INVESTIGATION OF PRE-MONSOON TO MONSOON TRANSITION OF ATMOSPHERIC CONDITIONS AS OBSERVED WITH A 205 MHZ WIND PROFILING RADAR OVER COCHIN

by

SRUTHI K P

(2016-20-004)

THESIS

Submitted in partial fulfillment of the requirement for the degree of

B.Sc.- M.Sc. (Integrated) Climate Change Adaptation

Faculty of Agriculture

KERALA AGRICULTURE UNIVERSITY

COLLEGE OF CLIMATE CHANGE AND ENVIRONMENTAL SCIENCE

VELLANIKKARA, THRISSUR – 680656 KERALA, INDIA 2021

DECLARATION

I, Sruthi, K.P (2016-20-004), hereby declare that the thesis entitled "**Investigation of pre-monsoon to monsoon transition of atmospheric conditions as observed with a 205 MHz wind profiling Radar over Cochin"** is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or the similar title, of any other university or society

Place: Kochi Sruthi K P

Date 2016-20-004

CERTIFICATE

I, hereby certify that the thesis entitled "**Investigation of pre-monsoon to monsoon transition of atmospheric conditions as observed with a 205 MHZ wind profiling Radar over Cochin"** is a record of research work done independently by Ms. Sruthi K P (2016-20-004) under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to her.

Place :Kochi

Date:

Dr. Manoj. M. G
Major Advisor, Advisory Committee
Scientist-D
Advanced Centre for
Atmospheric Radar Research
(ACARR)
Cochin University of Science and Technology
(CUSAT), Kalamassery, Kochi-682022, Kerala

CERTIFICATE

We, the undersigned members of the advisory committee of **Ms. Sruthi K P. (2016-20-004)**, a candidate for the degree of **B.Sc.-M.Sc. (Integrated) Climate Change Adaptation** agree that the thesis entitled **"Investigation of pre-monsoon to monsoon transition of atmospheric conditions as observed with a 205 MHZ wind profiling Radar over Cochin"** may be submitted by **Sruthi K P (2016-20-004)** in partial fulfillment of the requirement for the degree.

Dr .Manoj M.G
(Major Advisor, Advisory Committee)
Scientist-D
Advanced Centre for
Atmospheric Radar Research
(ACARR) Cochin University of
Science and Technology
(CUSAT)
Kochi-682022, Kerala

Dr. P.O. Nameer
(Member, Advisory Committee)
Dean
College of Climate Change and
Environmental Science (CCCES)
Kerala Agriculture University (KAU)
Vellanikkara-680656, Kerala

Dr. S. Abhilash
(Member, Advisory Committee)
Associate Director
Advanced Centre for
Atmospheric Radar Research
(ACARR) Cochin University of
Science and Technology
(CUSAT)
Kochi-682022, Kerala

Dr. Vijaykumar
(Member, Advisory Committee)
Scientist
Advanced Centre for
Atmospheric Radar Research
(ACARR) Cochin University of
Science and Technology (CUSAT)
Kochi-682022, Kerala

EXTERNAL EXAMINER

ACKNOWLEDGEMENTS

I would like to express my gratitude to God for the strength, health and keeping me on the correct path throughout the course of my studies.

I would like to express my heartfelt respect and sincere gratitude to my major advisor **Dr. Manoj M.G.,** Scientist-D, Advanced Centre for Atmospheric Radar Research, Cochin University of Science and Technology, Kerala for the guidance, useful comments, and support throughout the learning process of this master thesis.

I express my sincere gratitude to our beloved Dean **Prof. (Dr.) Nameer P.O.,** College of Climate Change Education and Environmental Science, KAU, Vellanikkara.

I am privileged to place my deep sense of gratitude to **Dr. Vijaykumar,** Scientist, ACARR, CUSAT and member of my advisory committee for his insightful suggestion and support. My sincere thanks to **Dr. S. Abhilash,** Associate Director, ACARR, CUSAT and my advisory committee for his great support.

I deeply express my whole hearted thanks to **Mr. Sivan C.**, PhD scholar ACAAR **Mrs. Angel Anita Christy** PhD scholar, and **Mrs. Rona sunil** PhD scholar, for their great support and guidance during my entire thesis work. Also, I would like to thank whole ACAAR team, CUSAT.

I sincerely acknowledge the help and support extended by each and every member of my CCCES family especially **Mrs. Krishna Priya** for their great support during the research work.

I respectfully thank Kerala Agricultural University, College of Climate Change and Environmental Science and all scientists and staff members of ‘Advanced centre for Atmospheric radar Research.

My heartfelt thanks to all my classmates and my entire senior batches for their support given to me during the whole college days.

I express my sincere gratitude to my parents and sisters for their support, blessing and sacrifice.

TABLE OF CONTENTS

LIST OF FIGURES

SYMBOLS AND ABBREVIATIONS

ABL-Atmospheric Boundary Layer

AIR- All India Rainfall

AWS-Automatic Weather Station

DBS-Doppler Beam Swinging

ECMWF-European Centre for Medium-Range Weather Forecasts

ENSO-El Nino and the Southern Oscillation

IAV- Interannual Variation

ISM-Indian Summer Monsoon

ITCZ-Inter Tropical Convergence Zone

IVT – Integrated Water Vapor Transport

LLJ-Low Level Jetstream

MC-Moisture Convergence

MLLJ-Monsoon Low Level Jetstream

MOK –Monsoon Onset over Kerala

NCEP -National Centres for Environmental Prediction

OLR- Outgoing Longwave Radiation

SCSSM -South China Sea Summer Monsoon

SST-Sea Surface Temperature

STJ-Subtropical Jetstream

TEJ-Tropical Easterly Jetstream

TT- Tropospheric Temperature

CHAPTER 1

INTRODUCTION

By monsoon, the layman means the rainy season as far as the Indian subcontinent is concerned. The Arabic root word 'Mausam' simply means 'Season'. Monsoon can be define as In many distinct ways in meteorological manner of speaking, monsoons are distinct wet and dry seasons, seasonal reversal of wind direction and the north-south oscillation of the ITCZ (Inter Topical Convergence Zone (Geen et al., 2020). Traditionally Asian summer monsoon was considered as a giant sea-breeze system evolved as a result of differential heating between the Asian land mass southern Indian ocean, now monsoons are considered as a part of large-scale global circulation and which has large importance in the Indian economy because monsoon is the life line of Indian economy as two third of Indian population depends on agriculture income and rain is the only source of irrigation in 40% of cropped area in our country. (Soman et al., 1992; Raju et al., 2005).

70 percent of annual rainfall in India occurs during July-September. 25 crores people depend on agriculture and allied sectors of agriculture in our country and agriculture planning and food security are closely related to the quantity of rainfall onset date of Indian summer monsoon and and its duration and any variation in these features should impact on food-grain production and the GDP and Forecasting of the onset over the southern tip of the Kerala has significant important for the Indian economy, because since its influence on agriculture, drinking water, power and irrigation are vital. (Joseph, 2009).

Monsoon onset over Kerala mark the transition from hot and dry season to a rainy season and it indicate advance of the southwest monsoon over Indian land mass (Joseph, 2009).

Slowly evolving as well as sudden changes in many atmospheric and oceanic parameters like low level winds, moisture, upper level temperature and SST are accompanied with the monsoon onset over Kerala. However, the arrival of the monsoon rains over Kerala is the prime consideration in defining the onset, because it paves the way for their further advance into the interior parts of India.

There are many atmospheric and oceanic parameters they were shows sudden changes accompanied with the monsoon onset. The prime consideration to declare the onset date over Kerala is the monsoon rains. The new normal of the monsoon onset over is June 1 and this has a standard deviation about 1 week. At the pre-satellite days the onset date are declared by subjectively by checking the pentad rainfall pattern over Kerala and there also have been many attempts to done for the objective definition of onset of the monsoon over Kerala. Subjective method has many limitations such that which does not always determine a clear onset since there is any small scale weather disturbances and rainfall occur before the monsoon onset. Since 2006 objective method of IMD is used for the declaration of monsoon onset over Kerala. Other features used to determine the onset are steady increase of convection over an area bounded by 0-15N and east of 60E about 3 pentads before onset and a steady acceleration of the cross-equatorial Findlater Low Level Jet (LLJ) in response to this heat source.

The purpose of the study is to understand the changes of atmospheric thermodynamic and dynamic characteristics in troposphere and lower stratosphere associated with Indian Summer Monsoon Onset, with the help of data acquired from the Stratosphere-Troposphere Radar, the Automated Weather Station (AWS) located in the Advanced Center for Atmospheric Radar Research I(ACARR) [in Cochin University of Science and Technology (CUSAT)] and the Radiosonde experiments done there. The data and methodology are briefly described, followed by the results and discussion of the study done. Finally, a summary of the results presented.

The objective of the thesis given below.

The purpose of the study is to understand the changes of atmospheric thermodynamic and dynamic variable in troposphere and lower stratosphere associated with Indian Summer Monsoon Onset (during pre-monsoon monsoon transition phase (May 15 to June 15) over a period of 2017 to 2020).

CHAPTER 2

REVIEW OF LITERATURE

2.1. MONSOON

The word ‘monsoon is derived from the Arabic word ‘mawsim’, which refers to seasonal reversing wind accompanied by precipitation. The word monsoon refers to the system that gives rainfall in the rainy season. Major Monsoons of the world are west African and Asian-Australian Monsoon. Monsoons are a dominant feature of the tropical and subtropical climate in many regions of the world, characterized by rainy summer and drier winter seasons(Soman et al., 1992). Summer monsoon and winter monsoon are two main circulations over South Asia with contrasting features. A number of meteorological parameters are coupled with the seasonal transition at the surface and in the upper air, which build up gradually with the progress of the season, and by the last of May, it reaches a critical stage, leading to a burst of the monsoon (Gadgil, 2018). Rainfall is the considerable meteorological parameters that signal the seasonal transitions and wind is an another important parameter and large seasonal variations in the wind and rainfall is the major characteristics of monsoon and seasonal variation of rainfall is more considered than that of wind direction (Fasullo and Webster., 2002). Monsoonal regions were recognized on the premise of seasonal variation in the direction of the surface winds. Many parts of the South Peninsula have the duration of the monsoon over more than 4 months, that over north-western parts of the country is only about half of that.

2.1.1. SUMMER MONSOON

In march after vernal equinox the apparent position of sun moves towards the tropic of cancer and high level of heating results a meridional temperature gradient with a low pressure over central Asia. This pressure gradient induces southwesterlies and heavy precipitation over Asian summer monsoon region. Hailey developed a concept about monsoon such that it is a gigantic land and sea breezes. Hailey fails to explain the workings of the monsoons because there was no answer for the question that why a monsoon does not occur everywhere where the thermal concept is true. The development of the monsoon is also influenced by the shape of the continents, orography, and the conditions of air circulation in addition to the differential heating, in the upper troposphere. Therefore, Hailey's theory has lost much of its significance (Xavier et al., 2007) commencement of the South China Sea Summer Monsoon (SCSSM) indicates the First transition of Asian summer monsoon causing major changes in both convection and winds (Pai and Rajeevan., 2009) during springtime, instabilities are formed in the atmospheric ocean system at which brings the transitions in the atmospheric circulations (Jeng and Abdullah, 2011).

2.1.2. ISM MECHANISM

Indian summer monsoon occurs due to the difference in temperature between landmass and ocean that triggered by Land-Sea heat gradient. The meridional gradient of Tropospheric heating drives the monsoon circulation that is Meridional gradient of Tropospheric Heating leads to the establishment of the Meridional gradient of Tropospheric Temperature (TT).(Shukla and Misra.,1977) In April, may months pre-monsoonal heating warms a vast area extending from east africa to North India including Arabia and Pakisthan and during the summer low pressure areas develop in the Northern hemisphere and intense surface heat low developed over the region and leads to southwest monsoon. The region of maximum surface air temperature slowly spreads northwestwards. By the first half of May whole of central India is heated up with the highest air temperatures and by the first week of June, maximum surface air temperature is observed primarily over the north-western parts of India (Pai and Rajeevan., 2009).

This is the triggering mechanism necessary for the setting in of the monsoon circulation and latent heat release due to large-scale organized convective activity provided further sustenance that is thermodynamics also play a major role, via the latent heat release from the rains which warm up the troposphere and fuel the circulation.(Wang et al., 2009). Indian summer monsoon is a physical phenomenon and the length and duration of ISM is influenced by inter-annual oscillations like ENSO hence the length of rainy season vary from year to year ,mainly high amount of rainfall is received in the west coast of Indian peninsula and the north-eastern parts of India in response to a large scale deep heat source the meridional gradient of troposphere temperature setting up and which leads to a cross equatorial monsoonal circulation and the low level south westerlies increases its strength at the onset of summer monsoon (Xavier., 2007, Parthasarathy et al 1991). Tibetan plateau has a large importance in setting up Asian summer monsoon because seasonal warming of lower and upper troposphere have large significance for the development of large scale monsoonal circulation because tibetan plateau act as an elevated heat source and which induces abrupt monsoonal transitions. In the south of tibetan plateau sign of meridional gradient of tropospheric temperature and pressure gradient are reversed and leads to onset of Indian summer monsoon. The tropospheric temperature means the temperature averaged over the 200hPa and 600 hPa pressure levels and the meridional temperature gradient largely proportional to the meridional gradient of tropospheric heating and which drives the deep monsoonal circulation (Xavier et al., 2007). In years of the low snowfall years, the Tibetan Plateau can warm earlier and generate a stronger monsoonal circulation. Deep snow depths influences albedo and soil hydrology, delay, and weaken the monsoon. In the winter, the continent cools relative to the ocean, the pressure gradient reverses, and the dominant flow across the Arabian Sea becomes northeasterly.

Low level south westerlies strikes the west coast of Kerala and the western Ghats is in almost perpendicular to the low level jet and which receives bout 3 times the India’s average rainfall. Western Ghats have a large significance in regulating the climate of India through regional climate modulations. (Varikodan et al., 2018). ISM season is a prime agricultural season of our country and the productivity from the crops is highly sensitive to the variability occurs in the ISMR. Mainly the moisture flux needed for the rainfall is obtained from the Bay of Bengal and Arabian Sea and a very small amount of moisture is provided by the evapotranspiration process over the land.

2.1.3. WINTER MONSOON

During colder months (October to April), Wind blows from cooler landmass (Himalayas and Indo-Gangetic plains) towards Indian Ocean. This causes precipitation over the ocean and in regions like Tamil Nadu.

2.1.4. PHASES OF MONSOON

The normal date of Indian summer monsoon onset is at June 1 and which happens in the west coast of Kerala, About 15 days before the ISM onset monsoon rains initially occurs over the equatorial eastern Indian Ocean, Myanmar, Thailand, and the Andaman Sea. Intense low-level westerly winds are driven by solid convection beat the locale toward the south of the Indian subcontinent. Early convection band southwest of India and it's going with westerly breezes accordingly stretch out toward the west to 50–60E along 10N, and their force further fortifies. When the strong westerly wind and convection are grounded over the area southwest of Kerala, the environmental condition is prepared for the initiation of the ISM season. Strong low-level westerly winds driven by strong convection prevail over the region to the south of the Indian subcontinent. (Xavier et al., 2007). The southwest monsoon of India goes through different phases within the period, that includes the onset and advance phase, the established phase, and the withdrawal phase. Pre-monsoon to monsoon seasonal transition is so sudden that it is often termed as a burst of monsoon over the country. The onset process starts by end of May or early June accompanied by the varying meteorological parameters like a reversal of pressure gradient, circulation changes, as well as strengthening of low-level cross-equatorial flow and the burst of monsoon simultaneously over Kerala and West Bengal, and Assam in northeast India. This abrupt transition, which is known as the onset of monsoon. The advance of monsoon occurs in a northward direction along the southern peninsula as Arabian sea branch of monsoon and from east to west along the Gangetic plains as Bay of Bengal branch of monsoon. The northward advancing Arabian Sea branch meets the westward advancing Bay of Bengal branch somewhere over the western part of India over Rajasthan by 1 July and together covers the entire country by mid-July.

