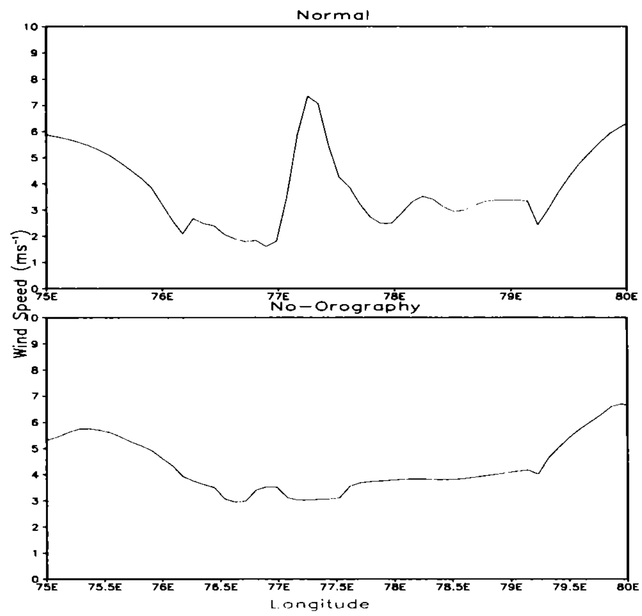


Figure 5.15: The surface wind speed along 10.2°N latitude during Summer with and without orography.

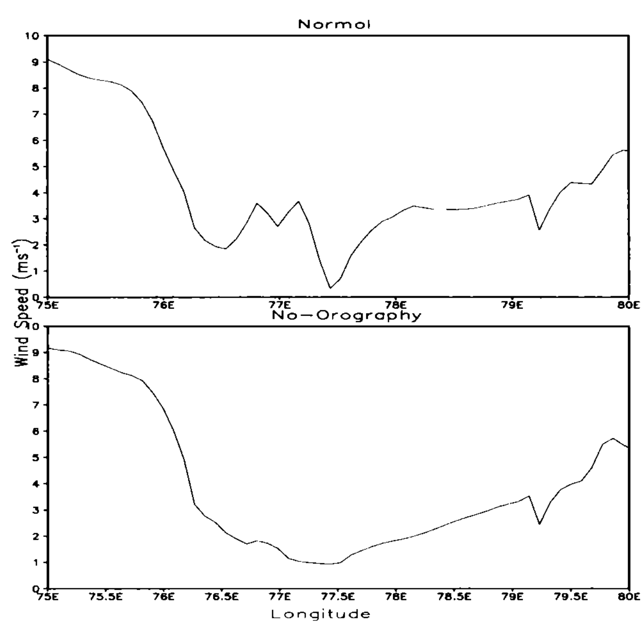


Figure 5.16: The surface wind speed along 10.2°N latitude during Autumn with and without orography.

is observed (fig.5.17). Again a secondary minimum is observed at 650-600 hPa level when the orography disappears. A 3 ms^{-1} increase is observed in the wind speed over the Kerala region and the central part of the study area in mid-tropospheric level. It is 1 ms^{-1} over Tamilnadu region at the 450 hPa level during Spring season. When the winds are stronger mountain is not imparting much influence to the flow at any levels and do not redirect to any direction instead the flow itself is trying to over come the barrier with its momentum. This is very clear in the analysis during Summer. There is absolutely no marked variation in the wind speed at any station when the orography was removed. In Autumn season the depth of the minimum wind speed layer increases in mid-tropospheric levels over the central part of the study region from where the orography is removed (fig.5.18). At the upper tropospheric levels the wind speed increases in the western side of the study area over Kerala.

Diurnal wind & Frictional velocity

The diurnal wind at 10 m level is plotted for different stations with removed orography. Generally a semi-diurnal pattern is seen even though the amplitude of the wave is small in all season. It may go upto 1 ms^{-1} in the Autumn season (fig.5.19). During Summer season the diurnal pattern is not prominent like other season (fig.5.20). But the effect of the mountain is very clear during this season. At the western and eastern side of the mountain wind speed increases by 2 ms^{-1} when the orography is removed. But over summit longitude the wind speed reduces than the normal conditions by 3 ms^{-1}. it can be inferred from the wind analysis that windward and leeward side of the mountain imparts its influence to reduce the wind speed over plain stations while it is increasing over the mountain region due to the orographic ascent initiated by the mountain.

Frictional velocity is maximum during the Summer season. From the earlier analysis we have seen that it varies from 0.2 to 1.1 ms^{-1} during Summer. The maximum value

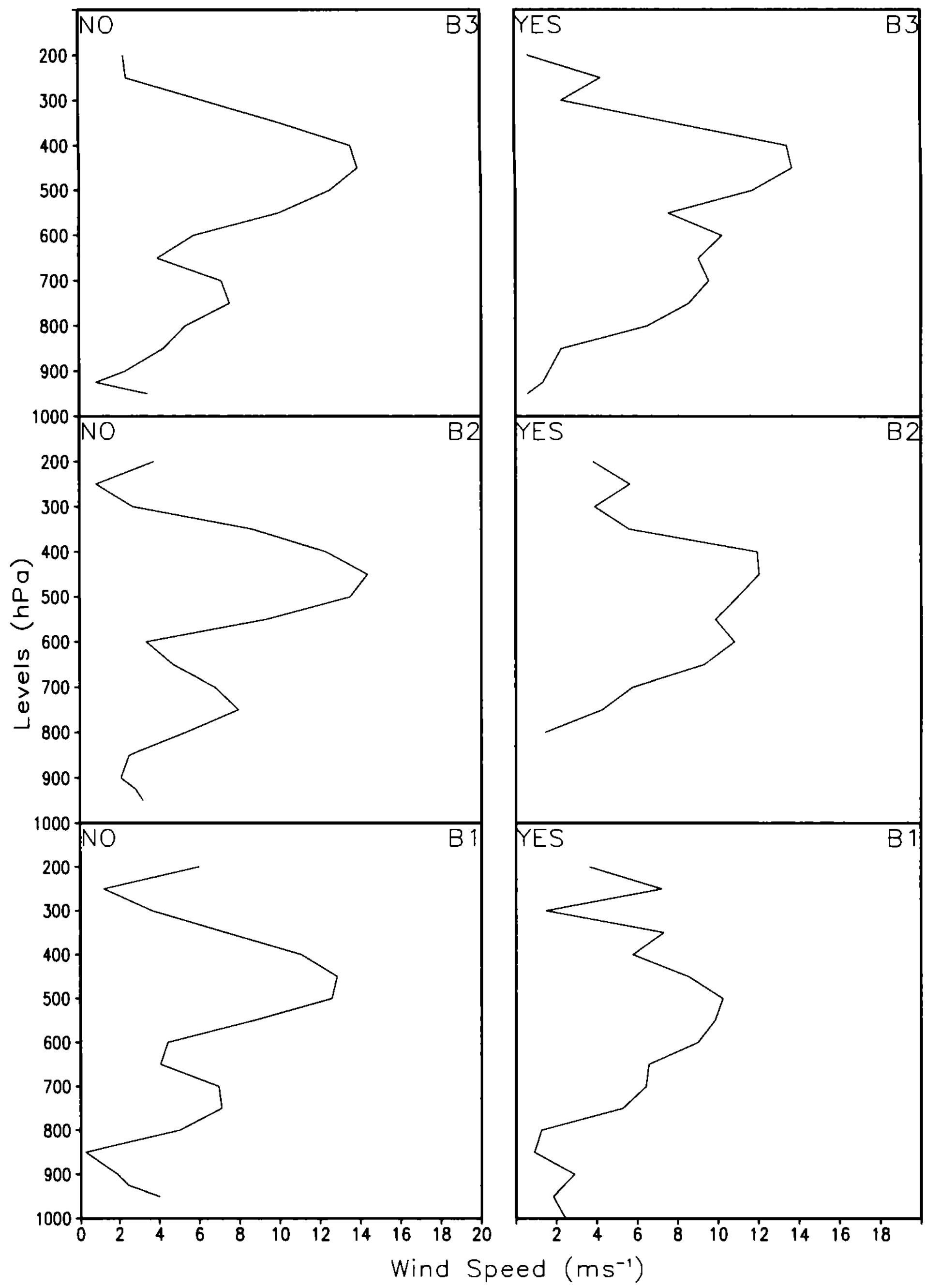


Figure 5.17: The vertical profile of wind during Spring in the study region with and without orography (No= No Orography & Yes= With Orography).

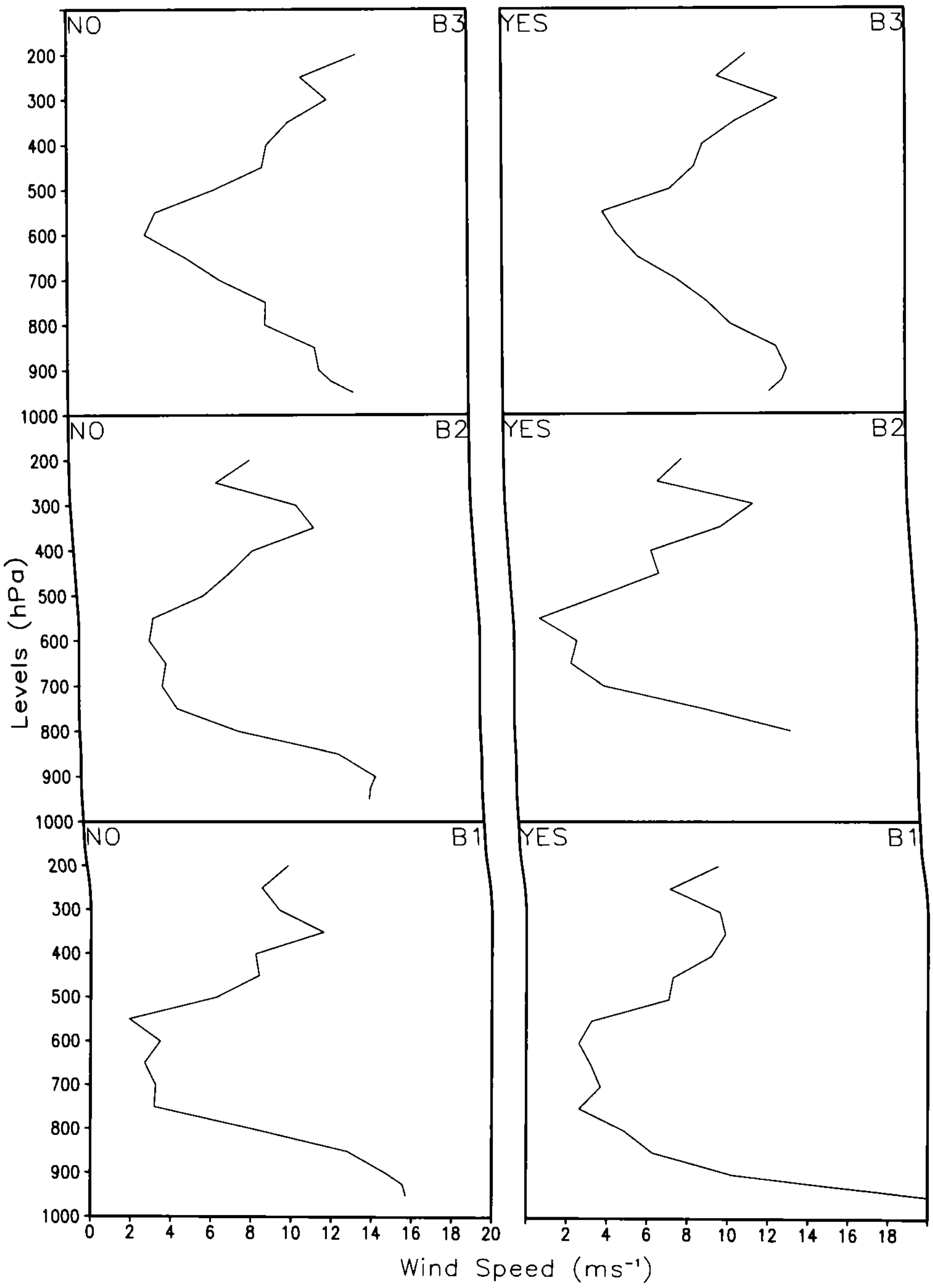


Figure 5.18: The vertical profile of wind during Autumn in the study region with and without orography (No= No Orography & Yes= With Orography).

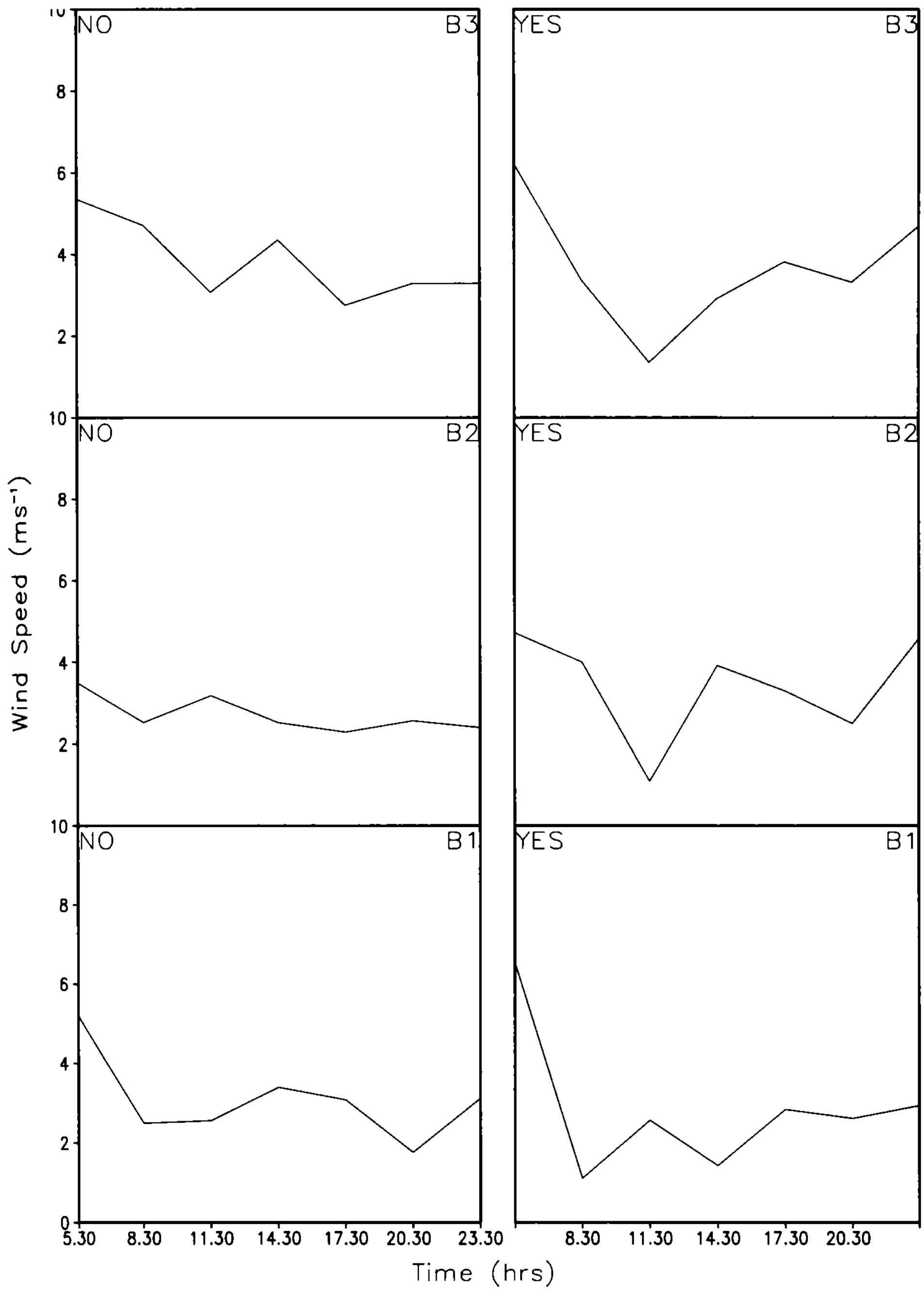


Figure 5.19: The diurnal variation of wind during Autumn in the study region with and without orography (No= No Orography & Yes= With Orography).