2.1.5. KEY RAIN-BEARING SYSTEMS OF THE SOUTHWEST MONSOON

Key rain bearing systems are includes the semi-permanent systems which present in the southwest monsoon period and exist most of the days in a particular location. The major quasi permanent systems associated with ISM includes heat low, Monsoon trough, Tibetan high, tropical easterly jet and Mascarene high The key rain-bearing systems of the southwest monsoon period over India include monsoon lows and depressions. The major transient rain-producing systems are Monsoon Depression, Cyclonic storms during monsoon, Mid Tropospheric Cyclones, Low-level jet (or Somali Jet), and Offshore Troughs /Vortices are also gives significant amount of rainfall.

Heat Low

Heat lows are major semi-permanent systems associated with the Indian summer monsoon and which starts to develops as a result of pre-monsoonal heating in the Indian subcontinent and over Pakistan and this heat low is fully established in the mature phase of monsoon and this is the major driving force of monsoon. Pre-monsoonal heating develops a low-pressure belt that starts from Africa to central Asia across Arabia, Iran, Afghanistan, Pakistan, and northwest India. The heat lows are a part of the low-pressure belt and that developed in the maximum heating areas and vertically extends up to 1.5 km and which is cloaked by a ridge in the upper troposphere, such as a part of the subtropical high-pressure belt.

Monsoon Trough

Monsoon trough observed in the central India and runs in west to east direction and the position of trough line has large importance because which is a major semi-permanent rain bearing system associated with monsoon and have a large control on monsoon activity. 'break-in monsoon' is referred as a drastic decrease in rains over the country when the Position of the trough line close to the foot-hills through the Himalayan mountain belt experiences heavy falls which can cause floods in the rivers originating there.

The advance of the monsoon into Kerala is often associated with a quite frequently develops system like weak trough along the southwest coast of India, and is responsible for the strengthening of the monsoon in terms of rainfall, in the adjacent parts of the coastal belt.

2.1.6. THEORIES ON ISM

Classical Theory:

In 1686 the Sir Edmund Hailey explained the driving mechanism of the monsoon caused from the meridional gradient in thermal heating between continents and oceans and he considered the monsoon as a gigantic Land-sea breeze system.

Air Mass Theory

Inter Tropical Convergence zone (ITCZ) is a heavy rain spell system and which moves in the north-south direction with the apparent position of sun and in tis zone the trade winds from northern hemisphere and southern hemisphere converges each other in the equator. In the summer season, the sun shines vertically over the Tropic of Cancer, and the ITCZ shifts northwards. The monsoon front is where the southwest monsoons meet the northeast trade winds. In the month of July, the ITCZ shifts to 20°- 25° N latitude, and ITCZ in this position is often called the Monsoon Trough.

Jet Stream Theory

Subtropical jet streams are fast moving westerlies in the subtropics of north and south hemisphere and the role of subtropical jet stream in the development of Indian monsoon is very large and the jet stream theory is the latest and significant theory regarding the origin of monsoon. Upper air circulations such as easterly jet stream and subtropical jet streams have great role in the quick onset of monsoon and hindering the monsoon winds (Nanda, 2018).in the winter the STJ flow pattern is completely different from the summer pattern such that in winter STJ flows along the south of Himalayas and which moves towards north in June with the commencement of monsoon onset. Southern branch of STJ in the south of Himalayas weakens and the ITCZ pushes northwards and tropical easterlies developed in the peninsular India. STJ has Ridges and troughs associated with it and the ridge associated with STJ moves northwards from NW India towards the central Asia, which burst the southwest monsoon winds.

2.2. MONSOON AND ITCZ

Generally ITCZ is considered the location where the trade winds of both hemisphere converges and which is coincident with the ascending branch of the hardly circulation. (Gadgil, 2018). For well over 300 years, the monsoon has been considered to be a gigantic land-sea breeze and the ITCZ and the monsoon system were considered as distinct phenomenon and then more recent works suggest that the monsoon as the extreme migrations of the convergence zone as a result of north south migration of the ITCZ. An alternative hypothesis, of Blanford's (1886) ,in which the basic system responsible for the Indian summer monsoon is considered to be the Intertropical Convergence Zone (ITCZ) or the equatorial trough. The spring to summer transition indicates monsoon onset that occurs with the establishment of the CTCZ in the core monsoon zone, and CTCZ fluctuates in this region in the peak monsoon months of July and August. At the end of the summer monsoon season, CTCZ retreats from the monsoon zone. The physical monsoon season is delineated by the establishment of the TCZ around 10 °N. As a result of the seasonal march of the tropical convergence zone (TCZ).

2.3. PRE-MONSOON TO MONSOON TRANSITION OF ATMOSPHERIC CONDITIONS

2.3.1 Lower Level Features

The changes in the pressure and wind directions at sea-level and mid-tropospheric levels which had started taking place from the month of April are almost complete by the end of May. At 850 hPa level which represents the lower troposphere, the surface synoptic situations are clearly reflected.

Important low level wind features are strong cross equatorial flow over the western equatorial Indian ocean and the low level westerlies are evolved as a result of meridional pressure gradient force developed between Indian subcontinent and Mascarene high, this induces the cross equatorial flow and the flow is completed by a descending of air over the region of 10-40S. lower troposphere flux divergence over the Somali coast and south west coast of srilanka and upper troposphere flux convergence are occur in the pre-onset days and which is the main characteristics features in the evolution of summer monsoon. Intensity of flux convergence increases during the onset phase and post onset periods. In the onset phase the south-westerlies extends its depth up to 600hPa and the wind carry moisture and which cause the relative humidity of the air increases up to a depth of 500hPa.(Raju et al., 2005).

The westerly zonal flow extends up to 600 hPa. The relative humidity of the air also increases at least up to 500 hPa (Pai and Rajeevan., 2009). The wind anomaly at 850 hPa level shows anomalous cyclonic circulation over the northwest Arabian Sea indicates the above normal cyclonic activity over the Arabian Sea. At the 500 hPa level, strong cross-equatorial flow over the Arabian Sea indicates above normal low-level jet stream during the season (Joseph et al., 1994).

Horizontal flux convergence of kinetic energy is noticed over the central Arabian Sea associated with the onset period, and the flux convergence is maintained during the onset phase and large increase of this zone is observed with maxima shifted towards the eastern Arabian Sea and extended into the Indian Peninsula.

Monsoon winds carry moisture evaporated from the warm Indian Ocean to converge over the mountains on the west coast of India, before continuing to the Bay of Bengal. There they turn north and towards the west, around the low pressure “monsoon trough” of northern India, where more rainfalls. The monsoon circulation pattern at any given time will also get modulated by the upper-tropospheric features and mid-latitude circulation patterns.

2.3.1.1. Monsoon Low-Level Jet Stream

Monsoon low level jet stream is the important feature of the monsoonal circulation, it is a fast moving narrow current of air and evolves its strength in association with the onset of summer monsoon and which observed in between 1 to 1.5 km in the lower troposphere. LLJ starts to evolve in May as major part of LLJ penetrates to East Africa then subsequently it moves towards north of equator and strikes the west coast of Kerala with the summer monsoon onset. Core speed of Monsoon low-level jet observe about 1500m above mean sea level, the strongest low level south westerlies carry moisture from southern Indian ocean to north of the equator.

Any variability in rainfall of the summer monsoon over the monsoon region may be well explained with the variations observed in the depth and core speed of monsoon low-level jet stream. Upwelling in the west coast of Kerala coincides with the path of LLJ, as the strong winds drive away the surface coastal waters move away from the coast towards the east, extremely cold waters from the depth of the sea rise upwards to balance the mass

2.3.1.2. Mean Sea Level Pressure

Surface pressure decreases during April- May corresponding to the heating of the sun, and a trough appears over the heated landmass and so known as heat trough and it is different from the trough associated with the TCZ, which have an ascending motion throughout the troposphere .heat trough is shallow with the associated ascent restricted to 2-3 km near the surface. Above this level, there is the descent of air. Spring to summer monsoon transition involves a transition from this heat trough to a dynamic trough/TCZ (Pai and Rajeevan., 2009). The pressure difference between the two major elements of the summer monsoon such as Mascarene high and the monsoon trough over northeast India drives the monsoon. (Xavier et al., 2007).

2.3.2. UPPER-LEVEL FEATURES

Upper level circulation features associated with monsoon transition are establishment of upper troposphere easterly jet stream and the pole ward movement of subtropical westerly jet stream to the north of Tibetan plateau. Upper air circulation reversed with the monsoon transitions, upper level easterly jet stream become very active and associated with the lower troposphere south-west monsoon winds (Pai and Rajeevan., 2009).

2.3.2.1 Tropical Easterly Jet-Stream

TEJ is an unique feature associated with Asian summer monsoon and flows from east to west over peninsular India and it is found between the latitude of 5^0N to 20^0N and it is Persistent from June through the end of September. Rainfall and establishment of easterly jet are have large significance in the warming of Tibetan plateau and melting of ice. High rate of warming associated with the elevated areas of Tibetan plateau have significant role in the establishment and maintenance of the TEJ and play an important role in brings the southwest monsoon. TEJ descents near Madagascar and the high pressure system is intensifies. The South China Sea to South India TEJ is accelerating and decelerates thereafter. Consequent upper divergence is regarded as favorable for convection upstream of 70° E and subsidence downstream. Position and speed fluctuate from day to day.

2.3.2.2. Sub Tropical Jet-Stream

Subtropical jet stream is a narrow band of fast moving westerly wind .STJ occurs in both hemisphere, in northern hemisphere it flows between the latitude of 25 ^{0}N-35^0N and have a large influence on Indian summer monsoon. In summer STJ shows an different pattern of flow compared to winter which moves towards the northern edge of Himalayas, this movement indicates the onset. STJ moves back to the original position with respect to the withdrawal of monsoon. A burst of monsoon is occurs with respect to the STJ pattern is switched to its summer pattern.

((Pai and Rajeevan., 2009)). Northward migration of STJ anticyclonic activity within the STJ trough that emerges a tropical easterly jet stream. The April May months are rainless despite high temperature due to good insolation above the tropic of cancer, and high evaporation because the ridge region of the Southern branch of STJ creates strong divergence (high pressure) in the north-west India

2.3.3. OUT GOING LONG WAVE RADIATION

OLR is an indicator of convection and cloud amount .small values of OLR indicates large-scale deep convection. With respect to the burst of summer monsoon southwesterlies increases its depth and strength and relative humidity and vertically integrated moisture transport in the southern peninsular India also increases. Large scale circulation in the late May and early June induces large scale deep convection takes place in the southern India and adjacent Arabian sea areas.

There is a negative correlation between 850-hPa zonal wind and OLR. OLR is the total amount of thermal radiation emitted from the earth to interplanetary space. Low values of OLR at low latitudes are associated with the cloud, as radiation from the low-temperature cloud top is weaker than that from the surface (Jeng and Abdulla .,2011). Low values of OLR fields over the north Indian ocean, southeast Arabian Sea and the East Bay of Bengal indicates the deep convective activity with the arrival of monsoon(Pai and Rajeevan., 2009).The amount of terrestrial radiation that is released into space and, by extension, the amount of cloud cover and water vapor that intercepts that radiation in the atmosphere defines the Daily Outgoing Longwave Radiation (OLR) CDR. After monsoon onset over Kerala, convection shifts to the East Bay of Bengal, and the convective activity over the Arabian Sea is decreases gradually. Rainfall, OLR, and the moisture budget have often been used to investigate the temporal and spatial characteristics of large-scale deep convective activity. There is a rainfall probability of 0.7-0.8 associated with the OLR values 220–240Wm^{-2} OLR = 180Wm^{-2} indicates the probability of rainfall greater than 0.9. 15 days before the onset the OLR anomalies in the southeastern Arabian Sea is greater than 20 Wm^{-2}. (Patwardhan et al., 2014)

2.4. MONSOON ONSET OVER KERALA

Monsoon onset over Kerala is the crucial meteorological phenomenon over India and a major event related to Indian agriculture and economy (Gadgil, 2018). Timely prediction of MOK is a challenging one and monsoon onset in the different stations of our country can be early or late as compared to the Normal date. In the most southern part of India beginning of monsoon rain is termed monsoon onset and this date is very important to agriculture planning and other socioeconomic activities of people in India (Lau and Yang.,1996). Declaration of MOK have a great importance and it is a synoptic phenomenon and have teleconnection with other phenomena like El Niño Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Madden–Julian Oscillation (MJO). The monsoon advances to northwards after the monsoon onset over Kerala and the monsoon rains cover all over the country in July 15. By the onset of monsoon the convergence of heat and moisture flux increases over the Bay of Bengal.(Jeng and Abdullah., 2011). All the different stations of our country has a normal onset date. As per IMD the normal onset date of Rajasthan is July 1. IMD gives the mean onset date of monsoon all different parts of India based on the long-term average of non-overlapping five days/pentad. The onset date of that station is considered as the middle date of the pentad which shows a sharp increment in rainfall. The onset of monsoon occurs during the early part of May over Myanmar Very rapid cooling of the Arabian Sea is observed soon after the onset of the strong southwesterly monsoonal winds. (Xavier et al., 2007). There is year-to-year variability in onset date at a single location and it changes significantly from the climatological pattern, a climatological pattern of onset date is obtained through averaging several decades of rainfall pattern. Before monsoon sets over southwestern India monsoon rain occur over Burma and Thailand in mid May and then the monsoon progresses to northwards cover all India and most of the Pakistan in the following month. (Pai and Rajeevan., 2009). Onset phase is associated with some kind of transient disturbances and in most of the cases it is sudden. (Xavier et al., 2007). Monsoon trough, lows, depressions and mid-tropospheric cyclones are helps to the progress of monsoon towards all over the country if once it sets, and these were considered synoptic scale weather system embedded in the basic monsoon system. Mainly the variability in rainfall marks the monsoon transitions and also many other thermodynamic and dynamic variables indicates the transition of monsoon.(Tyagi et al., 2011). The onset of the monsoon season can be defined using a wide range of criteria that includes lower tropospheric and upper-tropospheric features (Pai and Rajeevan., 2009). A delay in the MOK does not necessarily mean a delay in monsoon onset over NW India.

However, a delay in the MOK is generally associated with a delay in onset at least over the southern states including the city of Mumbai. In spite of its importance, there are not many studies attempting to predict the date of MOK (Pai and Rajeevan., 2009).

2.4.1. BOGUS ONSET

Heavy rainfall that has occurred before the beginning of the monsoon is most likely due to convection arising from local convective systems and not linked to the large-scale monsoon circulation but that accompanied by Simultaneous observations of rainfall and westerly winds. The Tropical intra-seasonal disturbances cause ‘‘false’’ or ‘‘bogus’’ monsoon onsets within districts (Jeng and Abdullah., 2011).as similar to a monsoon onset, enhanced convection and westerly surface winds are occurs associated with a bogus onset, and this is a smaller scale phenomenon and lasting only a weak.(Fasullo and Webster.,2002). A bogus onset often followed an extended periods of week winds and clear skies and that causing heat waves and droughts in India. Incorrect prediction of MOK and occurring of bogus onset should cause considerable agricultural and economic damage because of the failure of crops. Onset definitions based on rainfall over a geographically synoptic disturbance-sensitive small place such as Kerala ought to lead to ‘bogus’ monsoon onsets.

2.4.2. METHODS OF MOK DECLARATION

Many meteorologists have been established, both subjective and objective methods to determine the monsoon onset over Kerala over many years, the southern tip of India. understanding the characteristics of MOK and onset prediction is a most debated and researched topic. Attempt to understand and predict the Indian summer monsoon (ISM) onset dates has increased available data and computing resources since the 1940s. Old criteria determined MOK state that after 10 May, if any five stations out of the following seven stations, viz., Colombo, Minicoy, Thiruvananthapuram, Alappuzha, Kochi, Kozhikode, and Mangalore receive rainfall of 1mm in 24 h for two consecutive days, the MOK may be announced on the second day. Factors like an abrupt change in rainfall, relative humidity, strength, and depth of westerlies were subjectively taken into consideration to determine the onset date until 2005 (Pai and Rajeevan., 2009). Krishnamurti (1985) provided objective methods for the MOK which point out dramatic changes are known to occur during the monsoon onset that including a sharp increase in the daily rainfall, a sharp increase in the vertically integrated moisture, and an increase in kinetic energy of the low-level flows. Ananthakrishnan and Soman (1988)defined dates of MOK using daily rainfall data collected from a network of rain gauges in Kerala for the period from 1901 to 1980. According to their method, the date of MOK is declared as the first day of the transition from the light to heavy rainfall category and in addition, the average daily rainfall during the first 5 days after the transition should not be less than 10 mm, This onset criteria with the five-day persistence of rain incorporated for excluding the precipitation associated with synoptic weather systems. The rainfall associated with the monsoon onset has a larger spatial scale and it persists. Low level winds get strengthen during onset period in the southern peninsular region of India and can be treated as good predictor of ISM onset. (Joseph et al., 2006) Indian Meteorological Department determined the mean onset date over Kerala from the long period record is 1st of June with a standard deviation of 7.28 days (Pai and

Rajeevan.,2009). Xavier et. al proposed an Indian summer monsoon onset index based on Reversal of the meridional gradient of the average temperature of the layer between 600 and 200 hPa south of the Tibetan Plateau (Pai and Rajeevan., 2009). Pai and Rajeevan, 2009, proposed the KE onset such as there is a spectacular increase in the KE of low-level westerlies over the Sothern peninsular region of India above a threshold value of 40 m2s-2 and persisting for 5 consecutive days is taken as the KE onset.

2.4.3. ONSET VORTEX

Southeast Arabian Sea (SEAS) is one of the warmest regions in the Indian Ocean and the region in the SEAS with SST >30 °C is referred to as the Arabian Sea mini warm pool. Mini warm pool over the Arabian Sea has large importance in the prediction of monsoon onset. The onset vortex is a low-pressure system that forms over the east-central Arabian Sea (ECAS) it is not a common feature but the onset of Indian summer monsoon over Kerala.

2.5. KERALA TOPOGRAPHY

Kerala, is a south west state and lying between the Arabian Sea and the Western Ghats, a range of mountains running parallel to the west coast of India where orographic lifting plays a significant role in the formation of rain-bearing clouds during the monsoon season. The abundant monsoon rain in Kerala can be credited to this unique geographic location. With extreme weather events on the rise in a warming world, intense rainfall in these regions is predicted to be average. The highly localized nature of the precipitation in Kerala with complex topography makes it extremely difficult to verify numerical model performance.

2.6. INTER-ANNUAL VARIATION (IAV) OF ISM

Interannual variability's associated with a Indian summer monsoon rainfall (ISMR), includes droughts and floods and have a destructive effects on the people, agriculture and economy of country. Factors influencing the IAV of AIR are local air–sea interactions, and teleconnections with remote climatic phenomena such as El Nino and the Southern Oscillation (ENSO) and the North Atlantic Oscillation causing the IAV of all India rainfall pattern. The physical length of the Indian monsoon season vary from year to year, as the internal and external forcings responsible for the onset and withdrawal of the monsoon may vary. Indian summer monsoon (ISM) shows interannual variability major part of it is linked by unpredictable ‘‘internal’’ low-frequency variations and IAV causing poor predictability of monsoon (Bollasina et al., 2013). Monsoon ISOs are responsible for internal IAV of the ISM. Three features of Indian summer monsoon that exhibits variability such as variability in rainfall and interannual variability in onset date and active break cycle (Joseph et al., 1994)

2.7. EFFECT OF TIBETAN PLATEAU

The Tibetan plateau is considered to be one of the key factors in the development of monsoon circulation in the region. At 500 hPa level, which is rough, the elevation of Tibet, the air is warmer over the surface of the plateau than the surrounding at the same level. It is observed that during summer months of April and May widespread thunderstorm and rain occurs over the southeastern part of Tibetan plateau. This releases a considerable amount of latent heat into the atmosphere through rainfall. Coupled with the flux of sensible heat from the plateau the observation suggests a considerable amount of energy injected into the atmosphere. Due to latent and sensible heating over the Tibetan plateau, strong thermal convection develops over there. But, unlike the heat low over the Indian subcontinent, thermal convection is stronger over the Tibetan plateau because of high elevation. Consequently, while there is evidence of heat low over Tibet around 500 hPa, the ascending air rapidly spread outward both to the north and to the south of the plateau. The divergence of air leads to the formation of an anticyclone over Tibet around 300-200 hPa levels.

2.8. CLIMATE CHANGE AND ISM

Global climate models are trying to identify and project the possible climate changes, simulations of monsoon precipitation are coupled with large uncertainties compared to its simulation of temperature. The variability of the onset dates as compared to the present is more in the future. The time required to advance the monsoon is likely to be less in the future scenarios than the baseline over northwest India. The future simulations of PRECIS model in warming scenario also identifies the sharp rise in daily rainfall at the monsoon onset phase towards 2080s ,but the rainfall at the onset phase over Kerala may be less in future as compared to the baseline(Patwardhan et al., 2014). Due to the current global warming moisture supply to the atmosphere is increasing and due to this warming effect, models suggest that summer monsoon precipitation is going to be increases (Overpeck et al., 1996)

2.9. WIND PROFILER RADARS AND WIND PATTERN OVER KOCHI

Wind profiler radars are helpful to study various meteorological phenomena/processes in the ABL, free troposphere, and stratosphere because that provides very high time-height resolution data. Clear-air Doppler radars have been extensively used to continuously monitor all 3 components of air velocity components over a station. The mean altitude structure of the synoptic-scale southwest monsoon winds is studied using the radar data. Doppler Beam Swinging (DBS) techniques is using in the Stratosphere-Troposphere Radar and which provides real-time vertical profiles of horizontal wind speed and direction at heights of up to 20km above ground level. Clear-air Doppler radars have been extensively used to monitor continuously all 3 components of air velocity over a station.

CHAPTER 3

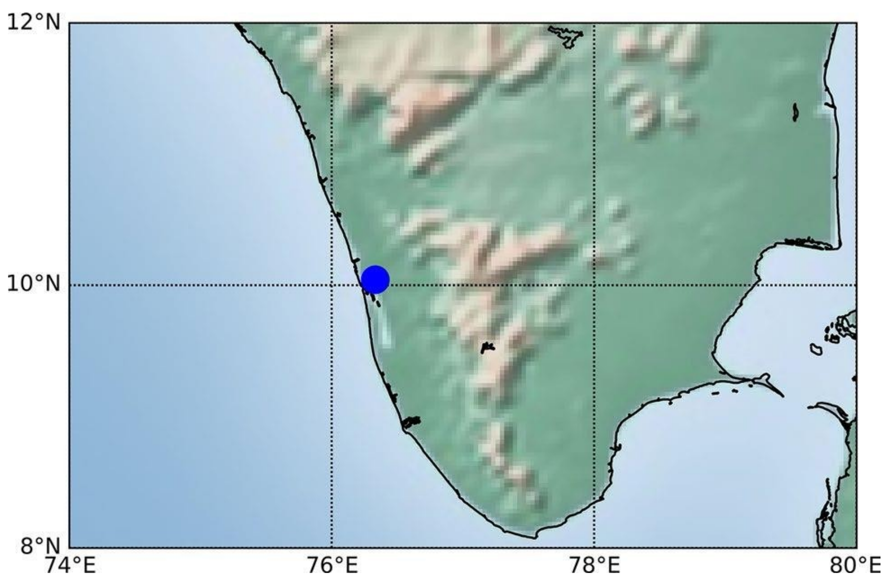
DATA AND METHODOLOGY

3.1. Site Description

The study area will be Cochin. Cochin is a coastal station in Kerala (9" 58' N; 76"41' E; 3 m) lying between the Arabian Sea and the Western Ghats running north-south direction and have large influence on the weather pattern of the state. Cochin, in Kerala, being the gateway of monsoon to advance towards the rest of the country, is the perfect place to collect data regarding the onset characteristics of the southwest monsoon.

The ST wind profiler located in this study area provides wind information in three dimensions with high spatial and temporal resolutions, which makes it an ideal tool to study the atmospheric processes before, during, and after the monsoon onset

The basic meteorological fields considered for the study include zonal and meridional wind patterns, the evolution of OLR field, precipitation, and Relative humidity during monsoon transition.



Topography map showing the radar location (blue circle)

3.2. Wind Data

Doppler Beam Swinging (DBS) techniques is used in a ST wind profiler radar to provide vertical profiles of horizontal wind speed and direction at heights of up to 20km above ground level. Vertical wind speed and the zonal and meridional wind speeds were the data used in this study from the Radar. Radar data was used for the period of May 15 to June 15 from 2017 to 2020. The vertical structure of zonal and vertical wind at the transition period is plotted and interpreted. Wind measurements are taken from the wind profiler radar for the height range of 315 m–5 km has been taken from 0.3μ s baud operation, which has a vertical resolution of 45 m and a height range of 5–20 km has been taken from the 1.2 μ s baud, having a vertical resolution of 180 m. In this study, the daily mean wind speed calculated by combining the data for a period of 17–18 h local time.

Radar antennas

European Centre for Medium-Range Weather Forecasts (ECMWF) Interim re-analysis (ERAInt) is one of the widely used reanalysis products for studying monsoon circulation and its variability. The profiles of zonal wind from ERA-Interim for the period of May and June (2017-20) are used, having a horizontal resolution of $0.25^\circ \times 0.25^\circ$ are used.

3.1.1 Methodology

The given data from the radar is of the type - UVW(.uvw). u – zonal wind. Component of wind in the x-direction. Zonal means in the west-east direction. the negative sign of u means it is a westerly and the positive sign is easterly. v – Meridional wind. Component of wind in the y-direction. Meridional means along a longitudinal circle or in the north-south direction. Meridional flow is a general airflow pattern from north to south, or from south to north., w – Vertical wind. Component of wind in the z-direction. The vertical wind is perpendicular to both zonal and meridional wind. The file contains values of u, v, w, and corresponding height. Wind from 5.00 pm to 6.00 pm is taken from May 15 to June 15 for the years of 2017 to 2020. The vertical structure of wind characteristics is analyzed using **math lab** programming.

3.1.1. Kinetic Energy

Analyzing the plot and measured the maximum value of LLJ. Then find out the value of kinetic energy per unit mass.

Kinetic energy = $\frac{1}{2} * \varrho * U^2$

ρ – unit mass

3.1.2. Moisture Convergence (Mc):

Moisture flux was calculated by obtaining the product of specific humidity and resultant wind speed in the considered area. Moisture Flux The product of a field of values and the wind speed is referred to as the flux of that field.

$\vec{Q}\rightarrow = qVh \rightarrow$ (1) is the moisture flux, where q is the specific humidity (g/kg) and Vh is the horizontal wind. Q is also often referred to as the water vapor transport. Equation (1) is normally integrated through the depth of the troposphere to obtain the Integrated Water Vapor Transport (IVT).

To analyze the spatial pattern of lower and upper circulation characteristics data collected from ERA-Interim for the period of May –June. European Centre for Medium Range Weather Forecast (ECMWF) Interim re-analysis (ERAInt) is one of the widely used reanalysis products for studying the monsoon circulation and its variability. (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=form).

3.2. Relative Humidity

Radiosonde is a battery-powered telemetry instrument package carried into the atmosphere usually by a weather balloon that measures various atmospheric parameters and transmits them by radio to a ground receiver. Temperature and Specific Humidity at different levels are also collected from National Centres for Environmental Prediction (NCEP) and ERA interim (ERA5). (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single- levels?tab=form).

3. 3. Rainfall Data

Rainfall data set are collected from India Meteorological Department (0.25 ^{o} x 0.25^{o} horizontal resolution).Used to get the area averaged rainfall over Kerala at monsoon transition phase. (https://www.imdpune.gov.in/Clim_Pred_LRF_New/Grided_Data_Download.html). The Automated Weather Station, AWS is a meteorological station where observations are made and transmitted automatically. rainfall

AWS

3.4. OLR Data

The outgoing longwave radiation (OLR) observed by satellites have long been used as a proxy to detect deep convection over the tropics. Data downloaded from Atmospheric infrared sounder.

https://giovanni.gsfc.nasa.gov/giovanni/#service=TmAvMp&starttime=1998-01-01T00:00:00Z&endtime=1998-01-04T23:59:59Z&data=AIRS3STD_7_0_OLR_A&dataKeyword=Outgoing%20longwave%20radiation

3.5. Latent Heat Flux

Latent heat flux is the flux of heat that released to the atmosphere from the Earth's surface with evaporation of water at the surface and subsequent condensation of water vapor in the troposphere. It is an important component of Earth's surface energy budget.

https://giovanni.gsfc.nasa.gov/giovanni/#service=TmAvMp&starttime=&endtime=&data=GLDAS_CLSM025_DA1_D_2_2_Qle_tavg&dataKeyword=latent%20heat%20flux

Main items to be observed:

Features of three dimensional winds during pre-monsoon to monsoon transition period.Vertical wind, moisture convergence and rainfall. Correlation between wind shear and rainfall. Evolution of OLR field in relation to MOK. Spatial pattern of lower and upper level circulation. Reversal of Mean sea level Temperature, pressure at transition phase.

Correlation coefficient

The correlation coefficient is a statistical function and which measures the strength and relationship between two variables and which do not measures a nonlinear relationship. The value of C.C have a range between -1 and 1. A correlation of -1.0 shows a perfect negative correlation, while a correlation of 1.0 shows a perfect positive correlation. A correlation of 0.0 shows no relationship between the movement of the two variables

Correlation coefficient = covariance(X, Y) / (stdv(X) * stdv(Y))

CHAPTER 4

RESULTS AND DISCUSSION

In this section, the vertical structure of monsoon circulation is analyzed in detail, using wind profile radar data, and spatial structure of monsoon circulation is well studied using ERA-interim data sets. Many other meteorological features showing abrupt evolution during the monsoon transition phase over the Asian summer region also studied in detail. Thermodynamic environment of Indian summer monsoon region also shows changes associated with the pre-monsoon to monsoon transition process, there is a large relationship is observe between the LCL height and availability of moisture.