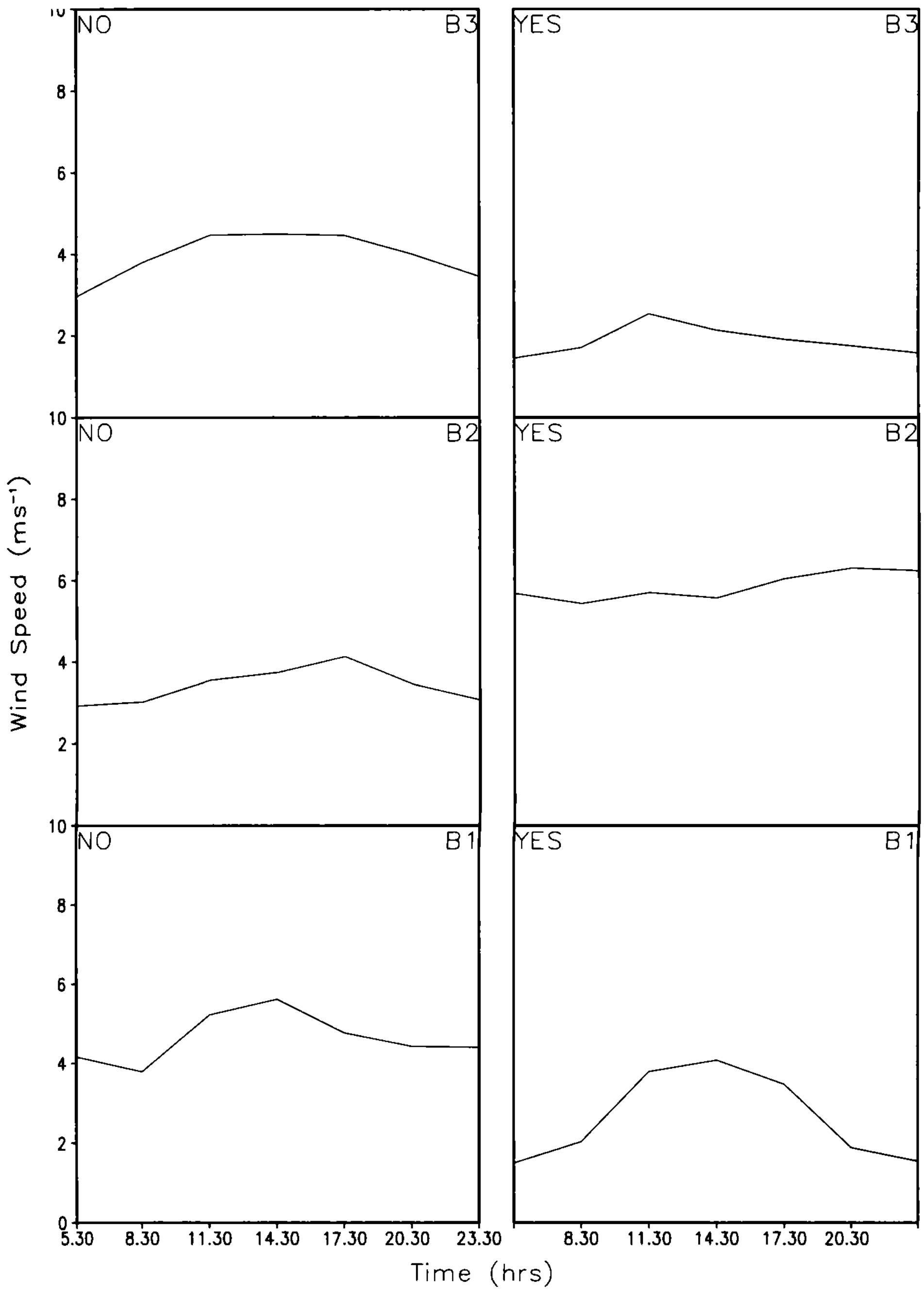


Figure 5.20: The diurnal variation of wind during Summer in the study region with and without orography (No= No Orography & Yes= With Orography).

of frictional velocity is occurring at the summit region and minimum along the coast and also some specific stations like Neriamangalam and Vyttiri. When the orography is removed, the frictional velocity changes in the study region uniformly at a value of about 0.4 ms^{-1} over the land area and decreases at the coasts (fig.5.21). The value at the

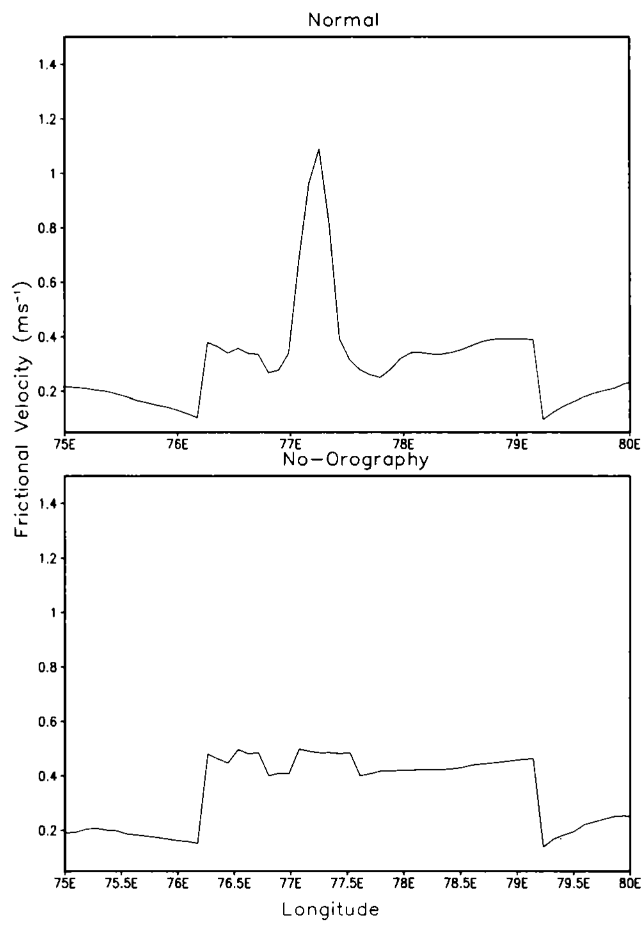


Figure 5.21: The variation of frictional velocity along the cross section of Anamalai hills with and without orography during Summer season.

summit longitude is coming upto 0.5 ms^{-1} which is just half of the normal value. The value at Neriamangalam is 0.4 ms^{-1} without orography which is 1 ms^{-1} more than normal condition there. Thus the slope of the terrain is very crucial in controlling the surface drag there. It is clear that even though Western Ghats is a barrier to the smooth flow of winds to the higher levels of the mountain it supports a smooth flow over plain stations in the study region.

5.2.4 Humidity

Humidity varies with height in a station and this variation is maximum above the mid-tropospheric levels (above 500 hPa). The maximum variation (by about 80-90% difference) is seen between the Winter and Spring season at that level. The control of the mountain in relative humidity over the windward and leeward side has been seen from the earlier analysis. The moisture transport is primarily controlled by the direction of wind over the region.

Horizontal and Vertical variation of RH over the study region

When the orography was removed the relative humidity is found to increase in Kerala except in Spring season (fig.5.22). But as we go to the upper levels (900-800 hPa) this variation is not prominent .Over Tamilnadu RH increases during Summer season when the orography is removed. All other season relative humidity decreases over Tamilnadu when the orography is removed. Thus mountain helps the summit stations to retain the higher humidity value in all season except in Winter. During Winter the land cooling over the summit reduces the surface humidity pattern. But during monsoon months humidity increases in those stations. The moisture flow to Kerala during Autumn season is blocked by mountain while it reduces the moisture amount at 950 hPa level by lifting the moisture filled air to upper level (900 hPa). Generally Western Ghats helps to keep the relative humidity high over plain stations on both sides. It take the relative humidity to high values over the summit regions.

The deviation (removed orography-normal) of RH in different season for Kerala in

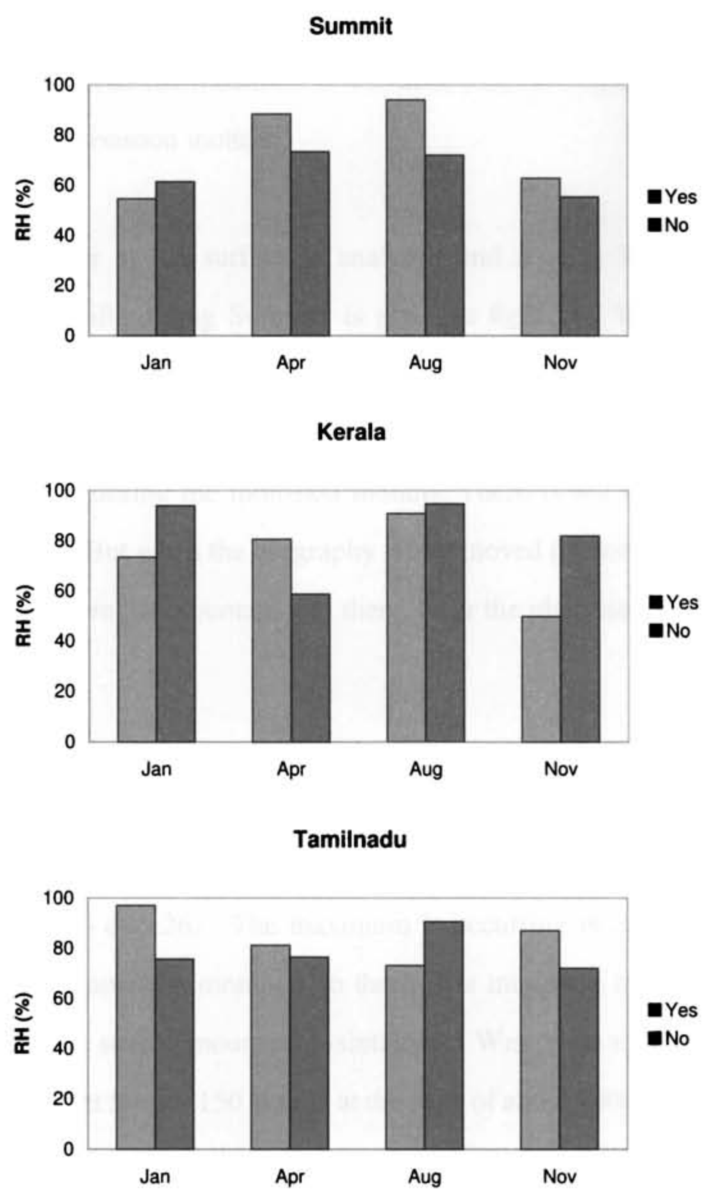


Figure 5.22: The variation of relative humidity in 3 stations along the cross section of Anamalai hills with and without orography during different season.

the lower troposphere is given in fig (5.23). It shows that in the boundary layer the variation is maximum during Winter and Spring (about -20 to 20 %). During Summer the variation is less and minimum in the lower layers while in Autumn it is minimum above 800 hPa level. Thus the mountain is not modifying the humidity of the atmosphere vertically during the monsoon months.

The precipitable water at the surface is analysed and a cross section of the analysis along the Anamalai hills during Summer is given in fig(5.24). The deviation (Normal-removed orography) of the precipitable water content in all season shows that as the terrain height increases the precipitable water content decreases and at about 1800 m height it is about 2.5 $KgKg^{-1}$ during the monsoon months. There is not much variation for this value in other season. But when the orography was removed it becomes 4.8 $KgKg^{-1}$ at the original longitude where the mountain was there. Over the plain station the variation is not there.

5.2.5 Radiation

The net radiative flux varies from 150 Wm^{-2} to 350 Wm^{-2} over the study region in different season (fig.5.25 & 5.26). The maximum is occurring in Spring and minimum in Autumn. During the monsoon months also the flux is minimum but Autumn value is the lowest. During Winter season mountain maintains 25 Wm^{-2} net radiation over both sides of it and reduces the net flux by 150 Wm^{-2} at the peak of about 1800 m. During Spring Kerala is benefited by a huge surplus of about 160 Wm^{-2} due to the impact of Western Ghats while no gains for Tamilnadu. When monsoon arrives mountain do not play much role in varying the net radiative flux over the surrounding plain lands. The change in the summit is also very small (80 Wm^{-2}). The minimum influence of the mountain is in Autumn. Thus mountain plays a major role in maintaining surplus net radiation over Kerala and Tamil-