4.1. RAINFALL

The southwest monsoon season from June to September accounts for about 70-90 percent of the annual rainfall over major parts of India. The highest rainfall pockets are generally those receiving orographically induced rainfall during the active monsoon period. The concentration of heavy rainfall zones are generally along the high mountain regions of the Western Ghats, the eastern Himalaya and along some mountainous regions on the central Indian Himalayan ranges. Monsoon rainfall over the Indian subcontinent provided by Arabian Sea and Bay of Bengal branch of monsoon low level jet stream. With the sudden establishment of the large-scale monsoon circulation a wetter monsoon condition developed over the country. Low level jet stream brings the moisture and moistens all over the country. Cloud characteristics also shows changes with the monsoon transition, and the pre-monsoon heating helps to increase the cloud cover and provides the significant amount of rainfall all over the country.

4.1.1. Time-Latitudinal Variation of Climatological Rainfall (Mm/Day) For India (70-80e).

Fig 1 shows a Latitude time cross-section of climatological rainfall of 4 year composite over the Indian monsoon region, within the Asian monsoon system. A rapid northward shift of rain-belt to the northern position seen around late May to early June and rapidly it returns to the equator in September. And this also portrays the monsoon onset that is a sudden shift between two semi permanent positions of two active rain belts. The rain belt in the equator is active from October to April and another one at the 15 N active in the period of June-July-august. There is a depressed Rain-belt in the equator during June-august. Studies and models shows there are a quite strong inverse relationship exists between monsoon rain belt and equatorial rain-belt. Indian summer monsoon rainfall is traditionally attributed to the north–south migration of the ITCZ, which follows the sun. low pressure area near the equator shows a North-South migration where winds are converges and rising and the water vapor in them condenses and forming clouds and rain, this can be attributed as the monsoon rainfall over continents.

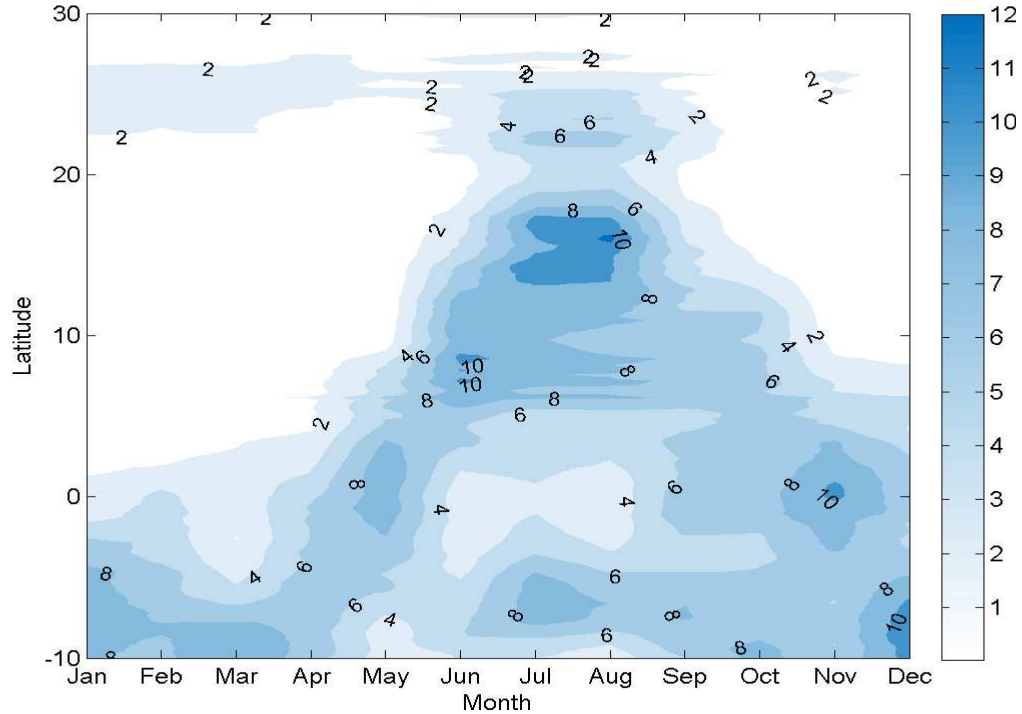


Fig.1.Time-latitudinal variation of climatological rainfall (mm/day) for India (70-80E).

4.1.2. Evolution of Rainfall

Beginning of the monsoon rains over the southern Indian peninsula indicates the arrival of monsoon and which marks the date of MOK. Fig.2. shows abrupts transition of area average rainfall over Kerala ,from -10th day of MOK to +10th day of MOK, The onset of monsoon can be observed here since monsoon is associated with high amount of rainfall maintaining continuity over the upcoming days. Changes in precipitation coincide with the development of low-level jets. The sudden increase in rainfall is similar to the LLJ trend during the MOK period. Krishnamurti (1985) provided an objective method for MOK, noting that drastic changes known to occur during the onset of the monsoon, including rapid increases in daily precipitation rates, sharp increases in vertically integrated humidity, and low-level flows.

In the present study similar observation is observe, the evolution of precipitation over Kerala with respect to the MOK showing a sharp increase in rate.

In fig.3. Daily rainfall for the years, 2017–2020 are composited over the southern peninsular India. The evolution rainfall over Kerala from 10 days prior to 10 days after the onset shows an abrupt increment, and this spectacular increment marks the MOK. LLJ carry moisture from Arabian Sea and the strength of LLJ controlled the moisture flux and rainfall along the west coast of Kerala.

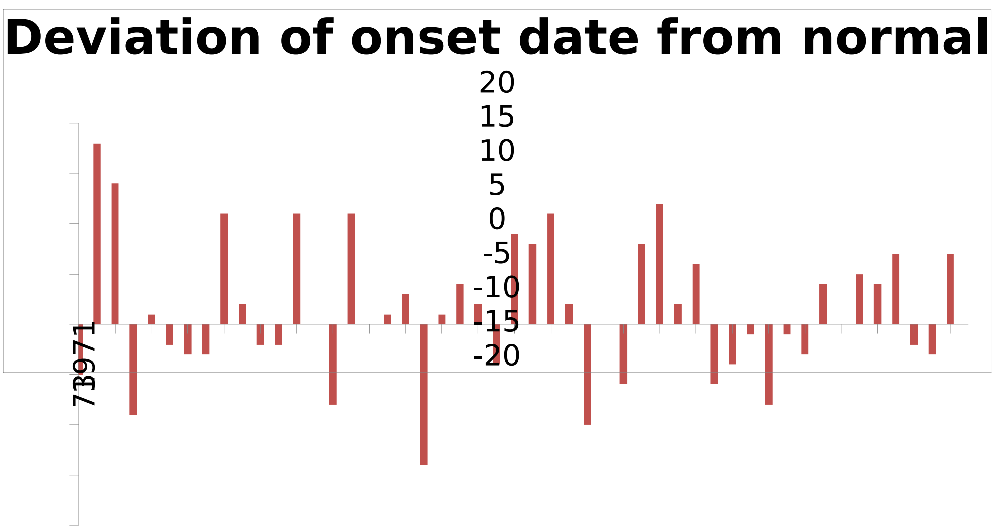


Fig.2.Deviation of onset date from normal onset date

As per the new normal, the monsoon sets over Kerala around 1st June. Monsoon onset over Kerala (MOK) has been considered the commencement of India’s rainy season. Graph showing deviation of onset date from mean date. Many synoptic and subsynoptic variabilities have control on the onset date. The first thing to declare correct date of onset is understanding of the atmospheric circulations and energetic associated with the onset. Interannual variability of MOK relates on the tropical cyclogenesis in the western pacific ocean, evolution of deep convection in the indian and western pacific ocean,evolution of the 850hpa and 150hpa wind fields and sea surface temperature in the indian and pacific ocean. There is intense convective heat source over south asia it is spatially large and MOK swithes on this. A surface pressure gradient is developed between Indian subcontinent and western equatorial Indian ocean, and this pressure gradient maintain the monsoon circulation and strength of LLJ. Therefore, the abnormally low surface pressure over Asia before the monsoon season increases this gradient and strengthens the jet stream. These developments lead to the early arrival of the monsoon in central India. Monsoon Onset date over Kerala show an increasing trend of about 0.9 days per decade, and have a significant of about 93% level (using a t-test). (Chakraborty., 2017). Objective criteria to declare MOK by IMD considered rainfall over 14 stations in Kerala. As the difficult to use the station-wise data, in this study evolution of rainfall over Kerala is defined as the rainfall averaged over 8–12N, 74–78E.

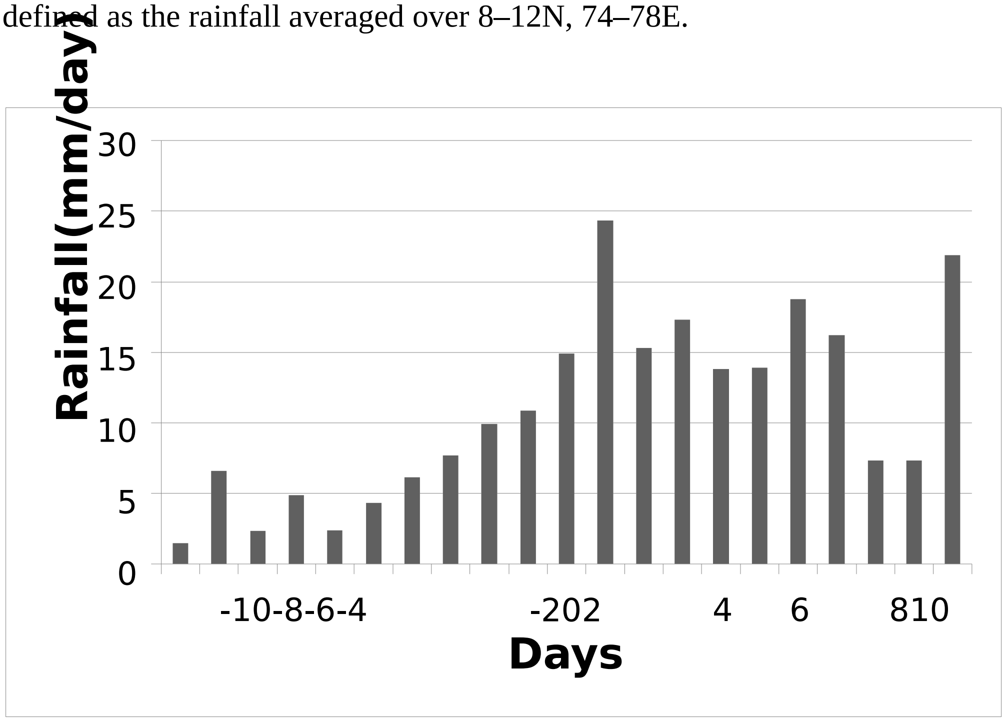


Fig.3 . Abrupt transition of rainfall (area average over Kerala). For a period of 10th day of onset to +10th day of onset.

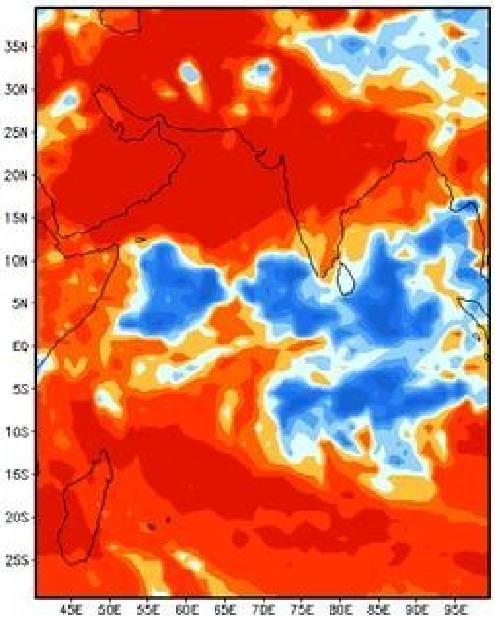
At -1st day of MOK the area averaged rainfall is 11 mm and this elevated value sustain on the next day and declares the 2nd day (MOK) as the onset day. IMD considering 14 stations of Kerala for the onset declaration, while in this study because of the difficulty to collect the station wise data, evolution of rainfall over Kerala is defined as the rainfall averaged over 8-12 N and 74-78 E longitude.

This shows a sharp and spectacular increase of rainfall and rainfall maintaining continuity over the upcoming days and variability in rainfall results from both local synoptic variability and large-scale dynamics of the summer monsoon.

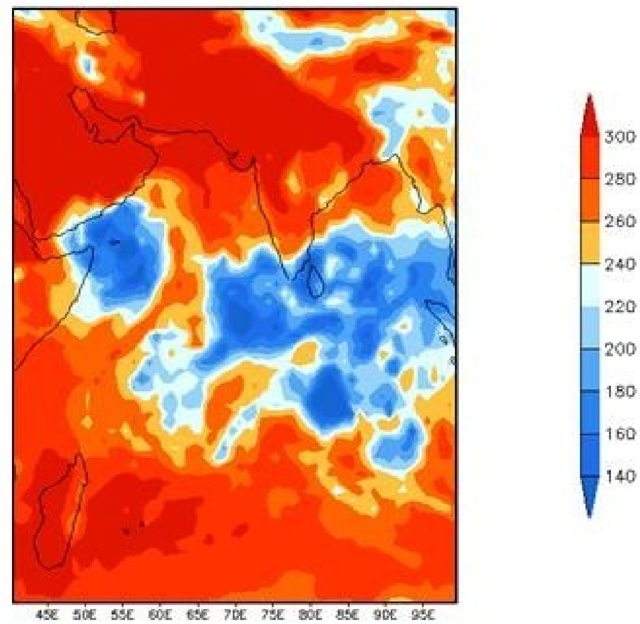
4.2. **Evolution Of Outgoing Long Wave Radiation**

To examine the two-dimensional evolution of monsoon circulation, the composite of daily OLR in a five day interval from 10 days prior to the 10 days after the onset is plotted. A strong convection band developed over the south of Indian subcontinent during the transition period driven by the strong low-level westerly winds and the convective area associated with the low -level jet stream extend to northwards to the Indian subcontinent in the post onset days.

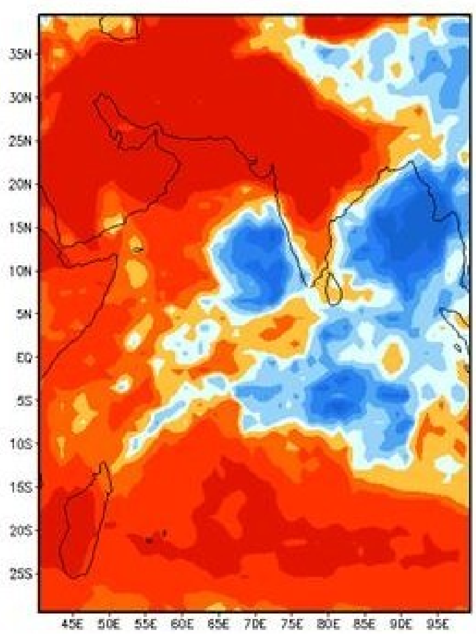
OLR on -10th day



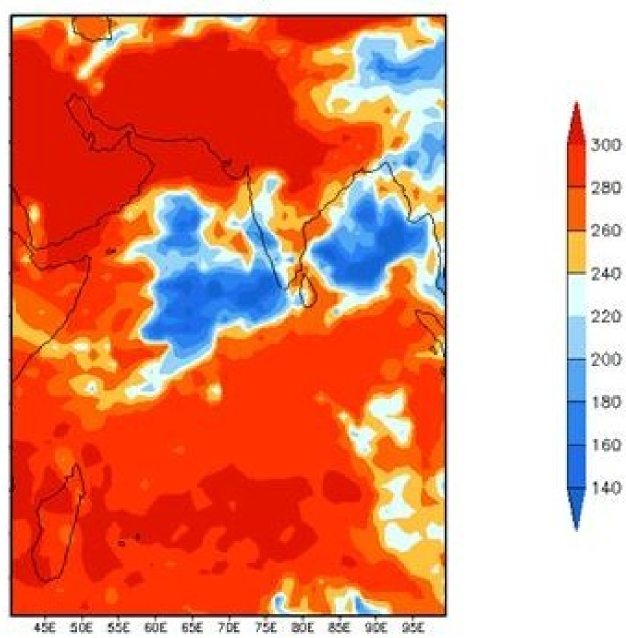
OLR on -5th day



OLR on MOK



OLR on +5th day



OLR on +10th day

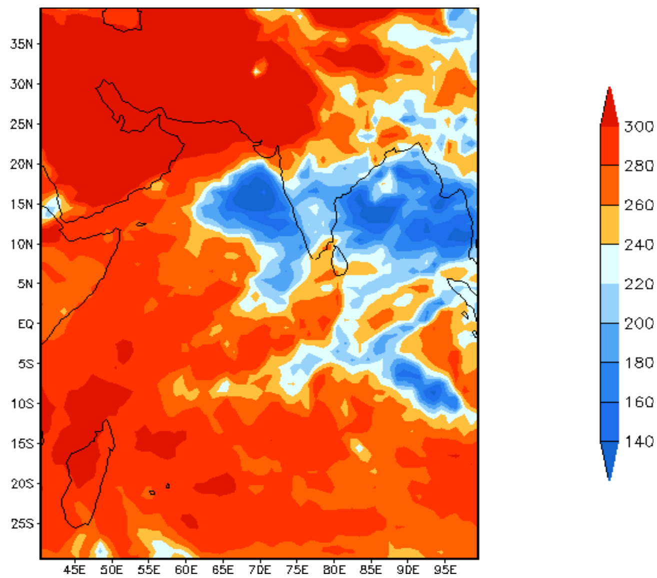


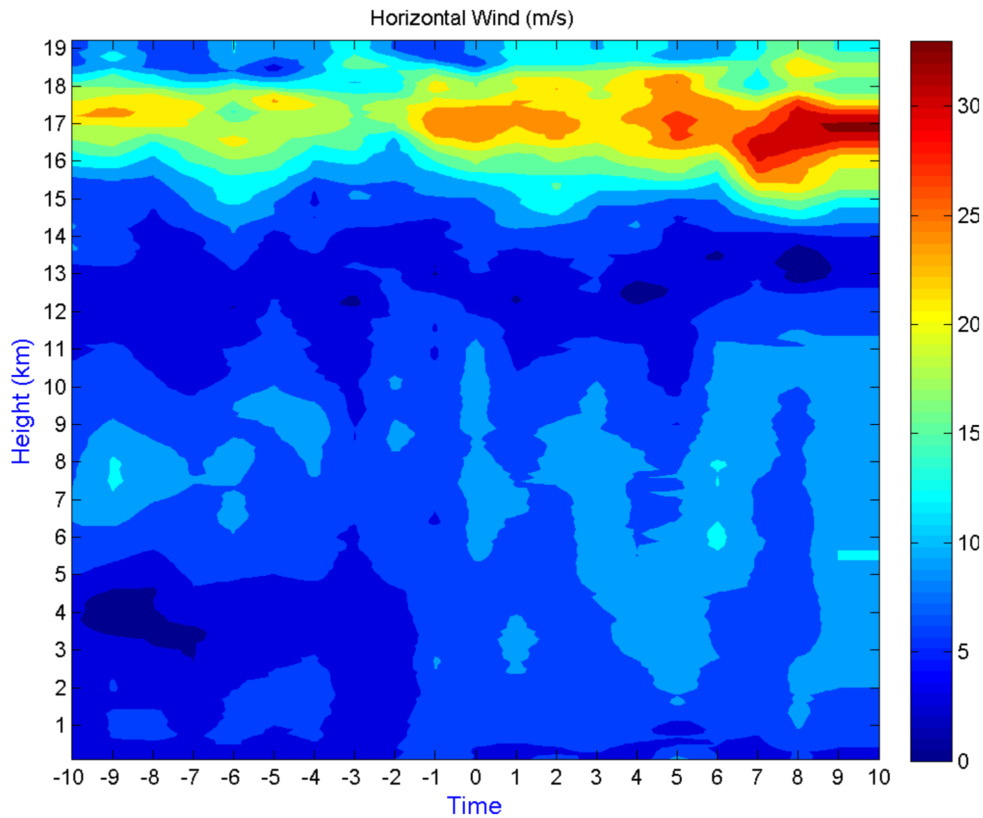
Fig.4. Evolution of daily OLR over the Indian Monsoon region

At -10th day Indian peninsular region have high values of OLR and at -5th day southwest coast have a small value. Major convective area is the northeast Arabian Sea north of equator about 70 E. At the onset the south-west coast and the north east Arabian sea becomes the high convective activity areas. Major convective areas have an OLR value below 200w/m2. On onset, the main convective area shifts to east Bay of Bengal and over southeastern Arabian Sea (OLR anomaly $< -60Wm{-}2$ from 220 w/m-2) .OLR anomaly $< -60Wm{-}2$ indicating probability of rain > 0.9 can be seen off the Kerala coast. The advance of south west monsoon also indicated by the increase of convective activity in the Arabian and Bay of Bengal Sea. Composite OLR field of 4 years (2017-2020) is plotted (-10th day to +10th day) depicts Northward propagation of the convection is well observed in the plot. Higher values of OLR imply less convection and hence indicate less cloudiness and rain. Convective activity over Bay of Bengal and Indian peninsular region increases in the post onset days and the strength of zonal component of LLJ shows a high correlation with OLR values.(Joseph et al.,2003).

4.3. **Radar Observation of Monsoon Circulation**

In this section, the vertical structure of monsoon circulation is analyzed in detail. The mean altitude structure of the synoptic-scale southwest monsoon winds is studied using the radar data. Radar wind observation gives clear picture of the evolution of monsoon circulation. The evolution of Tropical Easterly Jet in the upper troposphere and the progression monsoon low-level jet are important indicators of monsoon transition and clearly observed in the radar data.

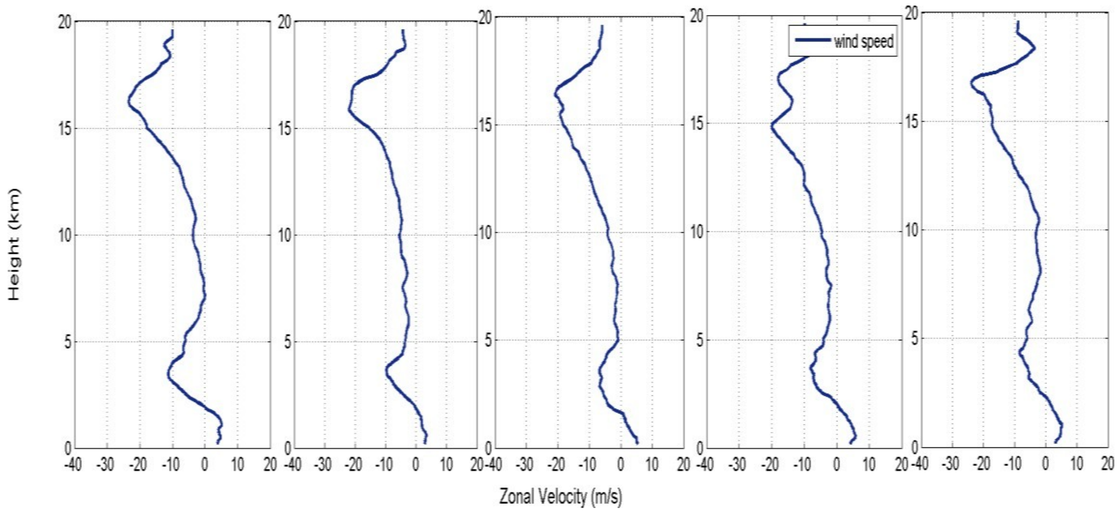
Daily mean time series of horizontal wind speed



Time-height cross section of daily mean time series of zonal wind speed for the period of 10 days prior to 10 days after the MOK.

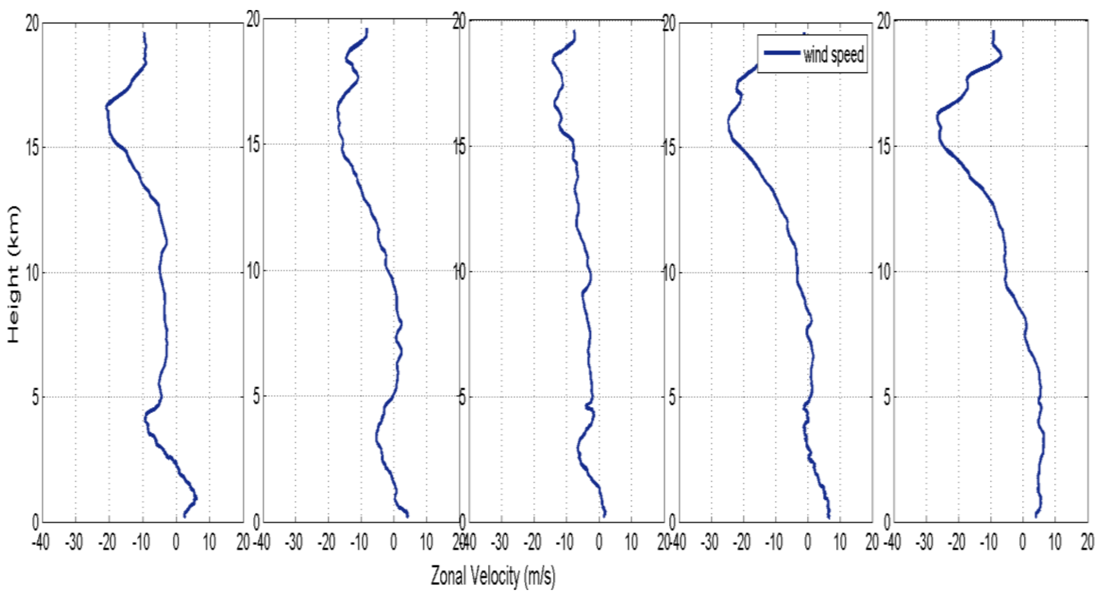
From this plot evolution of TEJ and LLJ are can be clearly observed, the detailed study of zonal wind meridional wind and their vertical structure will done in the upcoming section.

4.3.1. Vertical Structure Of Zonal And Meridional Wind (a)



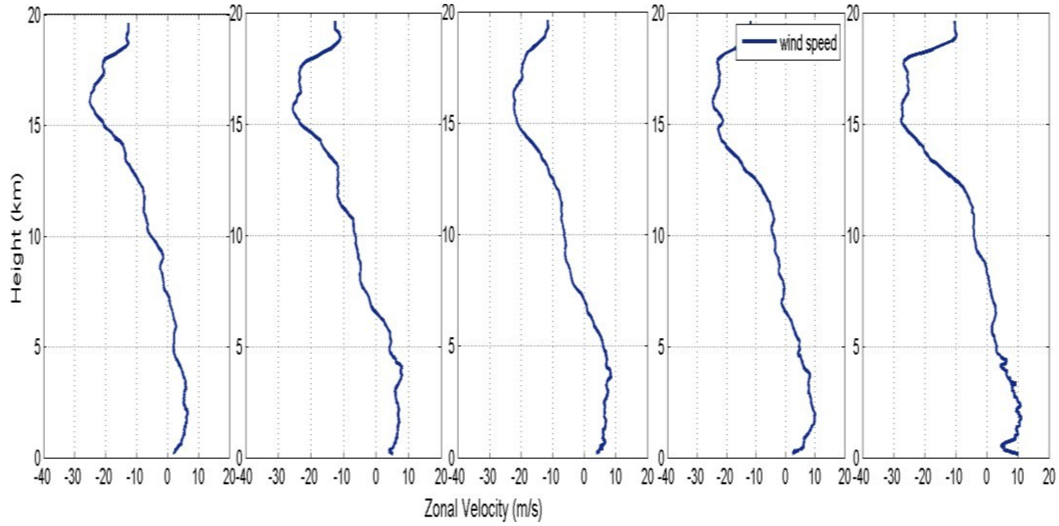
Height (km)
Zonal Velocity (m/s)
wind speed

(b)



Height (km)
Zonal Velocity (m/s)
wind speed

(c)



(d)

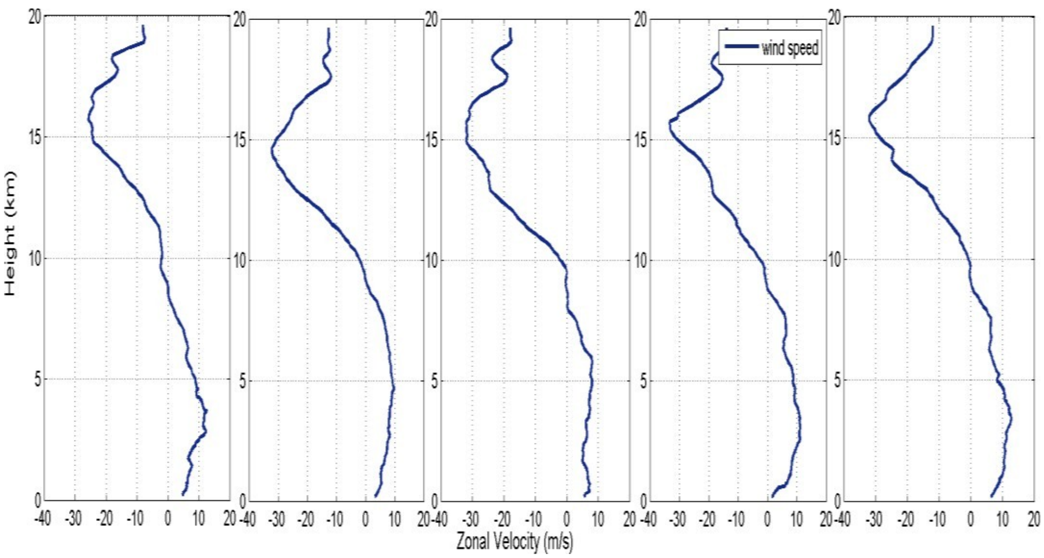
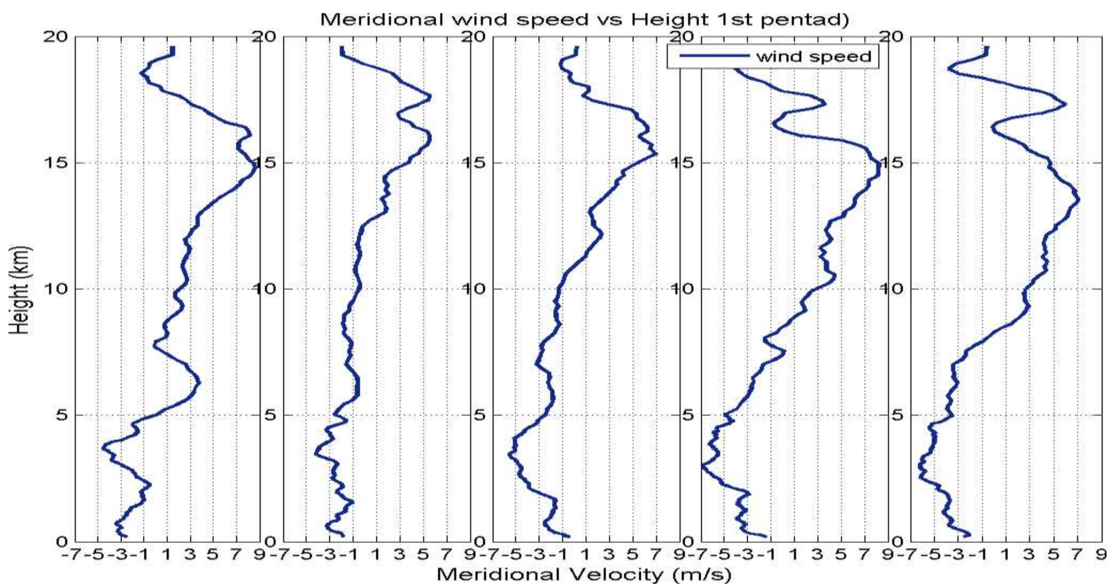