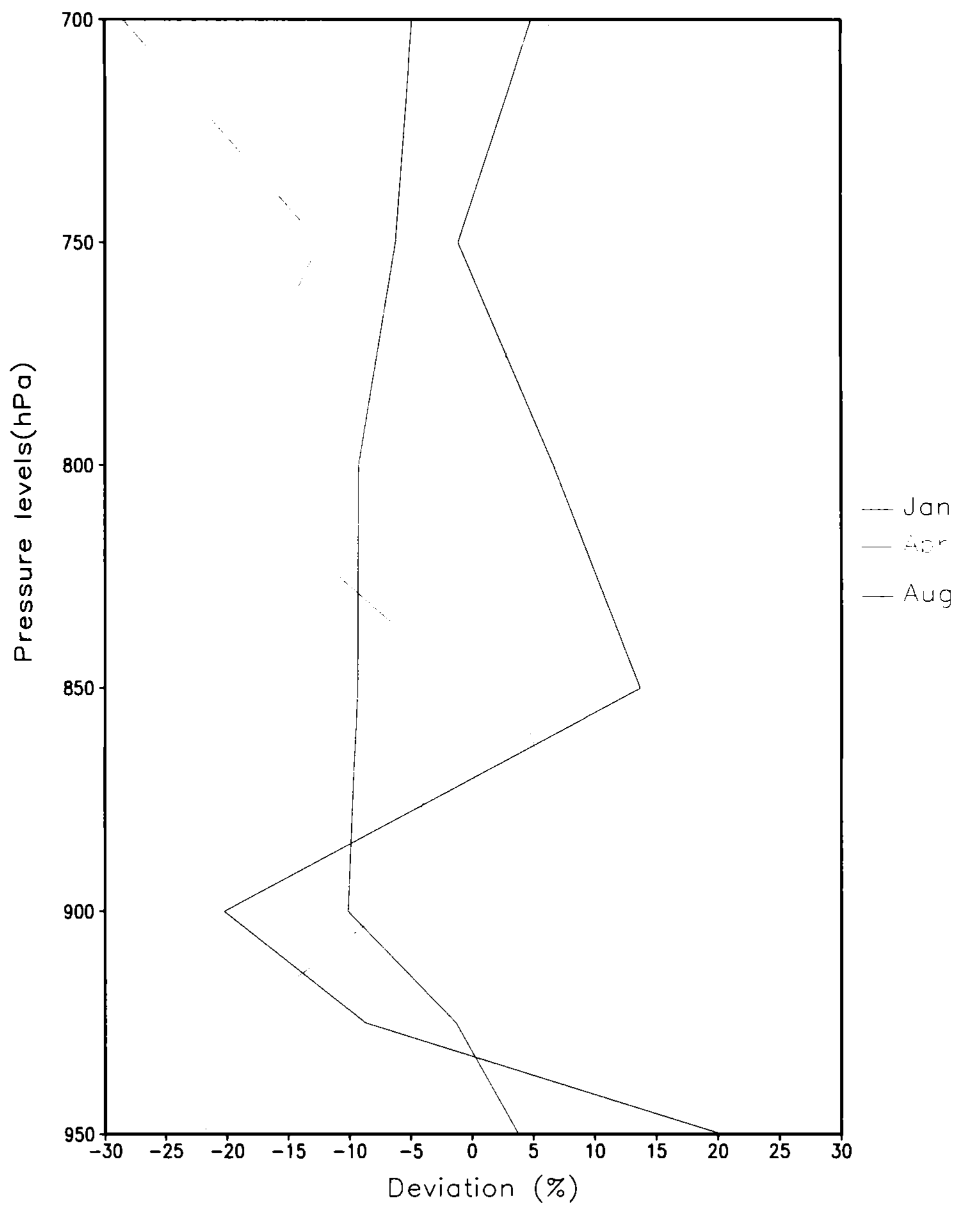


Figure 5.23: The vertical deviation (Normal-Removed) of relative humidity in the lower layers of troposphere with and without orography during different season.

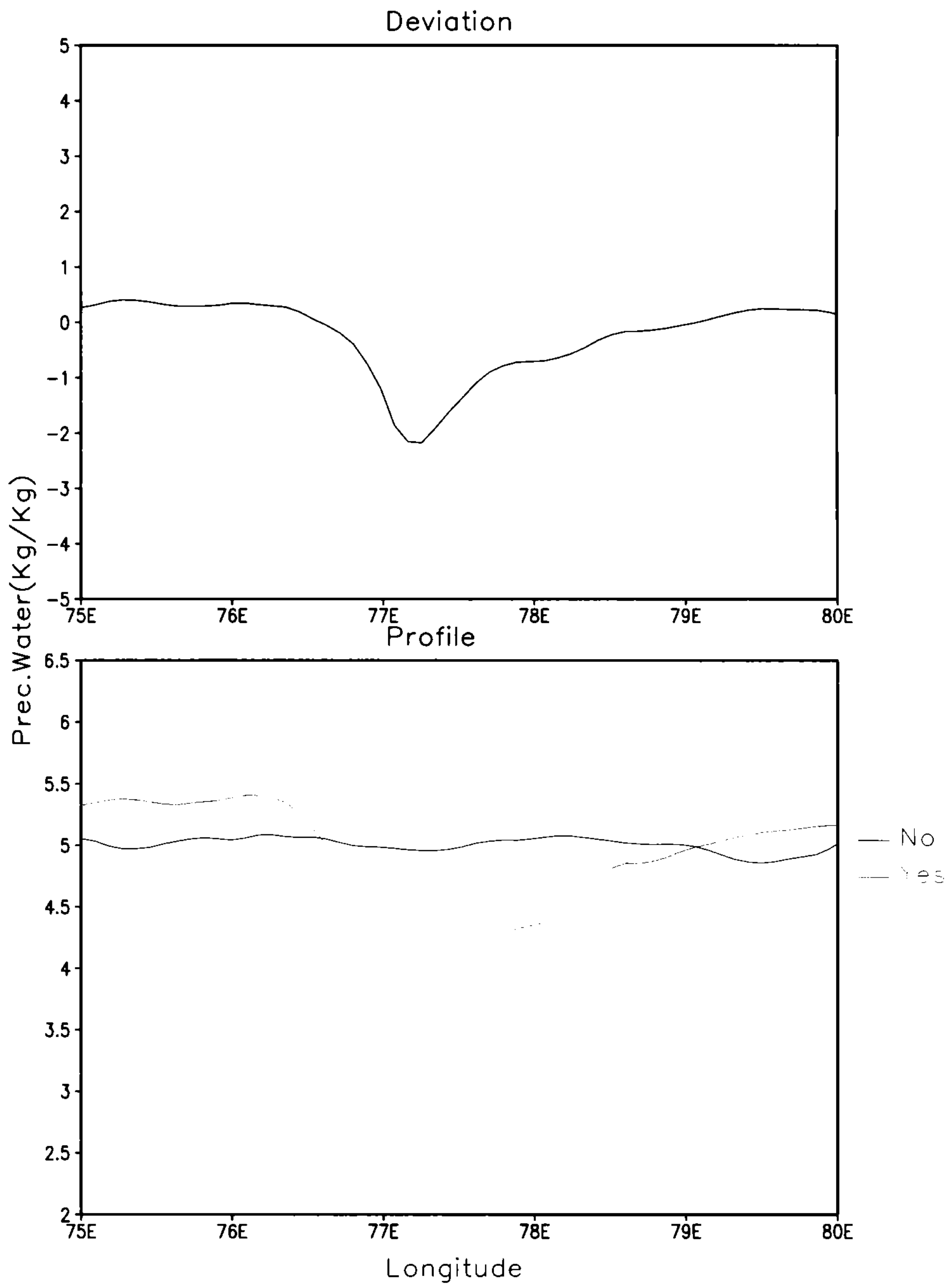


Figure 5.24: The variation of precipitable water in the surface layer along the cross section of Anamalai hills with and without orography and the deviation (Normal-Removed) from the normal during Summer.

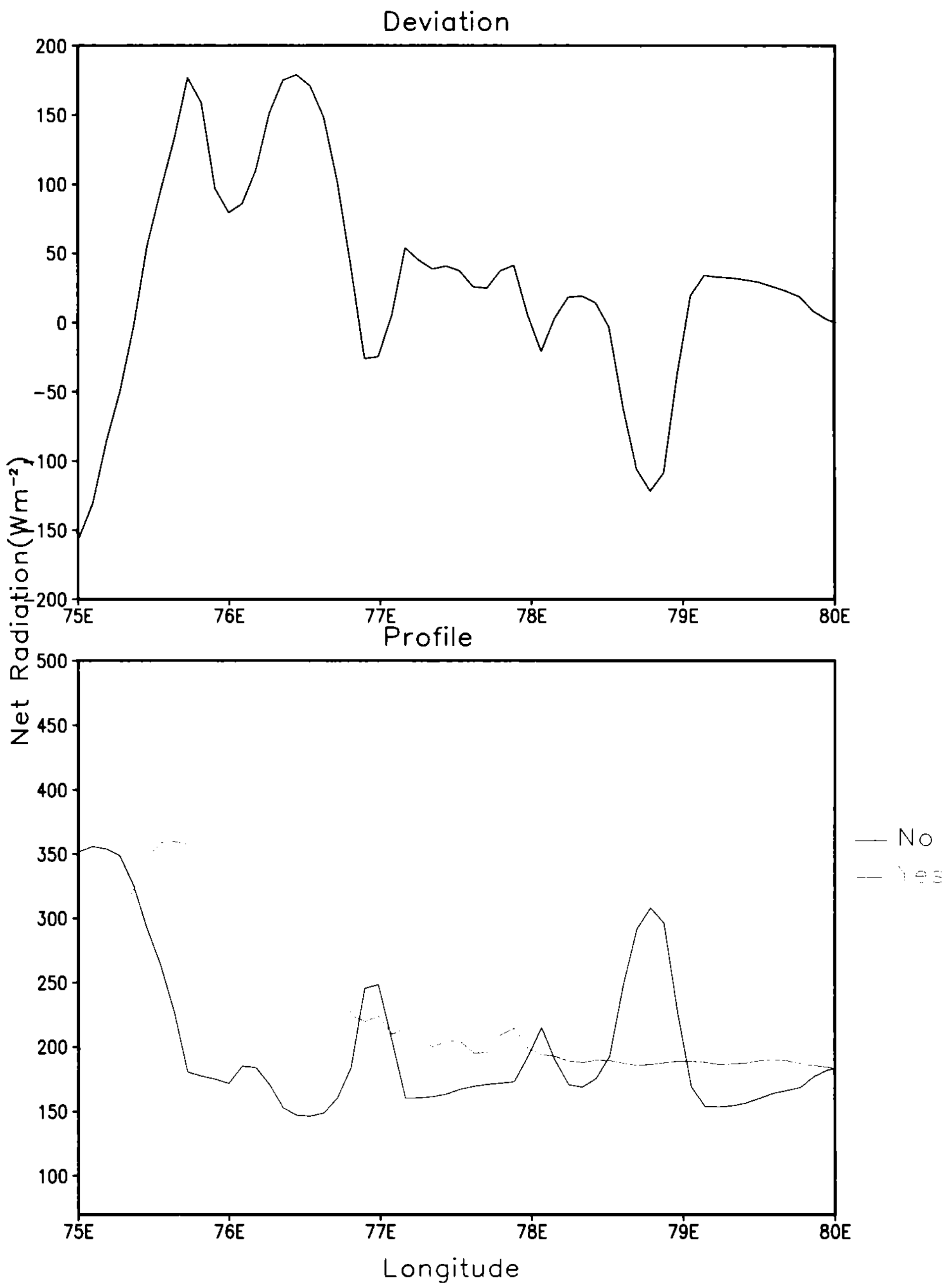


Figure 5.25: The variation of net radiative flux in the surface layer along the cross section of Anamalai hills with and without orography and the deviation (Normal-Removed) from the normal during Spring.

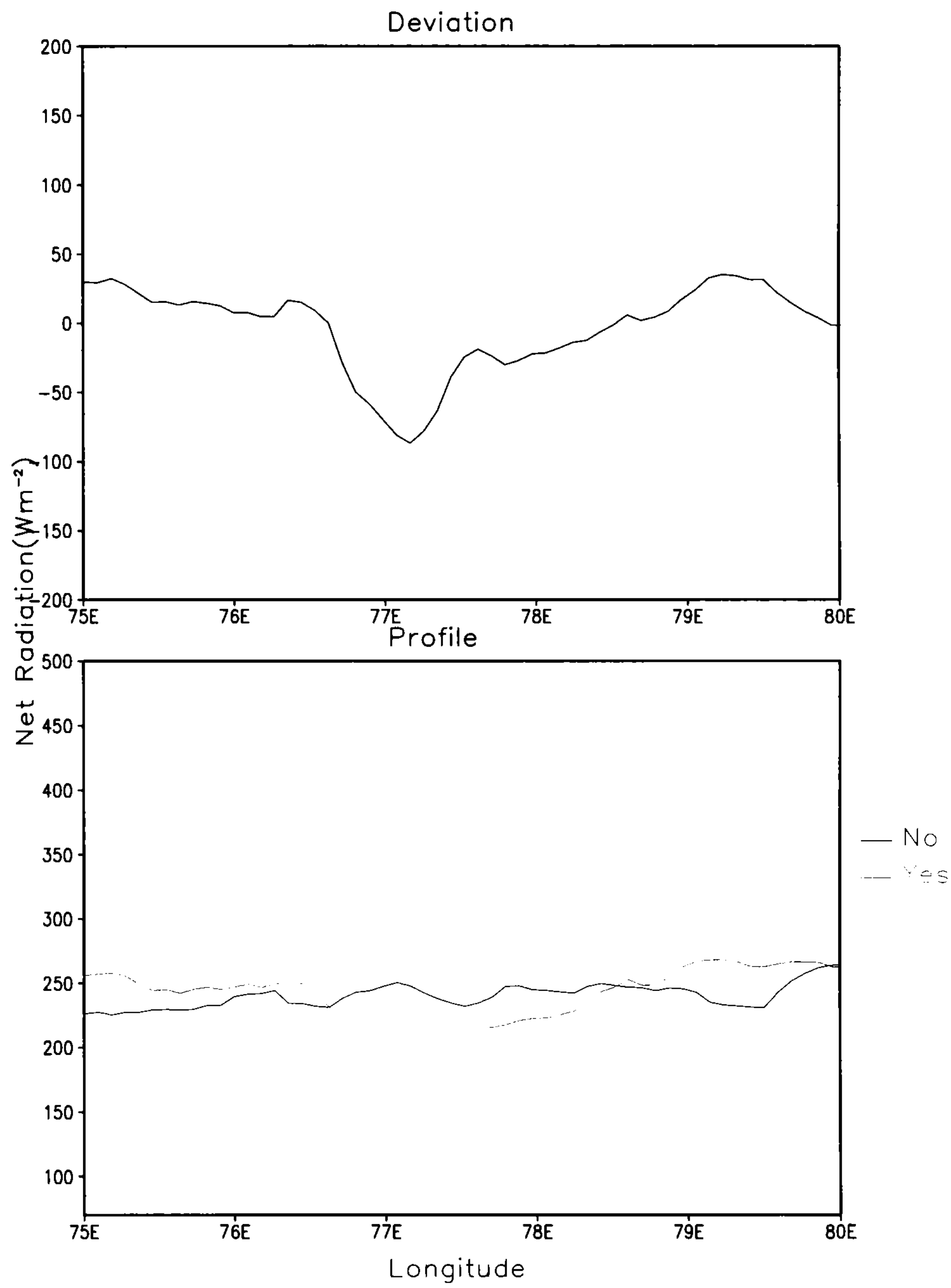


Figure 5.26: The variation of net radiative flux in the surface layer along the cross section of Anamalai hills with and without orography and the deviation (Normal-Removed) from the normal during Summer.

nadu in Winter and Spring and among which Kerala is more benefited than Tamilnadu in Spring season with a huge surplus of energy.

5.2.6 Clouds

Mountain imparts its influence on low clouds more than medium and high level clouds over Kerala (fig.5.27). Low and medium level clouds are controlled by the Western Ghats to a great extent during the Spring season in the region. There is not much influence on the formation of high clouds over plain stations. Clouds are generally less during the Autumn season and the role of Western Ghats on the suppression of low clouds over the region is very clear in this season.