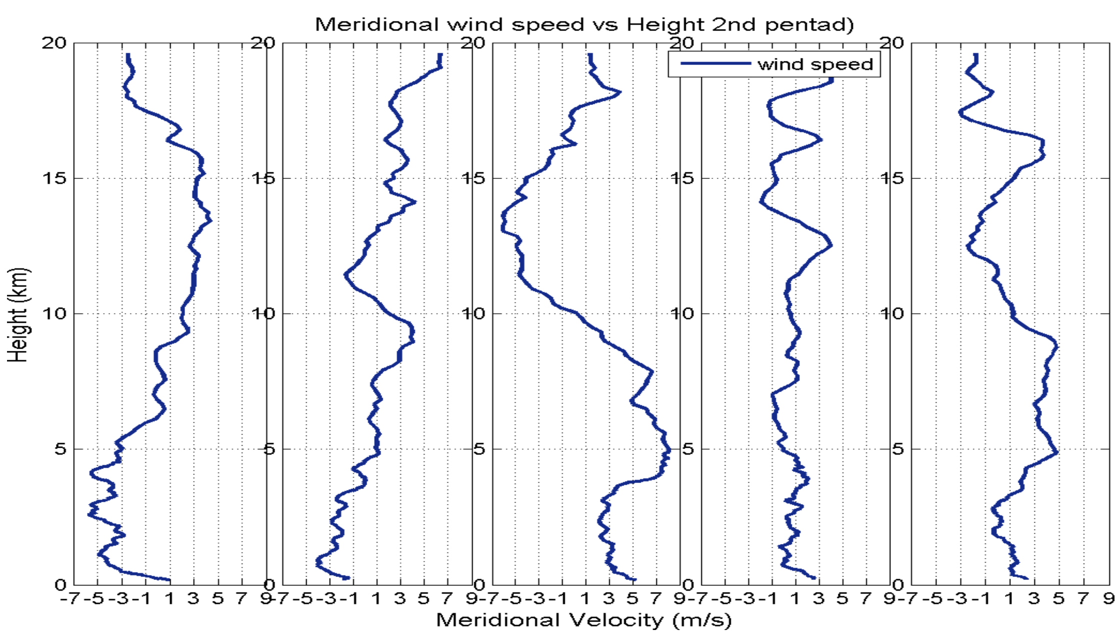
Fig.5.(a-d) Vertical structure of zonal wind (Wind profiling Radar observation 10 days prior to 10 days after of MOK**)**

(a)



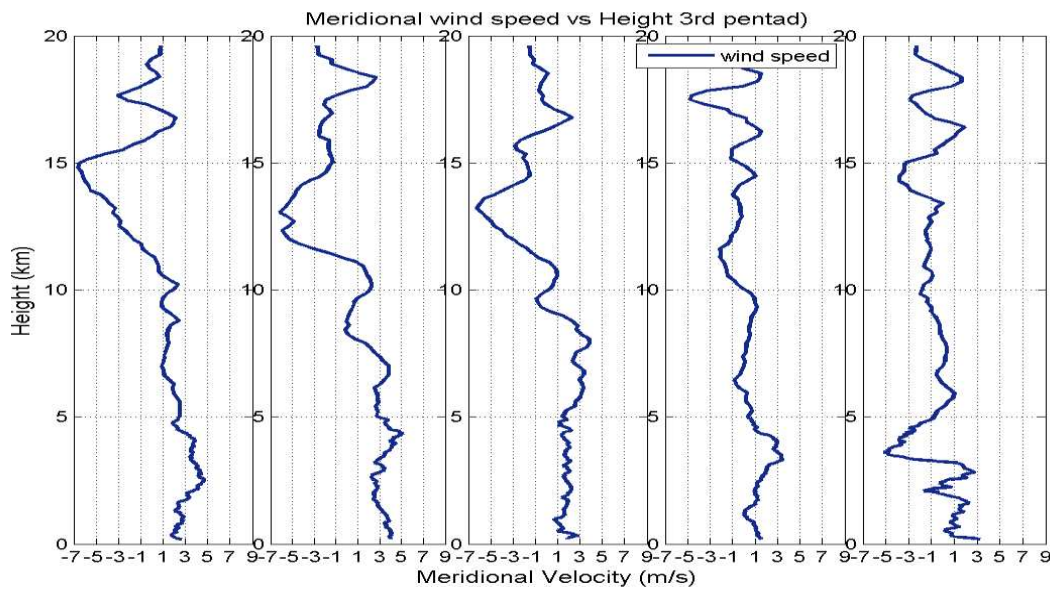
Meridional wind speed vs Height 1st pentad)
wind speed
Height (km)
Meridional Velocity (m/s)

(b)



Meridional wind speed vs Height 2nd pentad)
wind speed
Height (km)
Meridional Velocity (m/s)

(c)



(d)

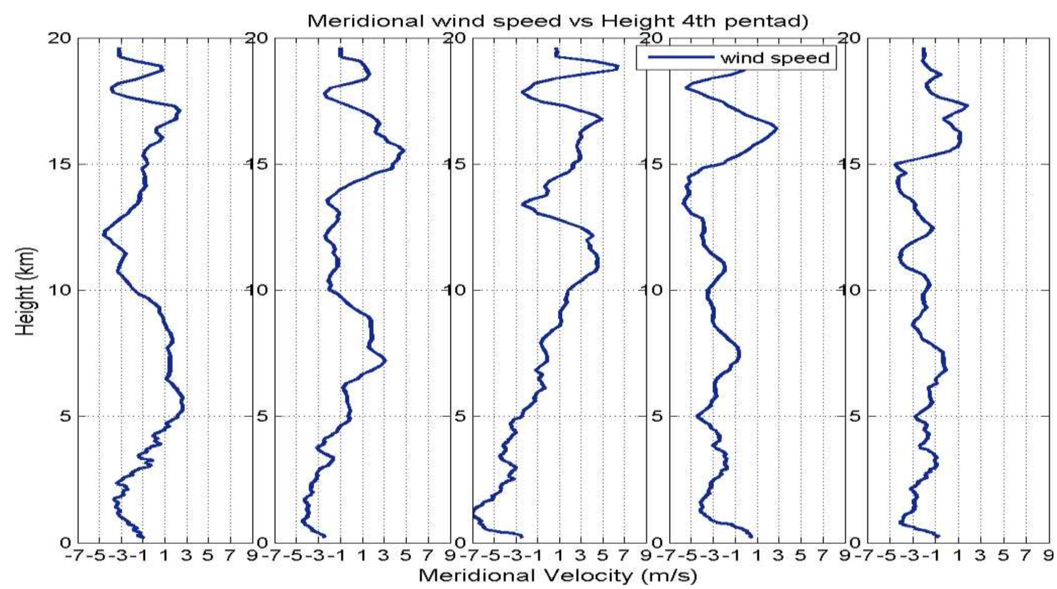


Fig.6.(a-d) Vertical structure of meridional wind (Wind profiling Radar observation 10 days prior to 10 days after of MOK**)**

The figure 5 showing the vertical structure of zonal wind observation from the Radar. A strong LLJ with its core at 1.5-2 km is observed onset phase. Lower tropospheric wind pattern is below 700 hpa, easterlies occurs before 2 days of onset, then an abrupt change in the direction of the wind occurs. There are westerlies observed in the surface (below 2km) from the 10 days of onset and that is increasing in strength and depth near to the onset. Tropical easterly jet streams are starting to evolve about one week before onset in the upper troposphere. One day before MOK the height of westerlies is observed about to 8 km .Vertically sheared flow is established near to onset. Low level wind maximum is observed about 2.5 km above ground level and a peak wind speed of 7 m/s is observed. A reversal of wind direction in to easterlies is observed above 7 km. low level maximum indicates the MLLJ of summer monsoon.

Transition of wind pattern occurs at an altitude of 4-5 km in the monsoon months. Strong westerlies at lower troposphere in 1.5 to 3km (Ruchith et al., 2016). Sometimes in the post onset days the westerlies extend into upper levels.

The figure 6 showing time-height cross section of the vertical structure of meridional wind pattern obtained from the wind profiler radar. Magnitude of meridional component is small as compared to the zonal wind component. X- axis show the velocity. Negative sign of wind velocity represents the northerlies and positive wind means southerlies. During south west monsoon period the wind in the west coast of Kerala is mainly northerly. Radar observation of vertical structure of meridional wind of 10 days prior to after 10 days of Monsoon Onset over Kerala showing northerlies prevailing before 2 week ago in the west coast of Kerala

4.3.1.1. Low Level Wind Features

Fig.7. shows the evolution of depth of westerlies from pre-onset days to post-onset days of the years 2017 to 2020. All year shows an abrupt increase in the depth

of westerlies near to the onset and continuous in the upcoming days. In 2018 low-level westerlies and the core speed of LLJ shows an abnormal decrease 2 days after the onset. This variability effects on rainfall pattern over the area. Westerlies show an abrupt increase in depth during the onset days all in the 4 years. Year-year variability in the maximum wind speed, depth of westerlies observed.

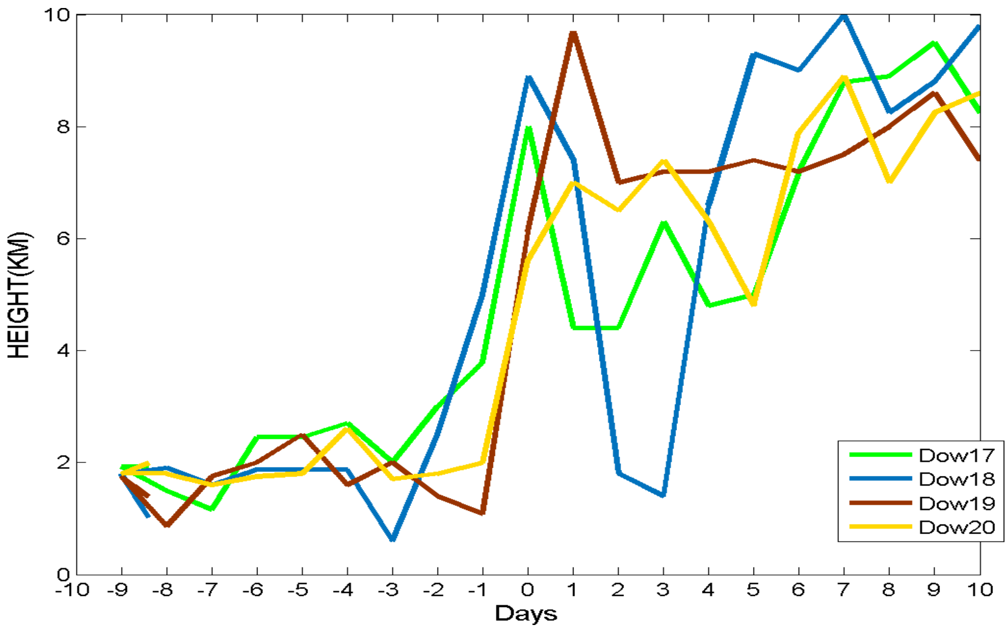


Fig.7.a. Evolution of depth of westerlies

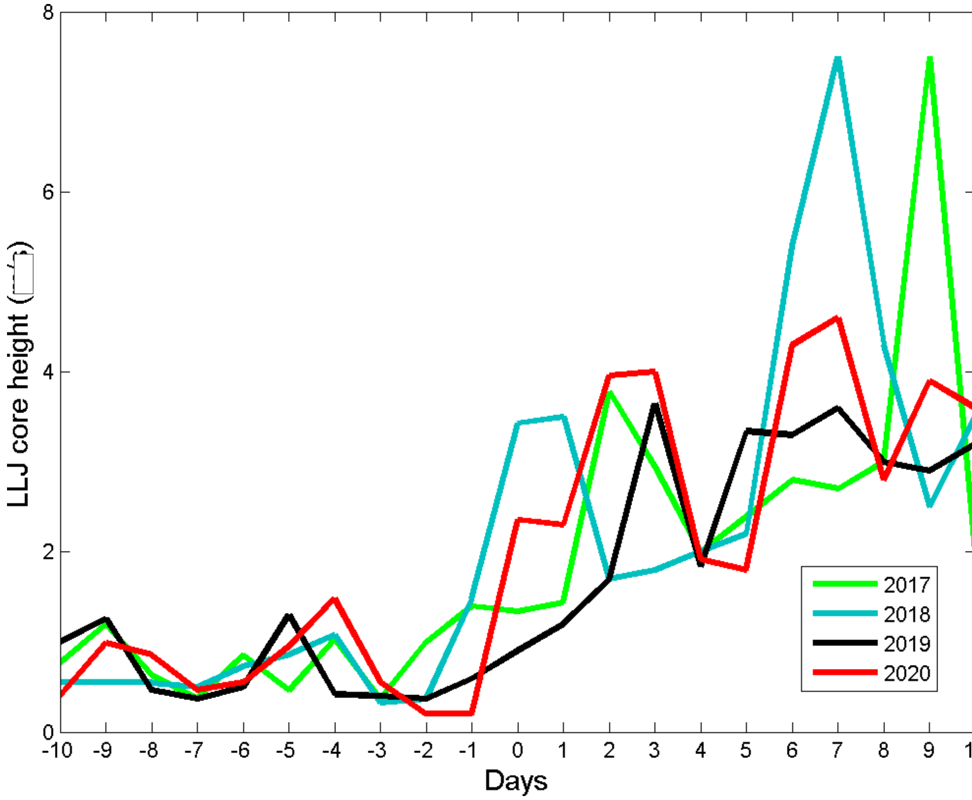


Fig.7.b. LLJ core height

MLLJ observed between the height of 1 to 4 km and the core speed of the jet observes at the height of 1.5 km above mean sea level and this carry moisture from the southern Indian ocean to the Asian monsoon region. Variability in rainfall over the Indian peninsular region have a large correlation with the strength and depth of LLJ, because the rainfall over the monsoon region increases when LLJ core speed is increases. The core speed and core height reach values of 10.04 m s−1 and 2 km, respectively, at the time of MOK in 2017. In 2018 the value of core speed and height reached a value of 16.67 m s−1 and 3.65 km during MOK. In 2020 the value of core speed and height reached a value of 16.67 m s−1 and 3.65 km during MOK. An abrupt increase in the core speed and height of LLJ is not shows in the 2019 as in the

IMD predicted onset date. But a strong low level westerly established 2 days after the onset date predicted by IMD.