Western Ghats plays a major role in the formation of all types of clouds in different season over the summit regions (fig.5.28). During the Winter mountain suppress the formation of low clouds to a great extent but the reduction of medium clouds over summit in the Autumn season is not due to the influence of the Western Ghats. The role of Western Ghats in maintaining all levels of clouds are more in Tamilnadu than Kerala (fig.5.29). The notable point is that, the low level clouds forming over the summit and eastern region of the mountain in Autumn season are primarily under the influence of Western Ghats.

5.2.7 Variation in Boundary layer Parameters

The effect of the Western Ghats on various boundary layer parameters which influences the weather pattern of the region is given this section. The PBL height controls the mixing height properties while the rainfall is having a negative correlation to the frictional velocity. Exchange of heat fluxes and soil temperature controls the temperature pattern of the region to a great extent.

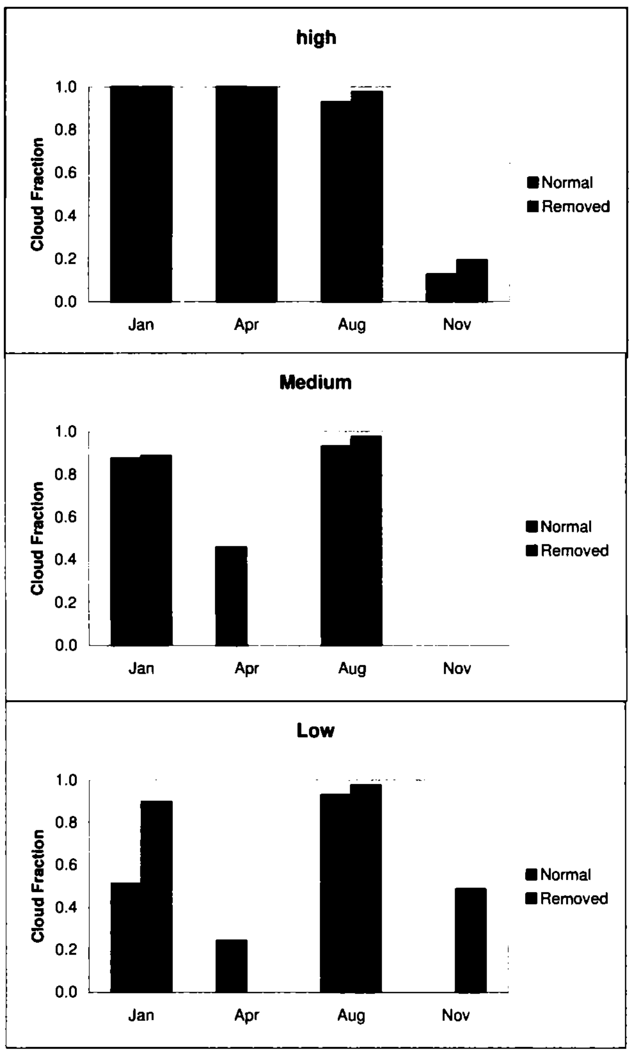


Figure 5.27: The variation of cloud amount over Kerala during different season with and without orography.

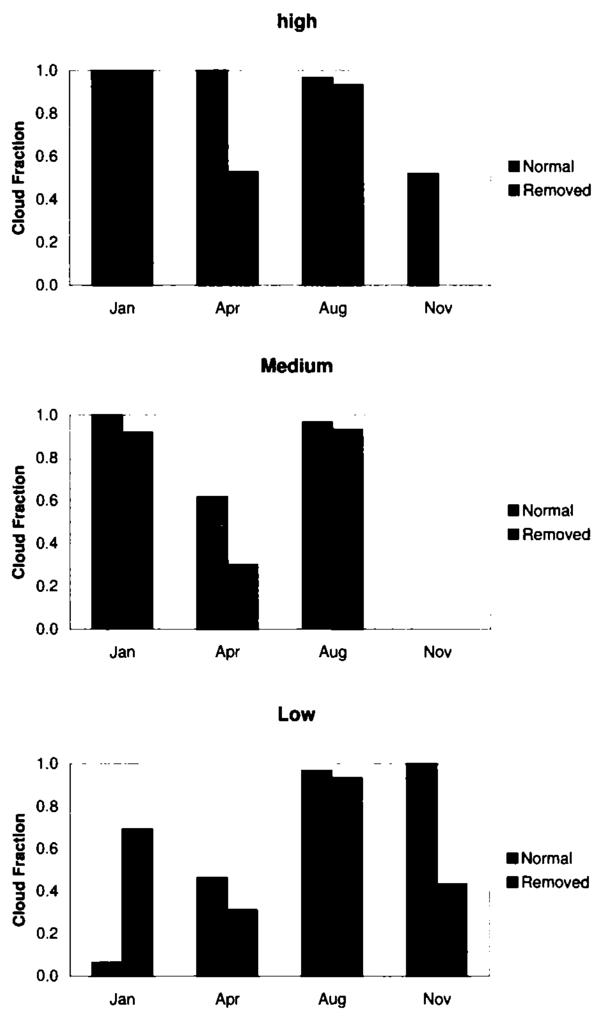


Figure 5.28: The variation of cloud amount over the Summit region during different season with and without orography.

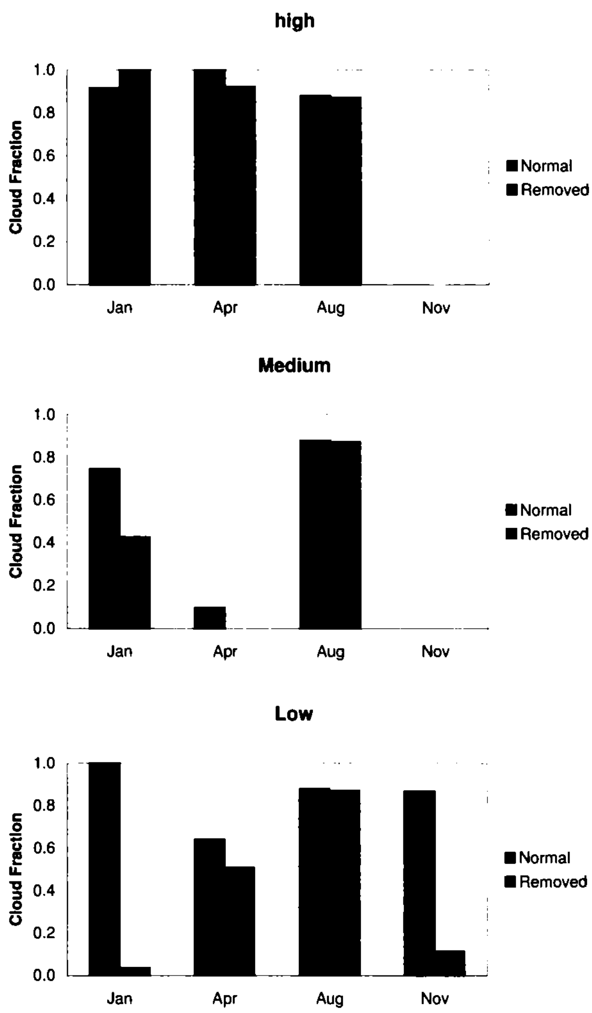


Figure 5.29: The variation of cloud amount over Tamilnadu during different season with and without orography.

PBL Variation

Generally when the orography was removed the PBL height increases in all season (fig.5.30). But in Kerala mountain helps to maintain the PBL height in the monsoon months while on the eastern side the effect is negative in those months. When the orography is removed the central part of the study region shows a variation of about 200 m increase in the PBL height. Thus Western Ghats negatively affects the formation of the PBL in the adjoining plain stations and over summit stations.

Frictional Velocity

As frictional velocity decreases the flow will be smooth over the terrain and increases the rainfall activity due to the smooth ascend of the air. Analysis of the frictional velocity by removing orography shows that the mountain's impact in frictional velocity varies dramatically in different season and with the altitude of the stations (fig.5.31). Over Kerala Western Ghats helps to reduce the frictional velocity and allows a smooth flow of the westerlies in the south-west monsoon. But generally the north-east monsoon period mountain imparts its effect on the atmosphere very clearly and try to increase the frictional velocity throughout the study region. it is found that over summit regions, Western Ghats interrupts the smooth flow of the air stream while in the eastern and western side of the mountain it helps to create a smooth flow during the Summer season. The change in the frictional velocity is very clear in the monsoon months than the rest of the months.

Latent Heat Flux

Western Ghats reduces the input of latent heat fluxes at the high range stations by about $30Wm^{-2}$ at a height of 1800 m in all season (fig.5.32). But on the western and eastern side of the mountain, it helps to increase the fluxes during most of the season. During Summer season the effects on both sides of the Western Ghats are just opposite. In Kerala

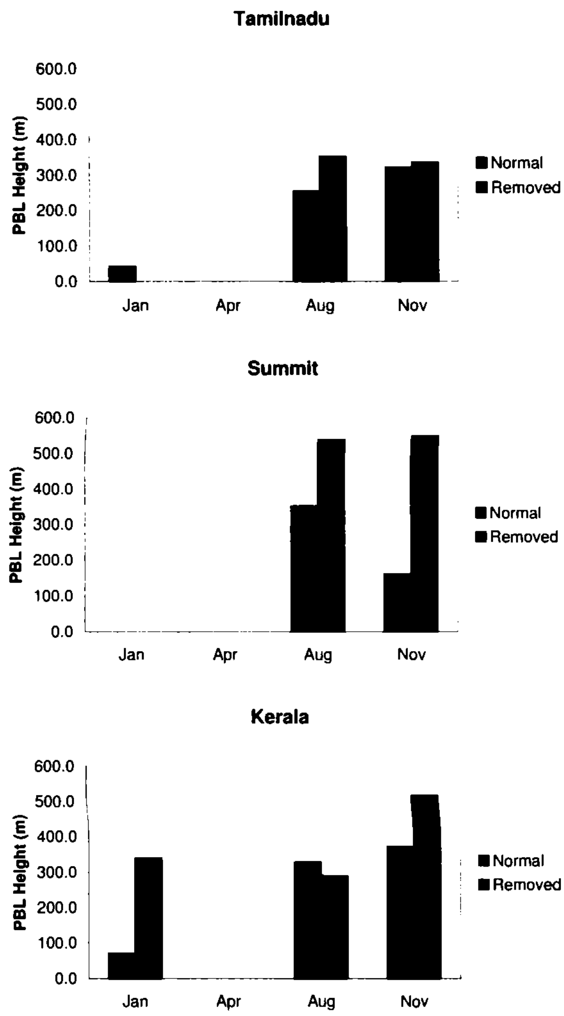


Figure 5.30: The variation of PBL height in 3 different stations (B1, B2, B3) along the cross section of 10.2°N latitude in different season with and without orography.

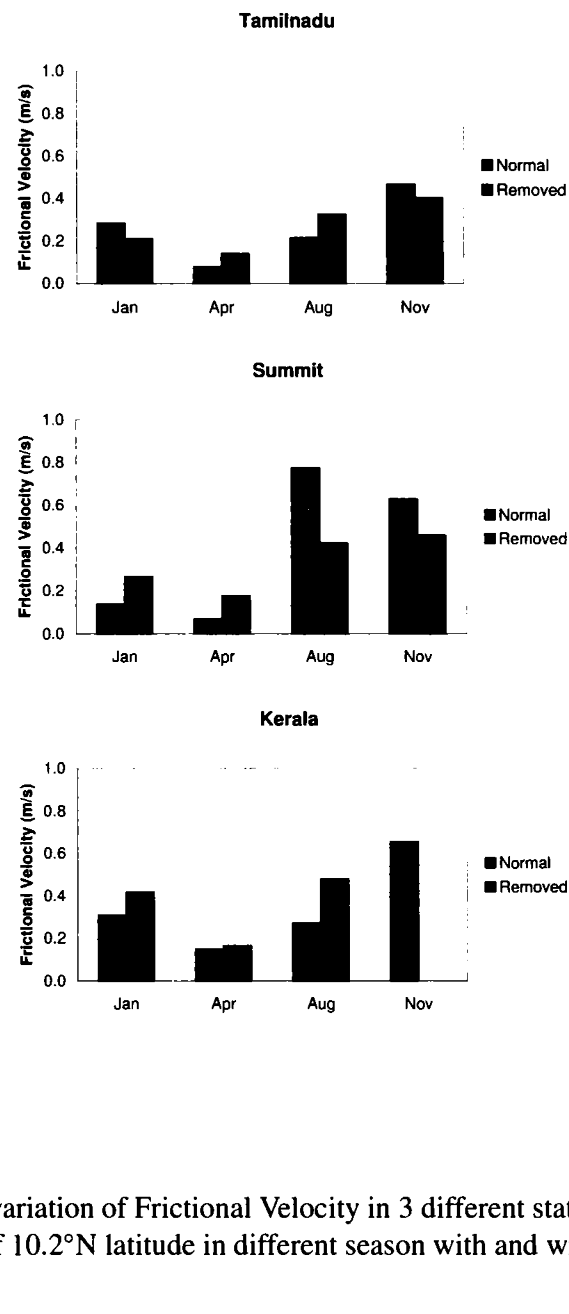


Figure 5.31: The variation of Frictional Velocity in 3 different stations (B1, B2, B3) along the cross section of 10.2°N latitude in different season with and without orography.

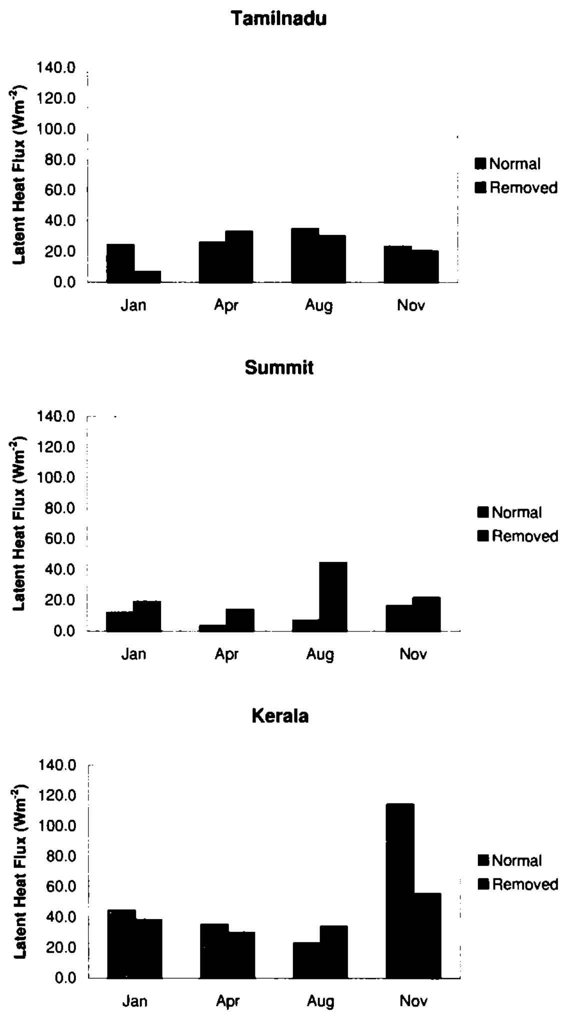


Figure 5.32: The variation of Latent heat flux in 3 different stations (B1, B2, B3) along the cross section of 10.2°N latitude in different season with and without orography.

Western Ghats reduces the latent heat flux while it helps to increase over Tamilnadu during Summer. During Autumn season Western Ghats raise the value of flux over Kerala to have a phenomenal increase by $60Wm^{-2}$ which really influences the weather pattern over those region. Thus it is seen that Western Ghats is playing a major role in controlling the latent heat fluxes over the region.

Sensible Heat Flux

Sensible heat flux variation at 0530 hours for the months representing different season are given in fig.(5.33). The negative value indicates that the heat flux moves from air to the underlying ground. Since the insolation is minimum at the time of analysis (0530 hrs LT) the flux values are negative throughout the region. The sensible heat flux exchange is minimum during Winter and Spring season. But the difference is prominent in all stations in Summer and Autumn. Western Ghats reduces the sensible heat flux input to the atmosphere in the south-west monsoon months, but during the north-east monsoon regime the effect of orography is more prominent.

Soil Temperature

The deviation (Removed-Normal) of the soil temperature at 10 cm depth is shown in fig.(5.34). It is clear from the figure that over plain stations in the eastern and western side of the mountain, the distribution of the soil temperature is not at all controlled by the Western Ghats much. But the terrain of 1800 m height reduces the soil temperature by a maximum of 11°C in Spring and a minimum of 8°C in Winter season. The change is exactly same at all levels (10, 40, 100 and 200 cm) of soil temperature over the summit.

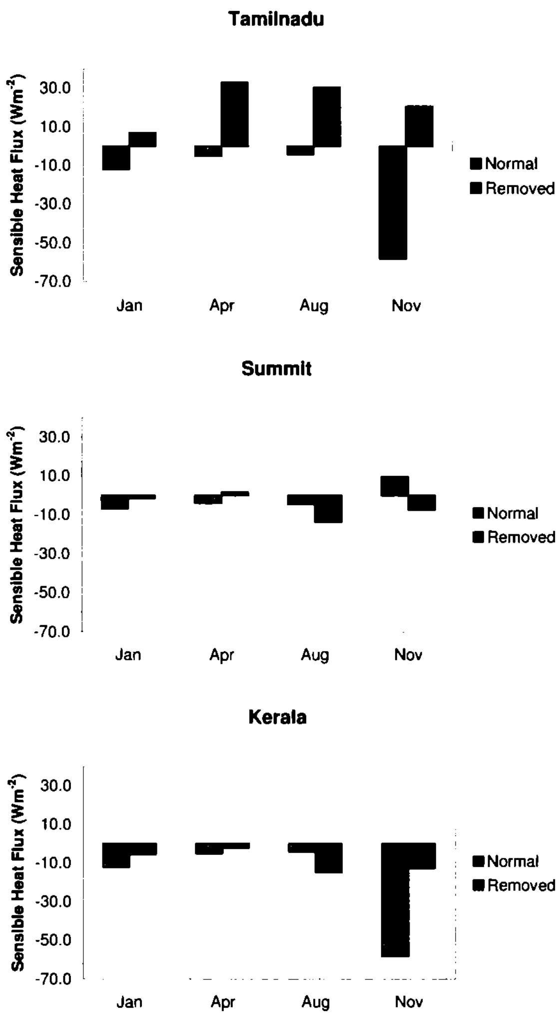


Figure 5.33: The variation of Sensible heat flux in 3 different stations (B1, B2, B3) along the cross section of 10.2°N latitude in different season with and without orography.

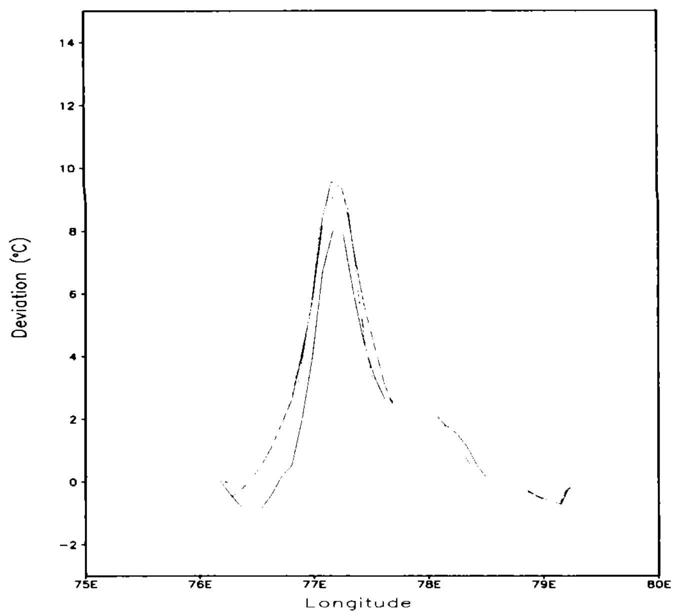


Figure 5.34: The deviation (No Orography-Normal) of Soil temperature at 10 cm level along the cross section of 10.2°N latitude in different season.

5.2.8 Rainfall

Model calculated the accumulative convective and non-convective rainfall for 48 hours with an interval of 3 hours. From this we can find out the precipitation rate of the region. The climatological mean of the observed total precipitation for the study region in different months are known. Thus the number of days required to reach this total rainfall amount with the model calculated precipitation rate can be calculated. These days are used to calculate the total precipitation of the study region derived from the model. The cross section analysis of rainfall along a latitude belt of 10.2 °N is given in fig.(5.35). The model simulates maximum of 250 cm of rainfall in Kerala at the coast and it reduces as we approaches the Western Ghats and it increases slightly at the Tamilnadu side and reaches a maximum at the east coast again (100 cm).

Here the model underestimated the rainfall in the windward side (Kerala region) and

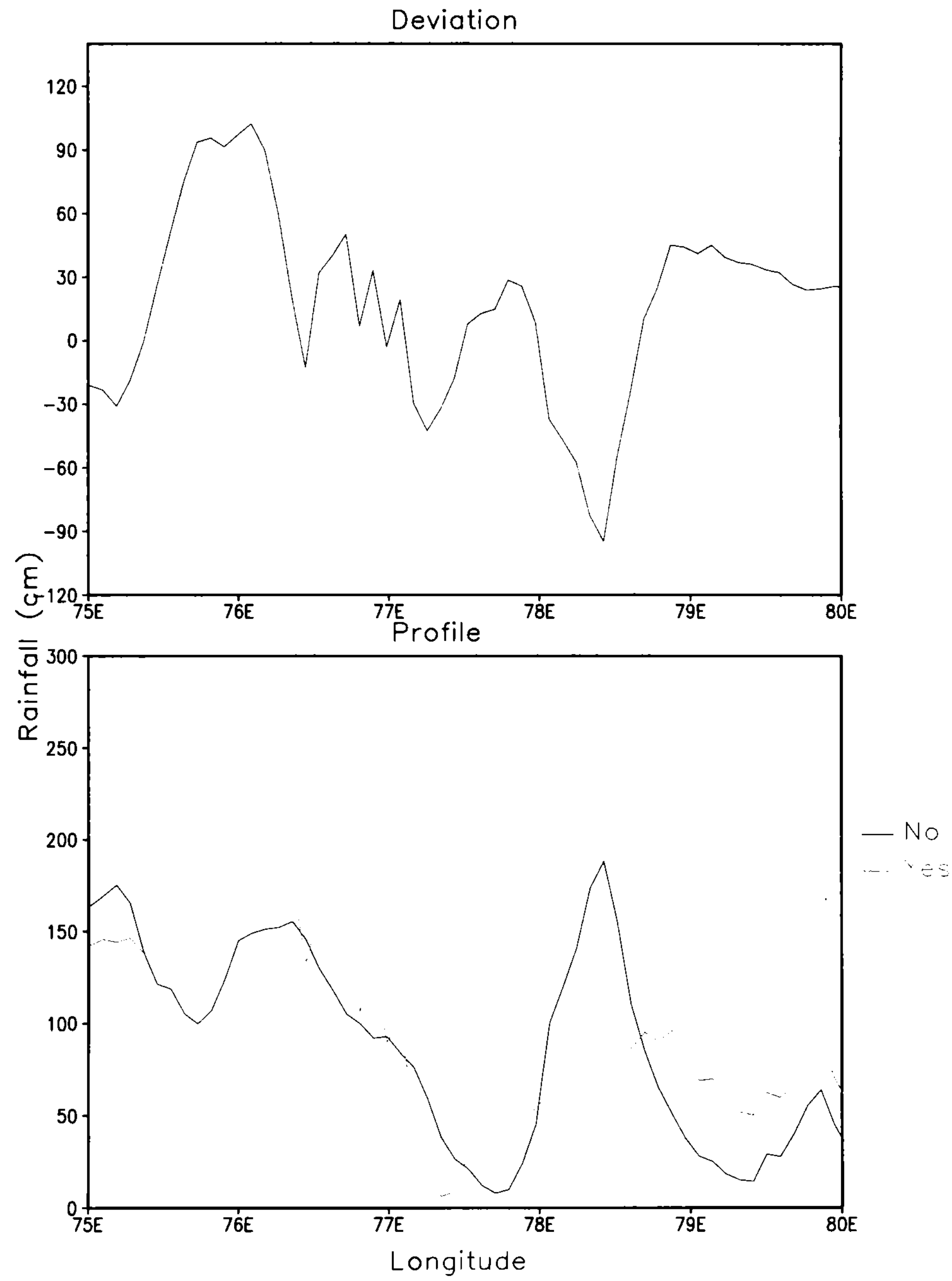


Figure 5.35: The cross section of total rainfall derived from the model with and without orography for the south-west monsoon season along the latitude belt of 10.2°N.

overestimated at the lee ward side (Tamilnadu region). When the orography was removed, the total rainfall in south-west monsoon rainfall shows a reduction over the plain stations over Kerala while the central longitudes receives more rainfall than the normal conditions. The notable point is that even when the orography is not there, there is a reduction of total rainfall to 77.8°E longitude which is the central part of the study region where the original orography was there. Which shows that between the coasts, there is a reduction of the rainfall activity at the mid-land region in the zonal direction. On the eastern side of the region, the influence of Bay of Bengal branch is very clear from the increased rainfall activity.

The changes in the rainfall amount of the normal and removed orographic cases can be very well understood if we do the analysis for different stations along 10.2°N (see table 5.1). Two coastal stations, two plain stations and one summit station have been selected

Lat	Lon	Stn	Normal	Removed	Diff.(m)	%
10.2°N	76.3°E	Kerala	211.9	152.2	59.7	-28.2
10.2°N	77.2°E	Summit	46.7	76.2	-29.5	63
10.2°N	78.2°E	Tamilnadu	83.7	141.1	-57.4	68.6
10.2°N	76.1°E	Ker.Coast	251.3	148.9	102.4	-40.8
10.2°N	79.3°E	Tam.Coast	51.9	15	36.9	-71

Table 5.1: Total South-West monsoon rainfall calculated by the model with and without orography for five different stations along 10.2°N.

for the analysis. A drastic reduction of coastal rainfall is observed at both coasts in the monsoon months. Rainfall at the Kerala coast reduces by 40.8% and 71% at Tamilnadu coast. Plain land of Tamilnadu shows 68.6% increase in rainfall when the Western Ghats is not there while it is 63% over the longitude where originally the mountain was there. But in Kerala, as we expected, a reduction of 28% is observed. Thus Western Ghats reduces the rainfall over the lee side of the mountain with a greater contribution of 68.6% while it enhances the rainfall activity over Kerala by 28%. In general the impact of Western Ghats over Tamilnadu is more than double that of Kerala.

5.2.9 Evaporation and Condensation

In the earlier sections of chapter 2, we have seen that the average variation of evaporation and condensation in every month over the study region. During Spring and Summer condensation is dominating over the region than the evaporation. Especially during the south-west monsoon months, both sides of the Western Ghats dominates with the condensation processes. But during Autumn the evaporation rate increases over the Kerala region.

The analysis in this section has been done by removing the Western Ghats terrain. The effect of the mountain on the evaporation or condensation processes is illustrated in fig.(5.36) with percentage increase or decrease from the normal condition. The analysis is carried out for 3 different stations located at western plains (Kerala), eastern plains (Tamilnadu) and a summit region (1800 m Anamudi hills) of the study area without the Western Ghats. In Winter season an increase of 41% is noticed in evaporation over Kerala and the summit region while the increase is 80% over Tamilnadu. During Spring 36% condensation increases in Kerala while a massive increase of 97% and 82% of evaporation is there over summit and Tamilnadu region successively.

During South-West monsoon months a reduction of 10% condensation activity over Kerala and an increase of 79% condensation is found at the 800 hPa level where the mountain peak was there originally. Tamilnadu shows a 14% increase in evaporation during this period. But in Autumn season a reduction of 32% and 19% is noticed at Kerala and summit regions respectively and an increase of 77% is observed over Tamilnadu.

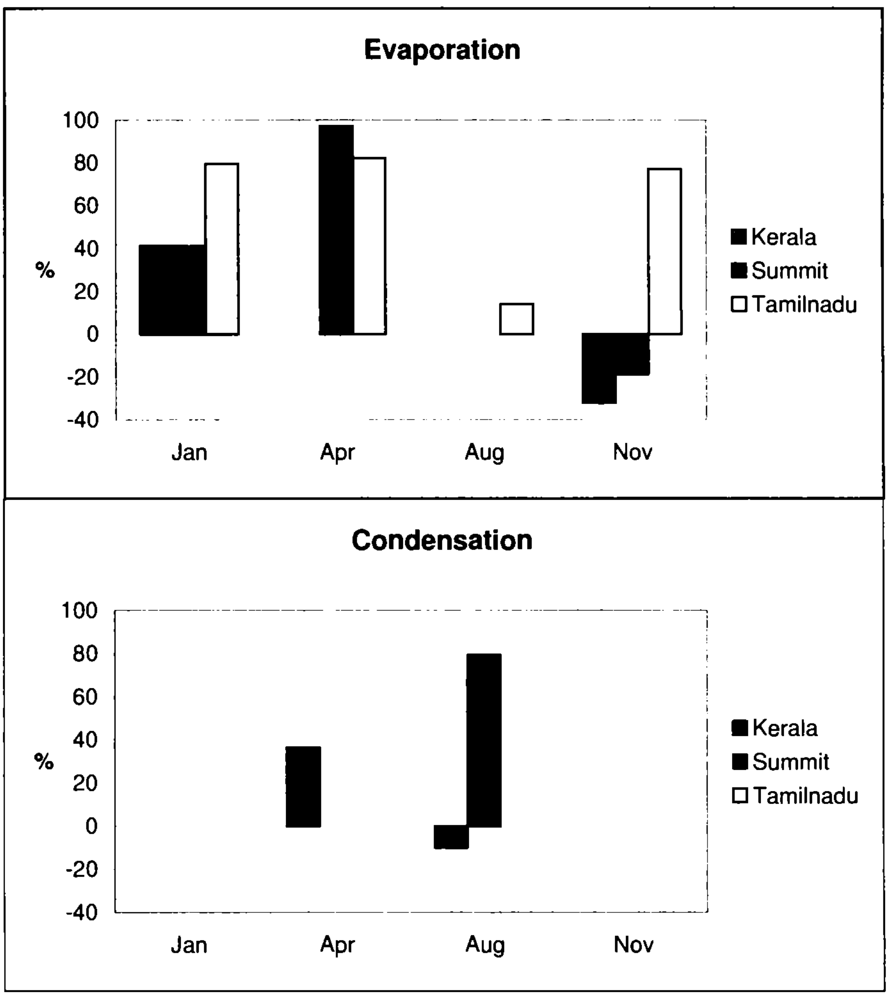


Figure 5.36: The percentage variation of evaporation and condensation over the study region during different season of the year without orography.