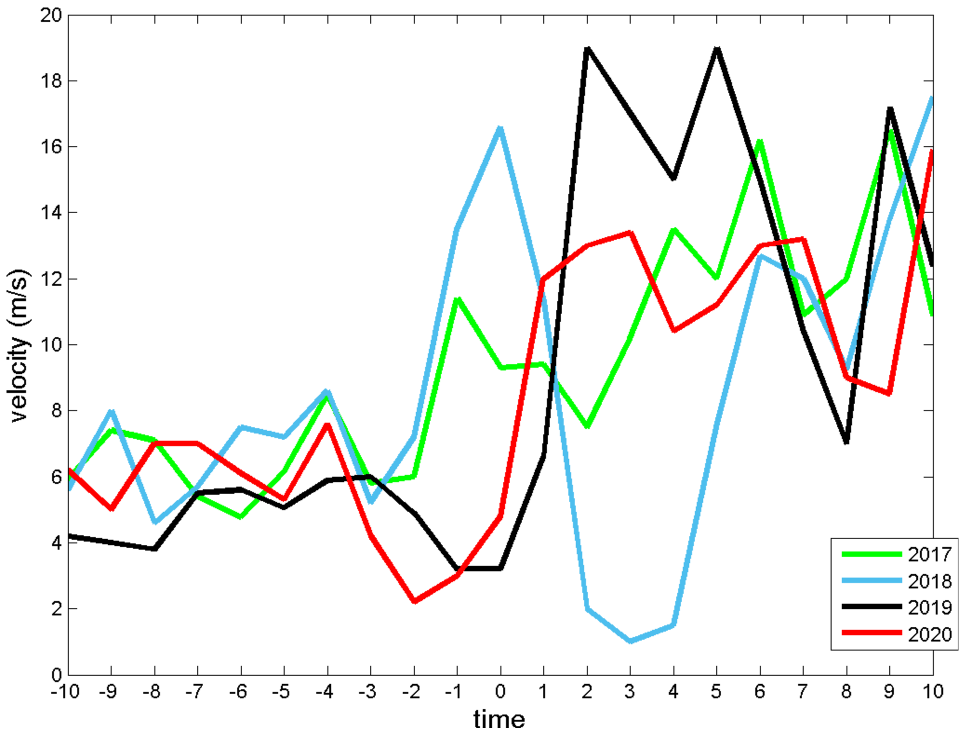


Fig.7.c. core speed of LLJ

4.3.1.2. . Kinetic Energy Of Low Level Westerlies

If the wind speed shows variation, kinetic energy associated should also change accordingly in the same manner. They have shows that the sudden rise in low level kinetic energy can be a potential predictor to declare onset. (Lau and Yang., 1996). Change in the strength of wind is representing by zonal kinetic energy. After 6th day of onset highest kinetic energy of 107 J/kg in the lower layers is attained it is representing a westerly with a speed of about 14 m/s. There is a sudden increase in kinetic energy of low-level westerlies from 20-30 J/kg to 100 J/kg before onset and this is maintained during the upcoming days. The gradual increase in Kinetic energy in the lower troposphere during the monsoon transition period is due to the gradual strengthening of monsoon low level circulation. A sharp increase in kinetic energy from the value of 25 and 65 $m^2 s^{-1}$ is observed over the Indian peninsular region . Sharp rise of kinetic energy at 850 hPa is an appropriate time to declare the onset of the summer monsoon over India (Raju et al.,2005)

The present study reveals that the evolution of low-level kinetic energy can be use as potential predictor for the possible onset of the summer monsoon over India.

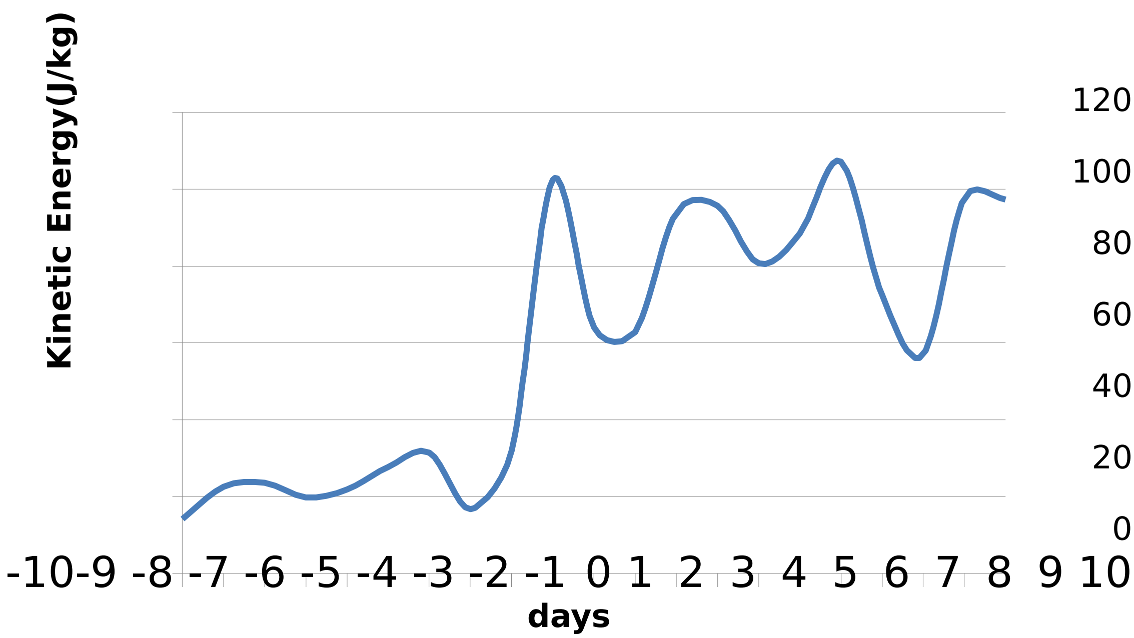
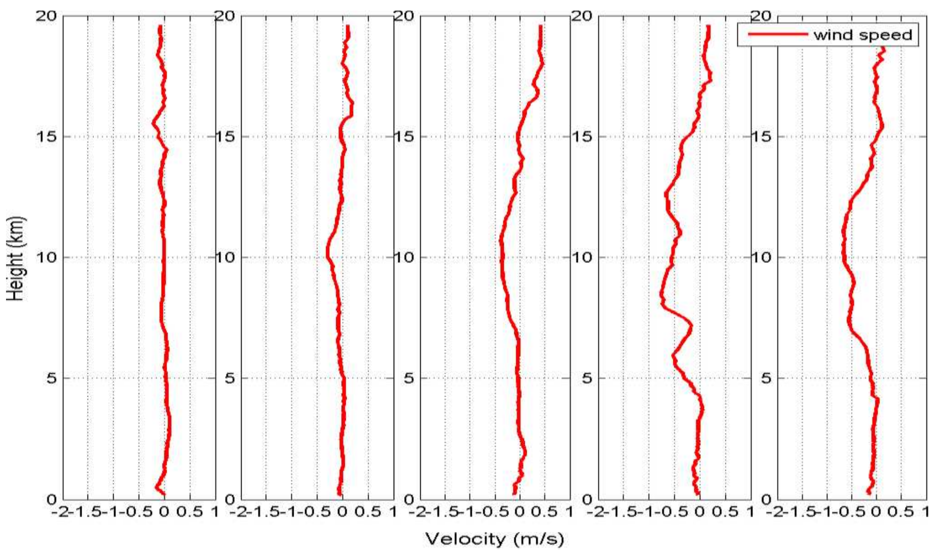


Fig.8.Kinetic energy of low-level westerlies

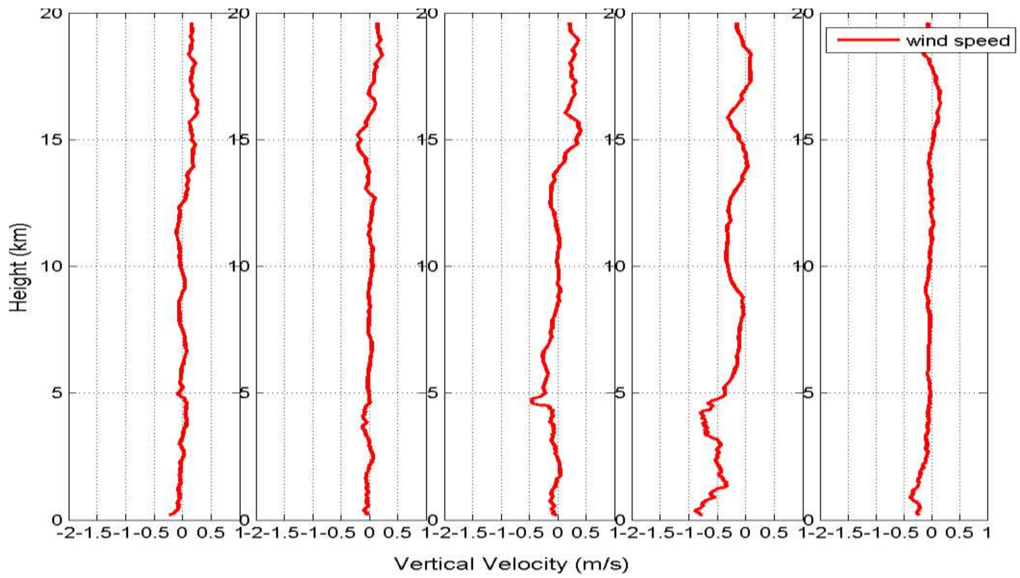
4.3.2. Vertical Wind

The vertical wind has to act, moisture has to converge, and it takes time for the final cloud formation. Vertical wind structure shows upward motions after onset in the lower atmosphere, indicates the strong convergence that occurs in the troposphere leads to cloud formation and rainfall. Vertical wind does not always vary in exact accordance with rainfall. This is because the vertical wind has to act, moisture has to converge, and it takes time for the final cloud formation, this time lag can range from 2-3 hours to 1-2 days. Pre-onset phase vertical wind is predominantly descending motion. Here vertical wind observed from radar is plotted from 10 days prior to 10 days after of the onset date. Vertical wind has a very low magnitude and its value varies from negative to positive.

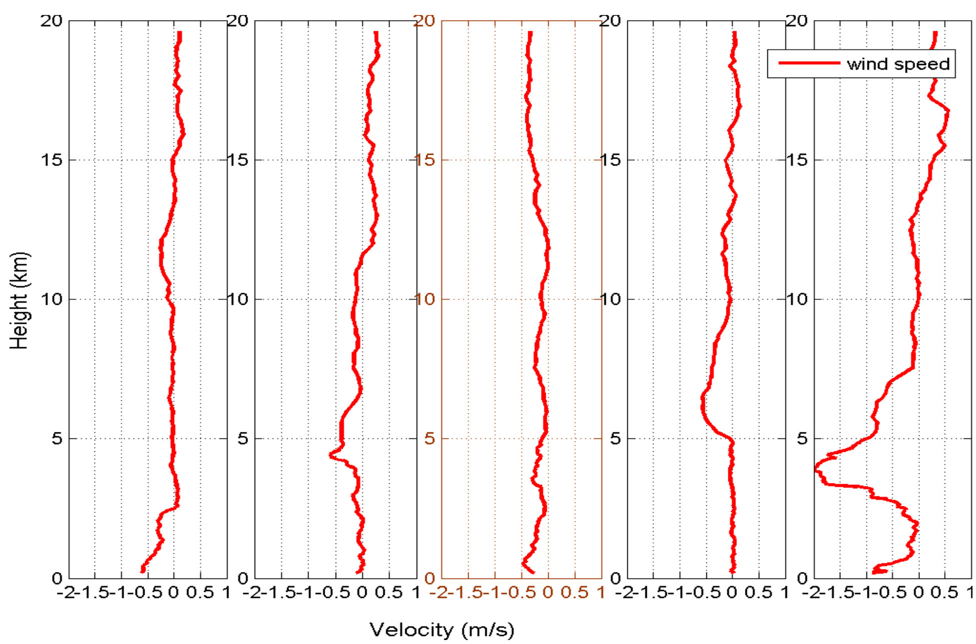
(a)



(b)


wind speed
Height (km)
Vertical Velocity (m/s)

(c)


wind speed
Height (km)
Velocity (m/s)

(d)