Thus Western Ghats suppress the evaporation activity over Tamilnadu throughout the months and in Winter over Kerala and summit regions. The control of the mounatin over the summit stations are very clear that the height of the stations totally brings down the evaporation activity over higher (800 hPa) levels. During south-West monsoon months the impact is opposite. Kerala experiance a reduction of condensation activity without orography shows the importance of the mountain in the rain making processes. Mountain also suppress the condensation activity at the peak of the summits as in the case of evaporation. Thus the maximum control of the mounatin in evaporation and condensation activity is at the summit region than the plain stations on both sides.

5.3 Change in Dynamical Factors Without Orography

From the earlier analysis it is seen that the dynamical factors like divergence,vorticity and kinetic energy depends very much on the terrain of the region. Absolute vorticity adjustments for crossing the wind over a mountain and the formation of the mountain anticyclonic rotations over the lee side of the mountains are analyzed in the earlier sections. It is of great importance to know the influence of Western Ghats over the divergence and vorticity field of the region.

Divergence

Over Kerala stations, the divergence in the wind field is found to be increasing from Winter to Spring and it is very small value in the Summer season (fig.5.37). Again in the Autumn season convergence increases drastically over the summit. But over Tamilnadu convergence is dominating in all season and its magnitude is more in Winter and Spring. The removal of the orography from the study area creates large changes in the divergence pattern. We can see that whenever there is a divergent field, It is converted to a convergent area in the

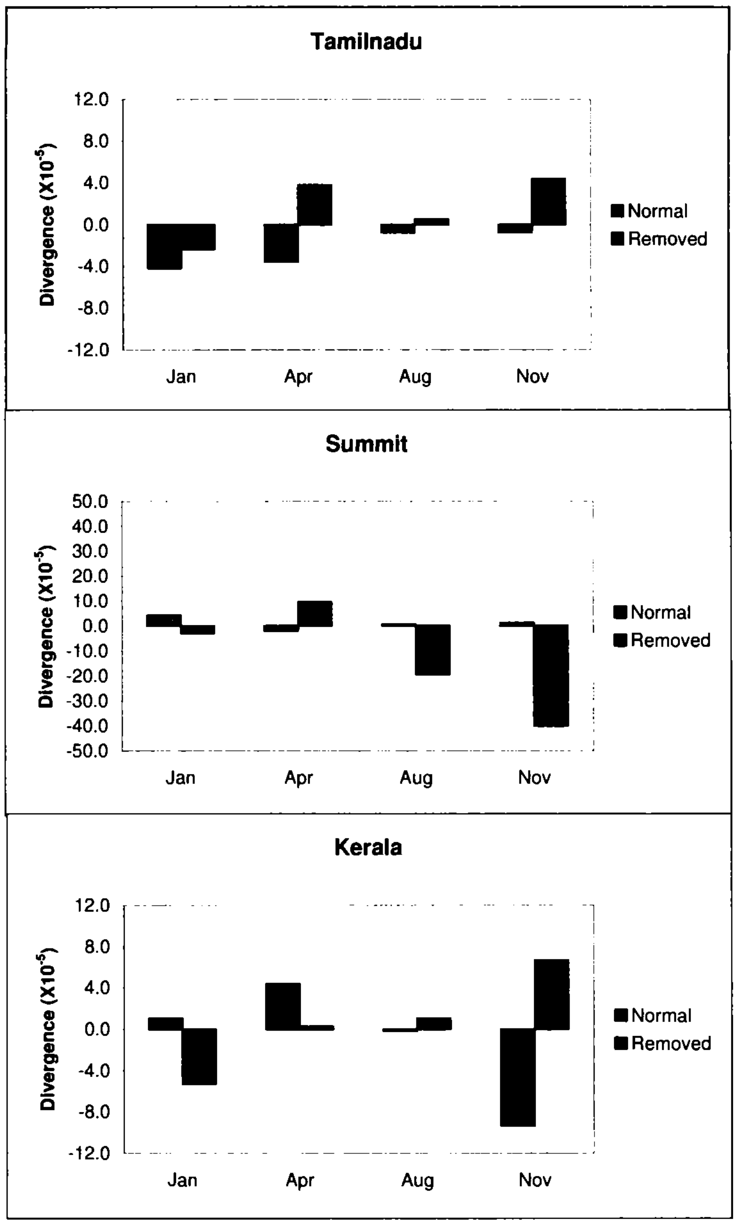


Figure 5.37: The variations in divergence above three stations in the study area representing two plain stations and one summit station in different season.

absence of Western Ghats. Thus the mountain redirects the wind field over the area to a large extent. Impact of mountain is very dominant in Autumn and least in Summer season. During the south-west monsoon months the convergence increases at 800 hPa level without orography. Thus at that level the effect of orography is very clear than the lower layers over plain stations. Also Western Ghats is having an upper hand with the north-east monsoon winds than the south westerlies.

Vorticity

Very similar to the divergence field the vorticity also changes when the orography is removed (fig.5.38). The change is large over the summit regions. It is seen that when the Western Ghats orography is removed the vortex field become more anticyclonic and its strength is more from Spring to Autumn over the central and eastern part of the study region. The impact of Western Ghats is very dominant during the Spring season than any other season over the study region. The effect of the mountain is minimum over Kerala than Tamilnadu. Also over summit stations the impact is 2 times higher than the eastern side and 4 times higher than the western side of the mountain.

Turbulent Kinetic Energy

The variation of turbulent kinetic energy over plain stations in the study area is not found to be any relation with the terrain over the region. In normal and removed orographic runs it shows almost a constant value of 0.2 JKg^{-1} for the entire study region. The turbulent kinetic energy is mainly depending upon the flow characteristics of the airflow. It is seen from the analysis that the impact of mountain in changing the flow characteristics is very nominal throughout the region except the major Gap regions like Palghat and Aryankavu.

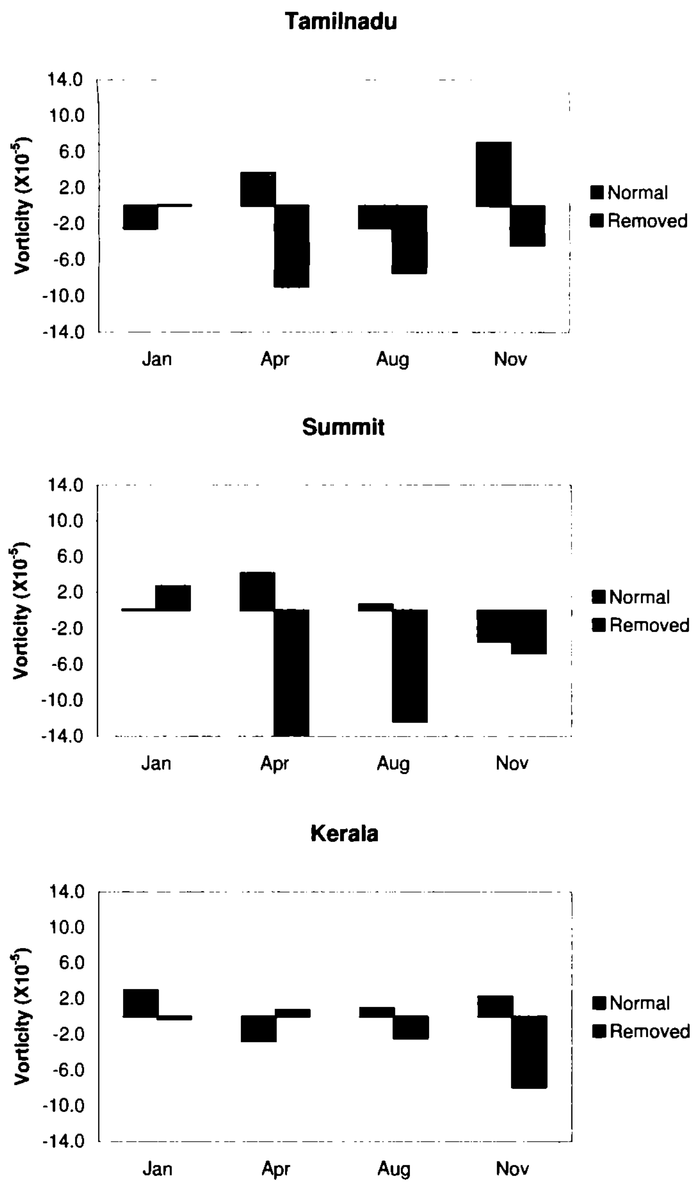


Figure 5.38: The variations in vorticity above three stations in the study area representing two plain stations and one summit station in different season.

5.4 Impact With Filled Palghat Gap

Palghat Gap is the major discontinuity existing across the Western Ghats and its effects on the weather and climate over the region in and around the Gap is very clear from the earlier analysis. The increase in the dynamical pressure, subsidence of air over the mouth of the Gap, temperature and wind modifications at the upwind and downwind regions of the Gap, the rainfall pattern over the region are all causing due to the tremendous influence of the Gap over the adjacent places. The fanning out of the wind at the down wind regions of the Gap is causing rainfall variability to parts of the Coimbatore district itself.

Variations of Surface Meteorological Parameters with filled Palghat Gap

Palghat Gap is a major discontinuity of about 25 km wide across the Western Ghats over the study region and which connects the Palghat district in Kerala and Coimbatore district of Tamilnadu. From our earlier analysis we have seen the impact of the Gap over the near by region on both sides of the Gap. In this analysis the model run has been given by closing the Gap and the variations of the basic meteorological parameters over two stations (10.7°N, 76.2°E & 10.7°N, 77.4°E) situated about 35 km away from the mouth of the Gap on both sides are observed. The variations of the parameters from the normal condition is expressed in percentage for the easy understanding of the analysis. The difference is taken as filled minus the normal condition. The positive percentage means the Gap negatively controls the parameters and if it is negative the Gap plays a positive role in maintaining the higher value of the parameters in normal conditions.

When the Gap is closed, the temperature (2m height) of the region near the Gap on both sides of the mountain experiences unusual reduction in all season (fig.5.39). During Winter and Spring Kerala shows more reduction in temperature than Tamilnadu while it is reverse on the south-west and north-east monsoon months. A maximum reduction

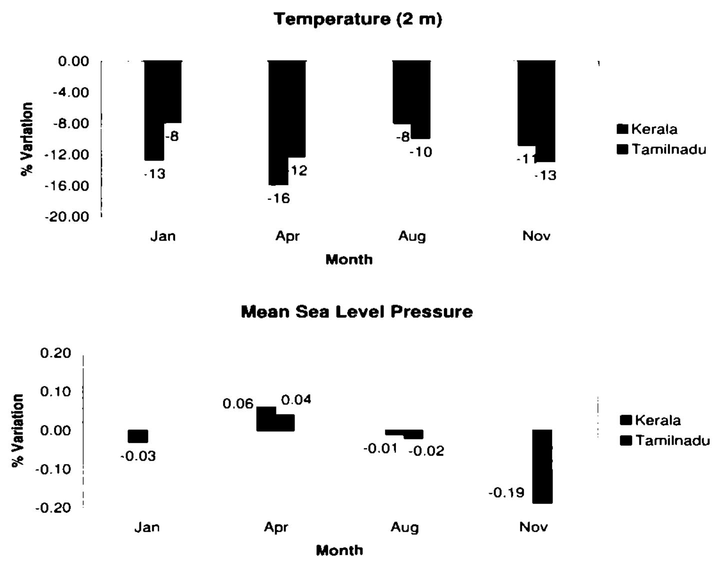


Figure 5.39: The percentage variations of 2m temperature and mean sea level pressure at 35 km from the mouth of the Palghat Gap on both sides during different season when the Gap is filled.

of 16% for Palghat and 13% for Coimbatore is occuring in Spring and Autumn season. The reduction in the pressure is very nominal when compare with the temperature. The maximum variation is 0.2% only in any season. Like the temperature pattern, the change is more in the Kerala side in Winter and Spring while it is in Summer and Autumn over Tamilnadu.

Variations in wind speed is much in Kerala than Tamilnadu due to the Gap (fig.5.40). Due to Bernoulli's effect, Palghat Gap reduces the wind speed over the western side (up wind region) by 61% which is the heighest for any season on both sides. Over the eastern side (up wind region) it reduces the wind speed by 33% which is just half of the Kerala side. During Winter and Autumn season Gap helps to gain the wind speed over Palghat (down wind region) by about 45% while it reduces again the wind speed by 29% over the

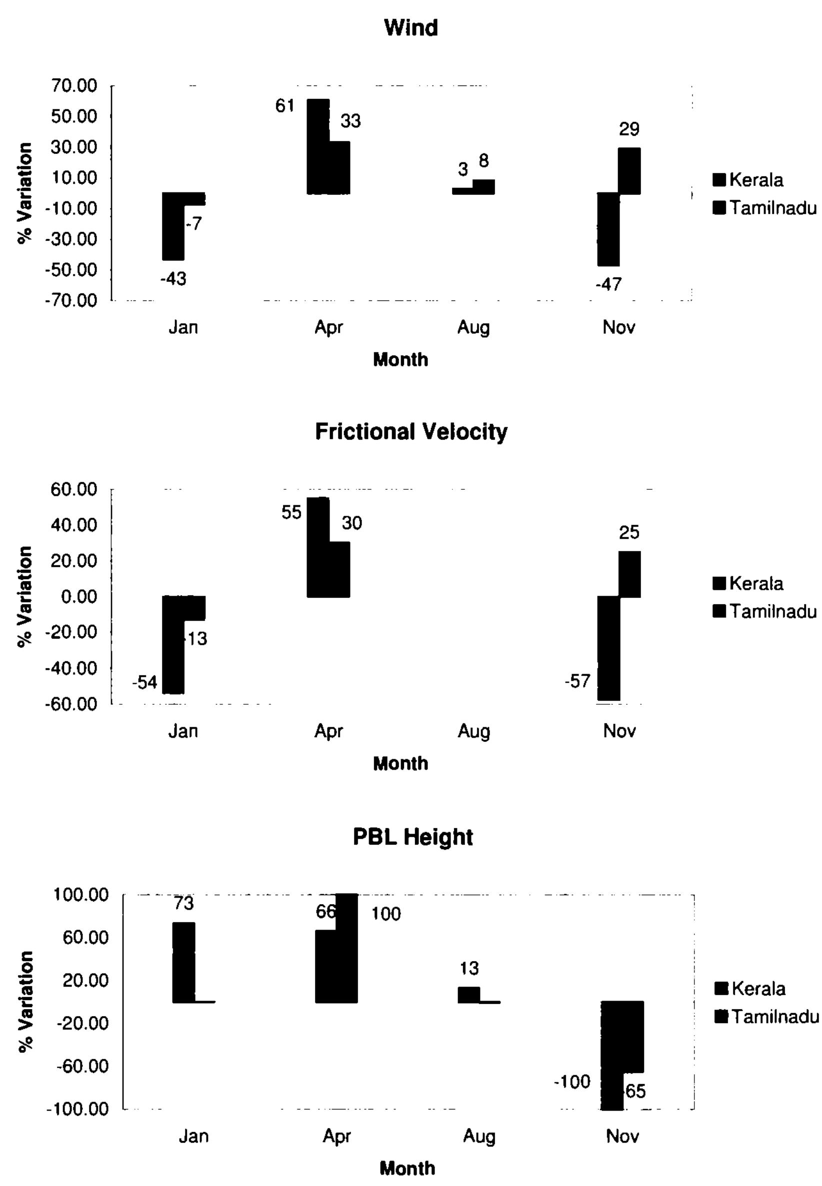


Figure 5.40: The percentage variations of wind, frictional velocity and PBL height at 35 km from the mouth of the Palghat Gap on both sides during different season when the Gap is filled.

eastern part of Coimbatore district. During south-west monsoon months the control of the Gap over the wind speed looses and the mean variation is only 5% over the region. On an avaerage 55% of the frictional velocity is created by the Gap over the western side during the Autumn and Winter season and 25% reduction over eastern side during Autumn. During Spring season Gap controls the frictional velocity considerably over both sides. But there is absolutely no control during the south-west monsoon months. Gap reduces the PBL height in all season except Autumn on both sides of the mountain. During the Autumn season a considerable increase in PBL height (about 100% in Kerala and 65% in Tamilnadu station) is observed due to the effect of the Gap.

Palghat Gap is not suppressing the rainfall activity over Kerala station except the stations near the exit mouth in all season while it is reverse in the case of eastern side (fig.5.41). There is a suppression of the rainfall activity even at 35 kms away from the Gap

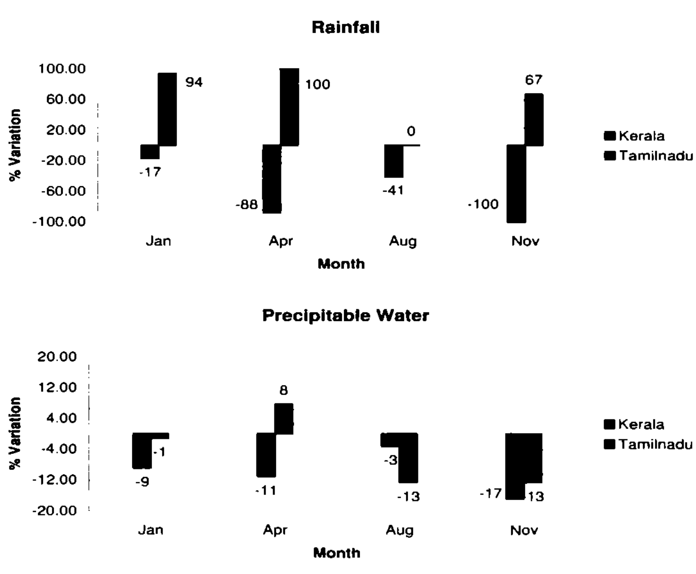


Figure 5.41: The percentage variations of rainfall and precipitable water at 35 km from the mouth of the Palghat Gap on both sides during different season when the Gap is filled.

which shows the effect of the intense subsidence over that region. But over Kerala the effect is very less when compares with Tamilnadu. The variation in the precipiatable water content is also very less (17%) over Kerala as in the case of rainfall when the Gap is filled. Palghat Gap always tries to keep the precipitable water content high on both sides of the Ghat. Thus it regulates the advection of the moisture through the Gap in a uniform pattern, but the condensation activity is reduced due to the intense subsidence over the eastern part of the Gap at the Coimbatore district.

Gap reduces the latent heat flux transfer over both sides of the Ghat in most of the months (fig.5.42) while it is enhancing the latent heat flux transfer at the Kerala station

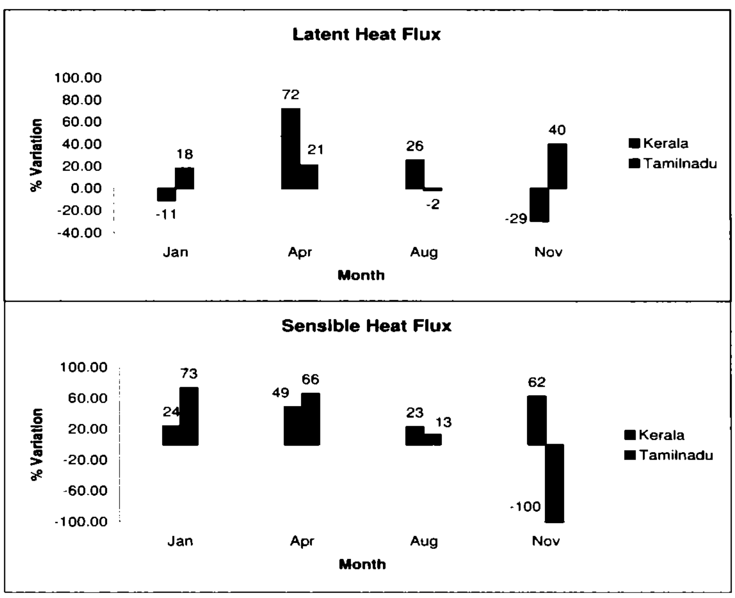


Figure 5.42: The percentage variations of latent heat and sensible heat flux at 35 km from the mouth of the Palghat Gap on both sides during different season when the Gap is filled.

during Autumn and Winter season. But during Spring 72% reduction in the latent heat flux is occuring over Kerala side. Due to the Gap sensible heat flux is increasing over the eastern side of the study region while it is reducing at the western side of the Gap. We found from the earlier analysis that the sensible heat flux input at the mouth of the Gap is creating higher temperatures over the region espaecially during Spring and Summer. But this happens very near to the mountain Gap only where the elevated land mass around the place is causing the increase of the sensible heat flux. Thus it is clear that the rise in temperature is also the impact of the Gap and it locally changes the temperature pattern near to it even when the advection of the heat fluxes are there over the other region.

5.5 Conclusions

The influence of the Western Ghats orography over the various meteorological parameters can be very well be studied if we remove the orography from the study region and observing the variation from the normal condition. Since we have applied same data set with same resolution and used same boundary conditions except the terrain, the variations in the parameters will be solely due to the presence of the mountain. When the orography is removed the isobars became parallel to the coast and a trough region is forming over Tamilnadu. There is a general reduction of pressure by 1.5 hPa throughout the study region and along the longitude of mountain regions the mean reduction is about 5 hPa. The variation is minimum in Kerala and maximum over Tamilnadu. So the effect of Western Ghats over the pressure pattern is more in Tamilnadu than Kerala and this may be due to the more spread of the mountain ranges over Tamilnadu. The isobars are more curved in the study region in all season except Summer when the orography is not there. Western Ghats do not interact with the diurnal change of the pressure in the region.

The variation of the temperature over the region is controlled by the mountain to a great extent. When the orography was removed the isotherms become parallel to the coasts and there is a kink of the isolines at the southern end of the study region as in the case of pressure. Generally speaking when the orography is not there, the temperature gradient is accumulating to the coastal regions otherwise it would have been over the mountain region. The isotherms will be more north-south oriented in the absence of the mountain. No variation is seen in the diurnal pattern of temperature over the region. The maximum variation in the vertical is about 2.5°C at the 700 hPa level without orography.

The mean deviation of the air temperature at the surface shows a uniform pattern over the region and it reduces the deviation over Tamilnadu. Hence Western Ghats is responsible for the increased mean deviation of the temperature over the eastern region and the effect is meager in the western side of the mountain. The variation in the soil temperature is also minimum over the plain stations when the orography is removed and it indicates that the control of Western Ghats in soil temperature flux at the plain stations are nominal. In general the height of the mountain makes the temperature pattern more complex over the region and without it the patterns would have been more uniform.

The diffluence pattern of the wind over the summit region is mainly created by the mountain peaks. When the orography is not there, generally the wind speed will be uniform like other parameters over the study region but the value will be 1 ms^{-1} higher than the normal condition throughout the region horizontally. In vertical, wind speed found to increase in Spring season in the upper troposphere by 3 ms^{-1}. In Autumn the depth of the minimum wind speed region increases over the summit longitude when the mountain is removed. The diurnal variation of the wind is not at all controlled by the mountain. Thus Western Ghats modifies the wind over the region more in the vertical direction than the horizontal. Frictional velocity also will be uniform over the region, but 0.1 ms^{-1} higher than the normal value when the mountain is not there.

When the orography is removed the value of RH increases over Kerala during Spring and in Summer over Tamilnadu (-20 to 20 %). Thus generally Western Ghats helps to maintain the high value of RH over plain stations on both sides. During Summer season the modification is minimum throughout the region. Mountain's control over the modification of RH is confined to the Planetary boundary layer only. A reduction of 2.3 kg kg^{-1} of precipitable water is occuring at the height of 1800 m terrain over the summit.

During the winter Western Ghats maintains the net radiative flux over plain stations on both sides while in Spring it gives a huge surplus of 150 Wm^{-2} over Kerala and without any input to Tamilnadu. Western Ghats controls the low and medium cloud formation of the study area to a great extent without any relation with the high cloud formation. It negatively affects the formation of the low clouds in the entire study area in Autumn season. But over summit regions Western Ghats plays a major role in the formation of all types of clouds.

Western Ghats negatively affects the formation of the PBL over the region in all season especially in the monsoon months. Eventhough the Western Ghats retards the smooth flow of the wind over the summit regions, in general it helps the smooth flow over the plain stations on both sides. The latent heat flux also is controlled by the Wesern Ghats dramatically. Plain stations on both sides receive more latent heat flux due to the presence of the mountain. As in the case of the sensible heat flux mountain's impact is less in Winter and Spring and maximum during Autumn when it helps the atmosphere over plain stations on both sides to give back energy to earth's surface. The soil temperature at the plain stations on both sides are not at all controlled by Western Ghats in the region.

Estimation of the monsoon rainfall with a mesoscale model will have its own difficulties. In this study, MM5 under estimated the total rainfall in a season over the western side and over estimated at the other side of the mountain. Over Kerala a maximum of 250 cm and in Tamilnadu about 100 cm of rainfall is predicted by the model for the south-west monsoon period at the coast. Still a qualitative study can be make with the model results. When the Western Ghats was removed, the rainfall over Kerala plains have reduced by 28% and an increase of 68.6% is noticed over Tamilnadu plains. Rainfall activity on both coasts reduces drastically without orography and the values are 40.8% for Kerala and 71% for Tamilnadu. Summit longitudes will get 63% more without orography. Thus in the case of precipitation, Tamilnadu is affected severly due the Western Ghtas than Kerala and the orography reduces the rainfall activity over summit stations in the Western Ghats even the precipitation rate is higher over the mountain.

Western Ghats suppress the evaporation activity over Tamilnadu throghout the year and in Winter over Kerala. Condensation activity reduces over Kerala in south-west monsoon months when the orography is removed. This shows the importance of Western Ghats in the rainmaking process. Also the maximum control of the mountain on the evaporation activity is on the summit region than the plain stations in the study area.

The divergent areas are converted into convergent when the orography was removed. Western Ghats is having a major role in north-east monsoon winds than any other season in the case of divergence. Similarly when the mountain is removed, the variation in the vortex field over the summit is 2 times higher than Tamilnadu region and 4 times more than Kerala. Thus it is clear that the effect of the Western Ghats are more over the eastern side of the mountain than the western side in the case with vorticity. The transfer of the turbulent kinetic energy over the plain stations on both sides have less dependence on the Western Ghats. Hence we can infer that, over the main land on both sides in the study region the flow characteristics are not changing much by the mountain and it takes the control only over the summit region and that also more in the vertical direction.

When the Palghat Gap is closed the reduction in the air temperature near the ground is noticed on both sides of the Gap. A maximum reduction of 16% over Palghat and 13% over Coimbatore is there in the Autumn and Spring season. The variation in the surface pressure is nominal. Due to Bernoulli's effect the wind speed is reducing over Palghat by 61% and over Coimbatore by 33% when it is in the upwind regime. The gain in the speed of the wind is found to be 45% over Palghat and no variation during the downwind regime over the eastern station which is 35 kms away from the mouth of the Gap in a strait line along the centre of the Gap.

Palghat Gap is not suppressing the rainfall activity much over the western side in all season but the case is reverse on the eastern side. Subsidence is intense over the eastern side. Gap supresses the latent heat transfer on both sides of the exit region in most of the months while it is enhancing over Kerala during Autumn and Winter season. Gap also changes the temperature pattern near the exit mouth region of the Gap appreciably.

CHAPTER 6

Summary and Conclusions

Western Ghats separates the states of Kerala and Tamilnadu by passing through the study area with an orientation of SE to NW with a length of about 700 km and an average height of 1 km in the study region. There is two Gaps for this mountain ranges in the study region, which is called Palghat Gap and Aryankavu Gap. Palghat Gap is a major Gap of about 25 km wide and connecting the Palghat and Coimbatore districts centered along the latitude belt of 10.7°N. While the Aryankavu pass is situated more southward along 9.04°N connecting the Kollam district of Kerala and the Madurai district of Tamilnadu. This pass is about half the width of Palghat Gap and the length also is very small.

The study region of the present research work extends from 8°N to 14.5°N and 75°E to 80°E. The southern part of the study region is very narrow and the terrain is less than 1000 m height which is known as the Cardamom hills or the Agasthya range. As move northwards, the height of the mountain increases. The highest peak in the Western Ghats is known as Anamudi in the Anamalai range. The height of the Anamudi is 2677 m and then it sharply decreases towards the Palghat Gap. In the north of the Gap, the terrain sharply increases and reaches the second highest mountain ranges in the Western Ghats known as Doda Beta of Nilgiri range which is about 2647 m. The northern part of the range is merging with the southern tip of the Deccan plateau. At those latitudes the slope in the western side of the mountain is sharp and it slowly declines as part of small mountain ranges in the eastern side.

The average distance of the coast from the 200 meter terrain of the Ghat in the western side is 100 km and that at the eastern side is about 200 km. The proximity of the high slope mountains in the western side especially at the northern end of the study region in Kerala is beneficial for the places thereby getting torrential rain in the major rain giving months of south-west monsoon. Eastern coast of the study region is in the regime of tropical cyclone and getting rainfall during the passage of these tropical systems through Bay of Bengal. Thus both sides of the Western Ghats are constantly influenced by Arabian Sea and Bay of Bengal and the ocean-land interaction is playing a major role in the weather and climate of the region as a whole. The high mountain ranges passing through the study area is also imparting its own influence on the climate system of the area and modifies the weather pattern in different seasons.

Since the study area covers by 5°latitude in the north-south direction, the variation of the surface meteorological parameters in the meridional direction is very small. Maximum variation is occurring due to the altitude of the stations. Spatial distribution of the temperature of the region shows that the northern part of the study area is cooler than the southern region generally. During the south-west monsoon months the western coast will be cooler than the eastern side of the mountain. The diurnal variation of temperature shows a marked difference in the north-south direction. The maximum temperature is not persisting for long hours in the southern stations. In summit regions, the persistence of the maximum temperature is only for short period and decreasing thereafter. Mean deviation of temperature in the Winter and the Spring shows that there is sudden change in the atmospheric temperature after crossing the Western Ghats from west to east. A critical level of 1200 m height is influencing the temperature of the air column to great extent and above that level a mountain type of temperature variation can be seen over Western Ghats. Penetration of the monsoon rainfall reduces the subsurface soil temperature at 10 cm level in Kerala, also seen at summit region but with reduced intensity and not at all seen over Tamilnadu.

In the study region, the horizontal variation of the mean sea level pressure in the plain land is minimum. But along the high terrain the variation is maximum. As the elevation increases the mean sea level pressure also increases over the region. Since the density and the temperature over the summit stations in the Western Ghats are slightly higher than the surrounding free air, the mean sea level pressure is found to be higher than the plain land. Due to the steepness of the terrain, the value of the pressure gradient will be higher in the western side of the mountain than the eastern side and this difference in gradient between western and eastern side of the mountain is maximum in Winter than any other season. The semi-diurnal pressure wave is very clear in all stations in the region and the amplitude of this wave is about 1 hPa every where. The amplitude is same for both oscillations during the day and the phase also matches with the temperature variation.

The presence of strong westerlies will be there over the study region for the 5 months in an year. The easterlies coming over the eastern side of the study region finds the Palghat and Aryankavu Gaps for a smooth passage to the western side of the mountain. Northerlies also will be channelized towards more southern latitudes by the Western Ghats. The strengthening of wind over the region is seen between 1130 and 1430 hrs LT in a day. Wind speed generally increase from May onwards and it has a dramatic reduction during October in most of the stations. November also brings strong winds over the eastern region of the mountain. the average annual wind speed is found to be 3 ms^{-1} over Kerala, 4.8 ms^{-1} over Tamilnadu and 5 ms^{-1} over the summit regions. The zonal component of the wind is stronger than the meridional component throughout the region in most of the season and it undergoes larger variability than the meridional. Summit regions are characterized by the undulating high winds.

Variation in the seasonal pattern or spatial pattern of vapour pressure is very small over the region. Palghat Gap plays a major role in transporting the vapour to the mouth of the Gap on both sides. The relative humidity value rarely goes below 60% over the region except in Spring season over the summit. There is an increase of 0.005 kg m^{-3} density over the summit region. A small increase in RH is seen in the after noon hours over the study area which is a slight change from the midlle latitude mountain environment. RH increses with height over all stations in the Winter season.

Summer and Autumn season creates a blanketing effect on the study region by generating more clouds and a reduction in the net radiative flux. Summit region also shows a reduction in the net radiative flux due to the increased clouding. As far as the noctural radiation is considered, the eastern side of the Western Ghats is found to be cooling faster than the western side in the night time. Presence of low cloud are more throught the study region and a higher concentration is seen in particualr at the summit region. A small diurnal variation can be seen for low and medium clouds and none for higher clouds in the study region. The surface meteorlogical parameters predicted by the model has been undergone ground truth check and the result is encouraging.

The potential vorticity adjustments makes the circulation around a summit more complex. The wind blowing at the surface level should have a minimum energy to over come a mountain in its flow path. But usually in the upper levels there will be a layer of air, that will try to cross over the mountain. During this process the potential vorticity readjusments will occur for the air flow and it will create a diffluence pattern of wind over the summit region and thereby creates cyclonic and anticyclonic vorticities over the mountain peaks. These patterns are quite visible over the Western Ghats in all season. It is generally called the curvature effect due to the generation of rotation of the flow over the region. It is found that the Coriolis adjustments are one order less than the vorticity adjustments over the mounatin in the Western Ghats. Hence the curvature effect is more dominant over the region.

Western Ghats modifies the synoptic scale meteorological parameters like relative humidity and temperature over the windward side. Ascend of air over the windward side creates more humid condition and the temperature is reduced by 2 to 3°C when compared with the lee side. All these changes makes considerable variations in the climate of the adjoining areas. Similarly an objective criteria has been developed for the surface air flow to cross over the Western Ghats. The condition prescribes that (1) *there should be a minimum wind speed of 12* ms^{-1} *at 950 hPa level* (2) *the minimum potential temperature of the air should be 28°C* and (3) *the positive vertical wind shear should be there from surface to the height of the mounatin.*

The parameters like Froud's number, Scorer's parameters are calculated for the months having high wind speed to know about the capacity of the air flow to make a hydraulic jump over the Western Ghats. It is found that only in July all the three conditions are satisfied and the possible wavelength of the lee waves have been found as 55 m during that period. Capturing of lee waves in the model is very difficult with this resolution of the data. The chances of the formation of lee waves on the easterly regime is found to be a rare event over the Western Ghats.

The modification of the wind by the peaks are common over the Western Ghats region. The accumulation of the pressure gradients and the wind pattern towards the left side of the ridge of the Western Ghats are common and this is called the Corner effect of the mountain by Bergeron in the mid-latitudes. These corner effects are developing both in the westerly and easterly regime over the mounatin and creates unusal gusty winds over the valley regions. The developement of Fohn wind over the Western Ghats mountain region is found during the day time and it increases the potential temperature and reduces the relative humidity pattern over the lee side. These conditions disappear within hours in a day over the mountain.

Like Fohn wind, the developement of Anabatic and Katabatic wind systems are also very prominent over the Western Ghats region. The maximum wind speed of 2.1 ms^{-1} is seen for the gravity flows over the valley region. This occurs at the 10 m level. The calculated value of the gravity flows using the Reiher's formula is 2.6 ms^{-1} which is very near to the model value. Thus the night time Katabatic and day time Anabatic wind systems are creating a high wind zone over the valley regions of the Western Ghats in all season.

The modification of the winds by the major Gap like Palghat is phenomenal. Palghat Gap reduces the wind speed over the upwind mouth and increases over the peripheral of the downwind mouth. The annual mean wind speed is calcualted by the model through the Palghat Gap is about 3 ms^{-1} at the surface. A fanning out of the wind is observed near the bounadry of the mouth at the downwind side. The adjustment of the dynamic pressure and staic pressure of the air flow through the Gap creates intense subsidence over the down wind side and which inturn causes the reduction of the rainfall activity over that region. In this regard Coimbatore faces much problem than the Palghat side because of the high wind speed of the Westerlies. The arid condition is severe over Coimbatore and which is not that much even in the extream bounadry of the funnel mouth of the Gap.

The net radiative flux shows there is a surplus amount of about 700 W m^{-2} over most of the region except during Summer. Summit faces an unusal deficit of net radiative flux during the Spring season, which can also be attributed to the formation of clouds. The energy budget of the region shows that the availbility of the latent heat flux will be half of the net radiative flux value and that of sensible heat is quarter times. The diurnal pattern in the variation of the net radiative flux is also there in the region.

Observed rainfall data of IMD shows that Kerala is getting about 298 cms of annual rainfall whereas it is only 94 cms for Tamilnadu. Only in December the rainfall in Tamilnadu exceeds that of Kerala by about 15 cms. The long term trend in rainfall indicates that the rainfall over Kerala is decreasing by about 2.4 mm per year, whereas Tamilnadu annual rainfall is decreasing at the rate of 1.4 mm per year.

The slope of the Western Ghats shows that the maximum slope is at the Western side of the Anamalai hills over Kerala (75.9°) and on the eastern side it is around 73.7°at the eastern side of the Nilgiri hills. The Malayattur-Neriamangalam stretch is having a slope of 14.5°and is quite favourable for the rainfall activity. Along the Gaps, the rainfall is found to be decrasing dramatically with height. The relationship between the rainfall and the terrain height in the Western Ghats region shows that more rainfall in the windward side of the Western Ghats (Kerala region) is getting at the medium class (between 200-600 m) whereas in the eastern side it is in the high class (between 600-1000 m). The coastal rainfall shows a high negative correlation of -0.8 with the terrain of 1000 m or more over Kerala and -0.5 in Tamilnadu. This shows that the rainfall decreases as the high terrain moves away from the station. The increased rainfall activity over the northern Kerala during south-west monsoon months are due to the influence of these terrain effect.

Spatial variation of the rainfall over the region is complex due to the orographic effect and also due to some other dynamical reasons of the air flow. Over Kerala there is an increase of 270 mm per deg latitude and over Tamilnadu 5 mm per deg latitude of rainfall is seen during the south-west monsoon period from south to north of the study region. Valley regions of the Western Ghats on wind ward side receives more rainfall during the south-west monsoon months over Kerala. The down wind regions of the Gaps receives more rainfall during easterlies. Southern districts like Trivandrum is highly deficient of rainfall. Maximum rainfall is found to be getting at places away from the peak of the mounatin by 20-40 kms. Places like Neriamangalam and Vyttiri gets maximum rainfall and minimum rainfall regions are located at the lee side of the Western Ghats. Maximum rainfall over Tamilnadu is getting at the southern district of Tamilnadu and the eastern coastal stations. Western and central region of Tamilnadu comes under severe shadowing effect of the Western Ghats.

The importance of the convective and non-convective rainfall is clear from the model results. The total rainfall in the study area is decided by the convective rainfall from the plain stations whereas the rainfall during the north-east monsoon is decided by the combined effect of plain as well as the summit stations. The contribution of the evaporation and condensation of the different region towards the total system is caculated by the model. Evaporation from Kerala region shows maximum input of 44% and minimum (11%) by the condenstaion over Tamilnadu towards the total input of the region. Thus Kerala is in the front run than Tamilnadu in evaporaton and condensation of the region. The negative correlation of the frictional velocity and the rainfall activity has been established over the region and the minimum frictional velocity over Neriamangalam and Vyttiri are the cause of the high amount of rainfall activity over the region.

Precipiation rate increases with orographic lift and it is found a high positive correlation of about 0.8 over the Western Ghats region at a height of 1700 m. Above this altitude precipitation rate decreases. Larger variability of the latent heat flux and sensible heat flux are seen over Tamilnadu compared to that of Kerala. The increse of 60 Wm^{-2} of sensible heat flux in the atmopshere is creating the high temperature pattern over the mouth of the Gap region. Bowen's ratio shows the incresed moisture stress over the region, and the value is compareable to that of an arid condition.

The influence of the Western Ghats over the atmospheric pressure pattern of the region is negligible over the plain stations. There is a general reduction of about 1.5 hPa pressure over the region when the orography is removed. Mountain makes kinking in the pattern of isobars and even in the isotherms. Western Ghats do not interact with the diurnal pattern of the pressure. Generally when the orography is removed the isolines will be concentrating over the coastal region. Mountain changes the temperature pattern in the vertical also. The mean deviation of the temperature over the region, especially at the eastern region is mainly controlled by the Western Ghats. The control of the Western Ghats over the soil temeprature of the plain stations around is nominal. The winds will be more streamlined in the absence of orography. A general increase of about 1 ms^{-1} is found all over the region. Frictional velocity stabilizes over the region, even if the value is higher than the normal condition by 0.1 ms^{-1}.

Western Ghats generally helps to maintain the high value of RH over the plain stations on both sides of the mounatin. An elevation of 1800 m reduces the precipitable water content by 2.3 $kgkg^{-1}$. During Spring season Western Ghats helps to get some surplus energy in the western side. Western Ghats palys a major role in the formation of low and medium clouds over the plain region and have no role with the formation of high clouds. But over summit region the formation of all types of clouds are due to the influence of the Western Ghats.

The PBL formation is retarded by the impact of Western Ghats over the region and the smooth flow of the wind over the plain stations are supporting by the mountain slopes. Plain stations on both sides of the mountain receives more latent heat flux. When the Western Ghats is removed, the rainfall activity over the main land over Kerala and the coastal regions on both sides reduces. The increase in the plains of Tamilnadu is 68.6%. In the case of evaporation Western Ghats reduces the activity over Tamilnadu in all season and in Winter over Kerala. Condensation activity is reduced when the orography is absent.

The divergence and the vortex fields are changing by Western Ghats dramatically. This is clear when the changes occur in these fields in opposit directions when the orography is removed. These effects are more in the eastern side of the Ghat than the western side over Kerala. Analysis of the Turbulent Kinetic Energy shows that the mountain is not much modifying the flow characteristics over the plain stations but the change is more over the summit and also in the vertical direction.

Palghat gap also controlls the climate of the nearby region considerably. When the Gap is closed there is a drop in the temperature pattern on the exit regions of the Gap. Due to Bernoulli's effect the wind speed in the upwind regions are reducing with a magnitude of 61% over Kerala and 33% over Tamilnadu. At the down wind region the wind speed increases by 45% over Palghat and the variation over central region of Coimbatore district is negligible.

Thus in all aspects Western Ghats play its role in the weather and climate of the region. The Gaps in the Western Ghats acts as a regulating mechanism for the climate of the region near to it on both sides. Lot of perineal rivers are originating from the upper regions of the Western Ghats which makeup the shortage of the water in the regions where the rainfall deficency is there and makes the region more fertile. The best example is the Bharathapuzha makes the Palghat region more agriculture oriented land and make it as the food granary of the Kerala state and also in the eastern side, Tiruchirappilly district is blessed with the river Kaveri which is controlling the vast agriculture land of the state. Thus by maintaining the river systems and the vast tropical rainforests over the region, Western Ghats plays a fair and remarkable role in making the southern peninsular India a beautiful land.

6.1 Future Outlook

The modelling study over the hilly terrain is needed with a high resolution data in order to study the dimensional effects and the relief effects over the terrain. The generation and impact of the Lee waves are to be studied with high priority, which also needs high resolution data set. The data sparse region of the hilly terrain makes the ground truth studies difficult and a meso-network observations should be initiated over the area to understand the variability of the meteorological parameters more clearly. A regular and precise observation network is needed at the valley region at least to understand the behaviour of the gravity winds emerging through the region and which makes tremendous changes in the local weather pattern over the region. The behaviour of the vast tropical rain forests over the land should be studied more clearly and the effect of the green surface canopy should be included in the model inputs at the terrain features, so that the representation of the atmosphere will be genuine and most of the chaotic nature of the atmosphere over the mountain ranges can be very well be quantified. The detailed study of the hydro-meteorological aspects of the main river basins of the region also should be included to the climatic studies for the total understanding of the weather and climate of the region.

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