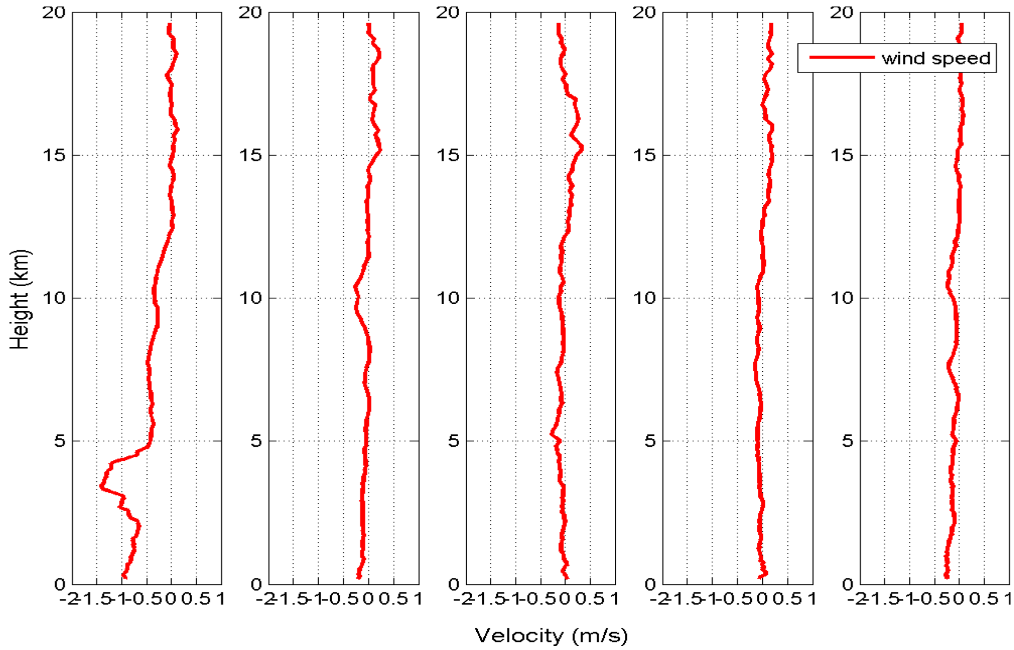
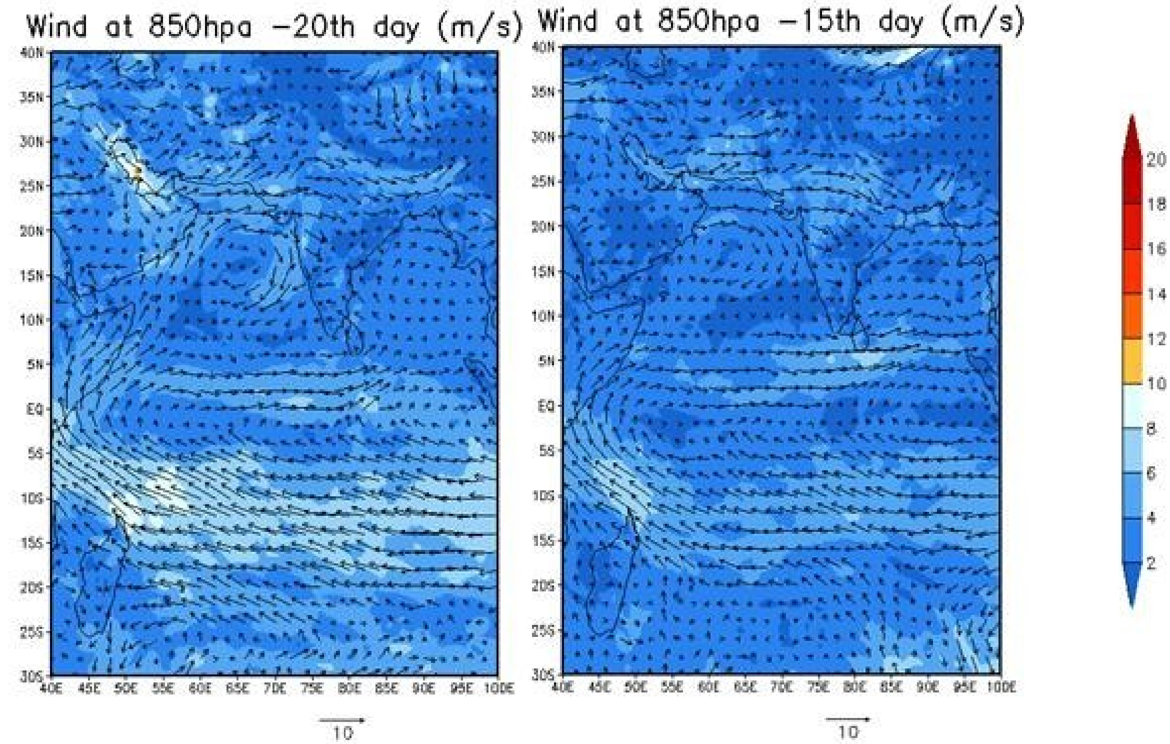
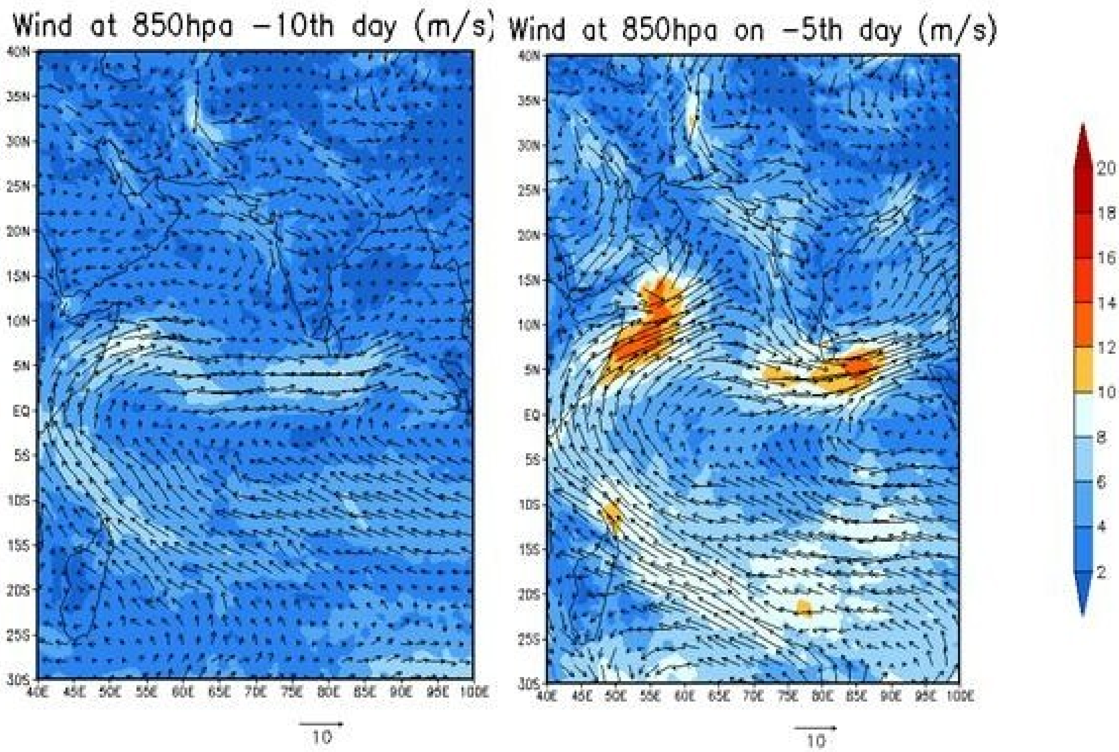


Fig.9.(a to d), Vertical wind observed from Wind profiler radar

4.3.2. SPATIAL PATTERN OF LOWER TROPOSPHERE CIRCULATION



Wind at 850hpa -20th day (m/s)
Wind at 850hpa -15th day (m/s)
40N
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
15S
20S
25S
30S
40E 45E 50E 55E 60E 65E 70E 75E 80E 85E 90E 95E 100E
10
20
18
16
14
12
10
8
6
4
2


Wind at 850hpa -10th day (m/s)
Wind at 850hpa on -5th day (m/s)
40N
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
15S
20S
25S
30S
40E 45E 50E 55E 60E 65E 70E 75E 80E 85E 90E 95E 100E
10
20
18
16
14
12
10
8
6
4
2

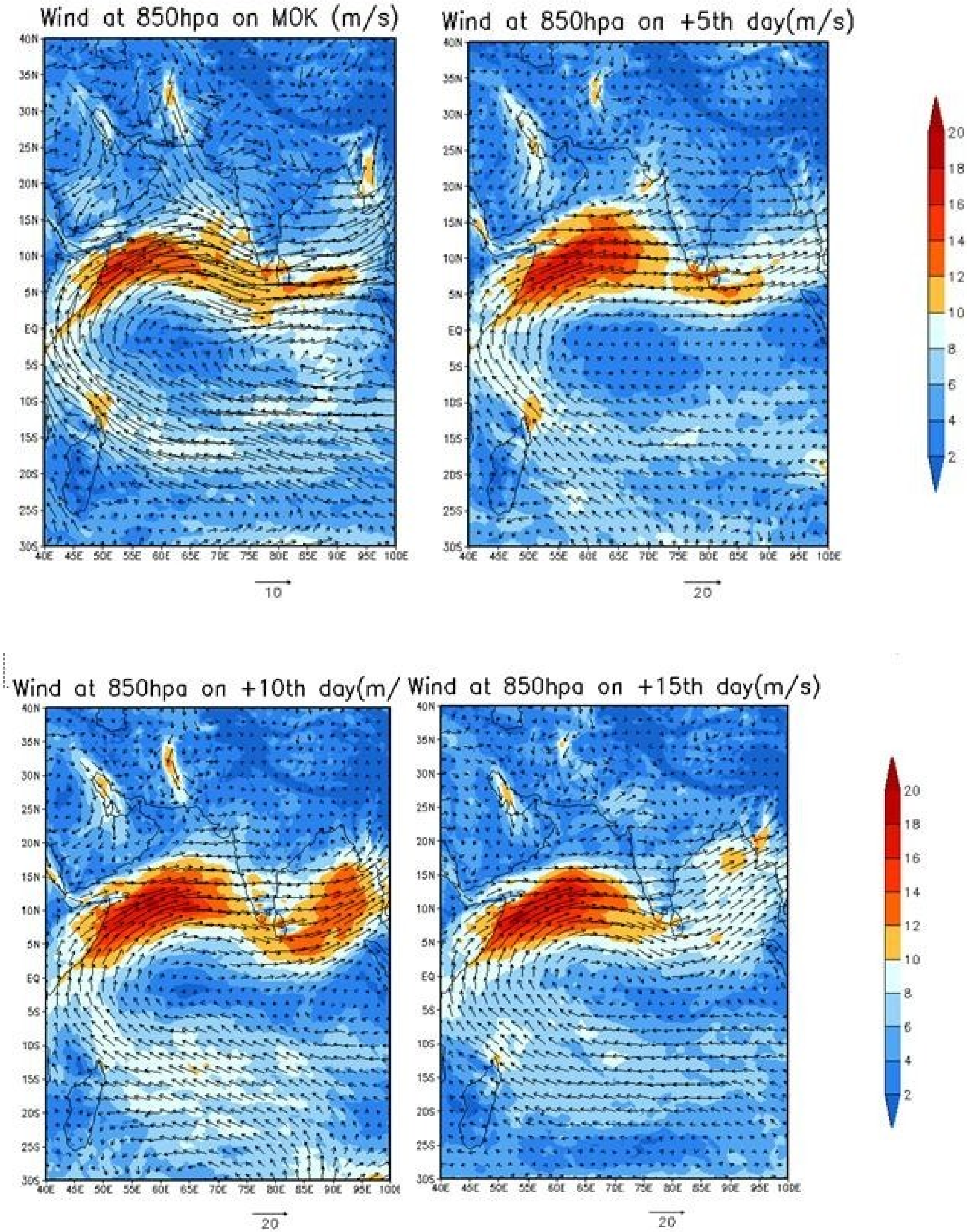
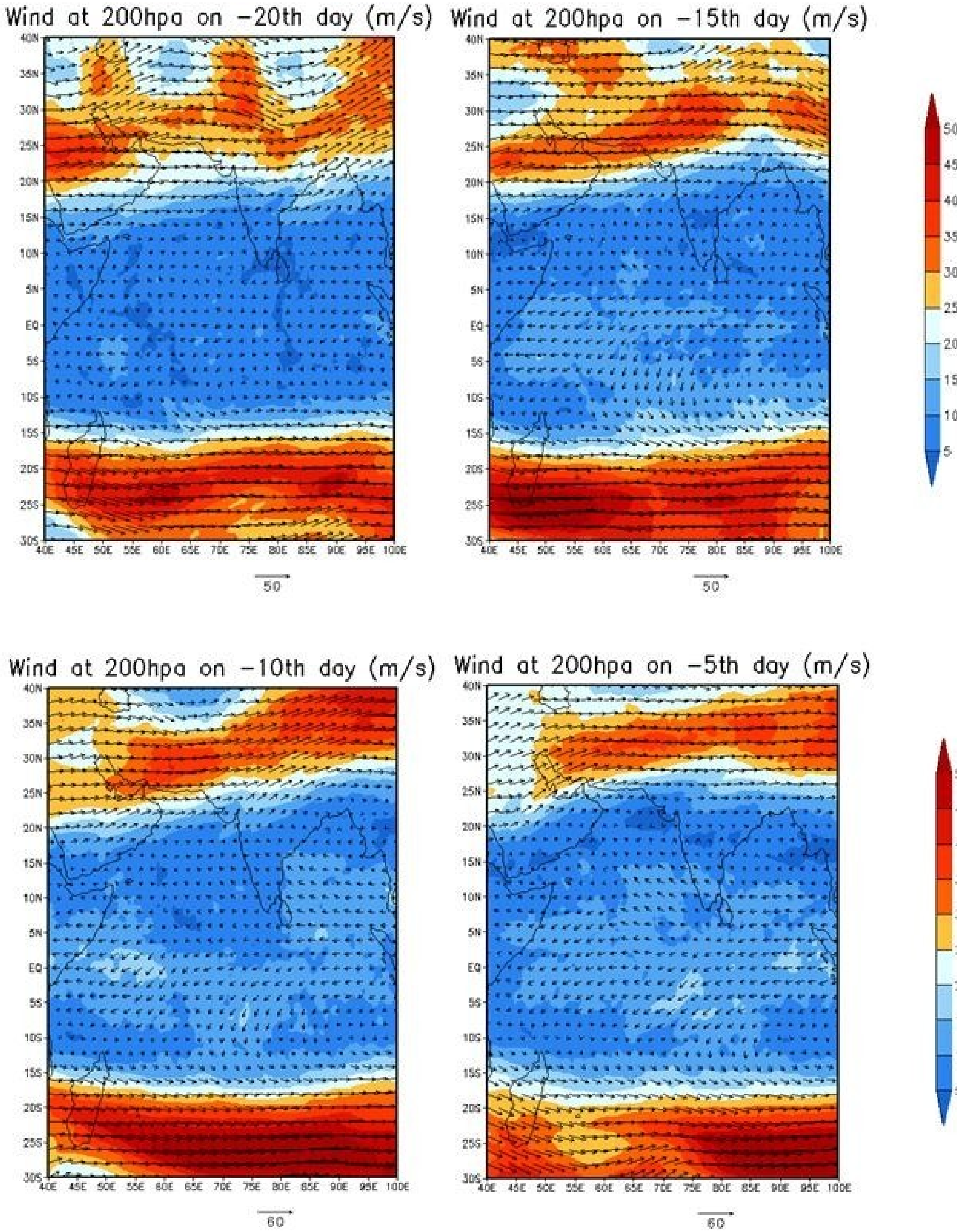

Wind at 850hpa on MOK (m/s)
Wind at 850hpa on +5th day(m/s)
Wind at 850hpa on +10th day(m/
Wind at 850hpa on +15th day(m/s)
10
20
20
20
2 4 6 8 10 12 14 16 18 20

Fig.10 . Lower level wind features (spatial pattern)

The transition of global circulation from the pre-monsoon to monsoon is remarkable. Large scale convection over Indian subcontinent and meridional sea surface temperature gradient brings monsoon low-level circulations. The wind pattern in the southern peninsula before 20 days of onset is easterly and in the north India the wind direction is eastward. Before 10 days of onset the speed of westerlies at the tip of southern peninsula increases. A trough line forms south of the southern peninsula. At -5th day the wind strength increases at the trough. The trough at +5th day moves northwards and disappears. Low level westerlies get strengthening over the Arabian sea associated with the onset of monsoon and then in the post onset days which intensifies and extend to northern latitudes. Cross equatorial monsoon circulation over the western equatorial Indian ocean have a C-shaped flow pattern and termed as Somali jet. Pressure gradient force and the coriolis effect of earth rotation controlled the monsoon circulation, strong cross-equatorial flow and northward propagation from the pre-onset phase to the post-onset phase are seen in the lower troposphere features. The main cross-equatorial flow takes place to the north of the equator between 40 and 60 °E (Raju et al., 2005). The southwesterly are relatively stronger over the southwestern Arabian seas. Nearer the west coast of peninsular India, the winds are westerlies with speed 5-10 m/s, this pattern persists throughout the active phase of monsoon. By 10 days after onset the westerlies extent to north and merges with the prevailing subtropical westerlies of north India. Low level jet that provides the enough water vapor for the convective activity occurring in the active monsoon region (Joseph and Sijikumar, 2004), and the depth and the strength of westerlies in the west coast of Kerala increases at the evening periods during the active monsoon season (Viswanadhapilly et al., 2019)

4.3.3. SPATIAL PATTERN OF UPPER TROPOSPHERIC CIRCULATION


Wind at 200hpa on -20th day (m/s)
Wind at 200hpa on -15th day (m/s)
Wind at 200hpa on -10th day (m/s)
Wind at 200hpa on -5th day (m/s)
40N 35N 30N 25N 20N 15N 10N 5N EQ 5S 10S 15S 20S 25S 30S
40E 45E 50E 55E 60E 65E 70E 75E 80E 85E 90E 95E 100E
50
50
60
60
5 10 15 20 25 30 35 40 45 50
5 10 15 20 25 30 35 40 45 50

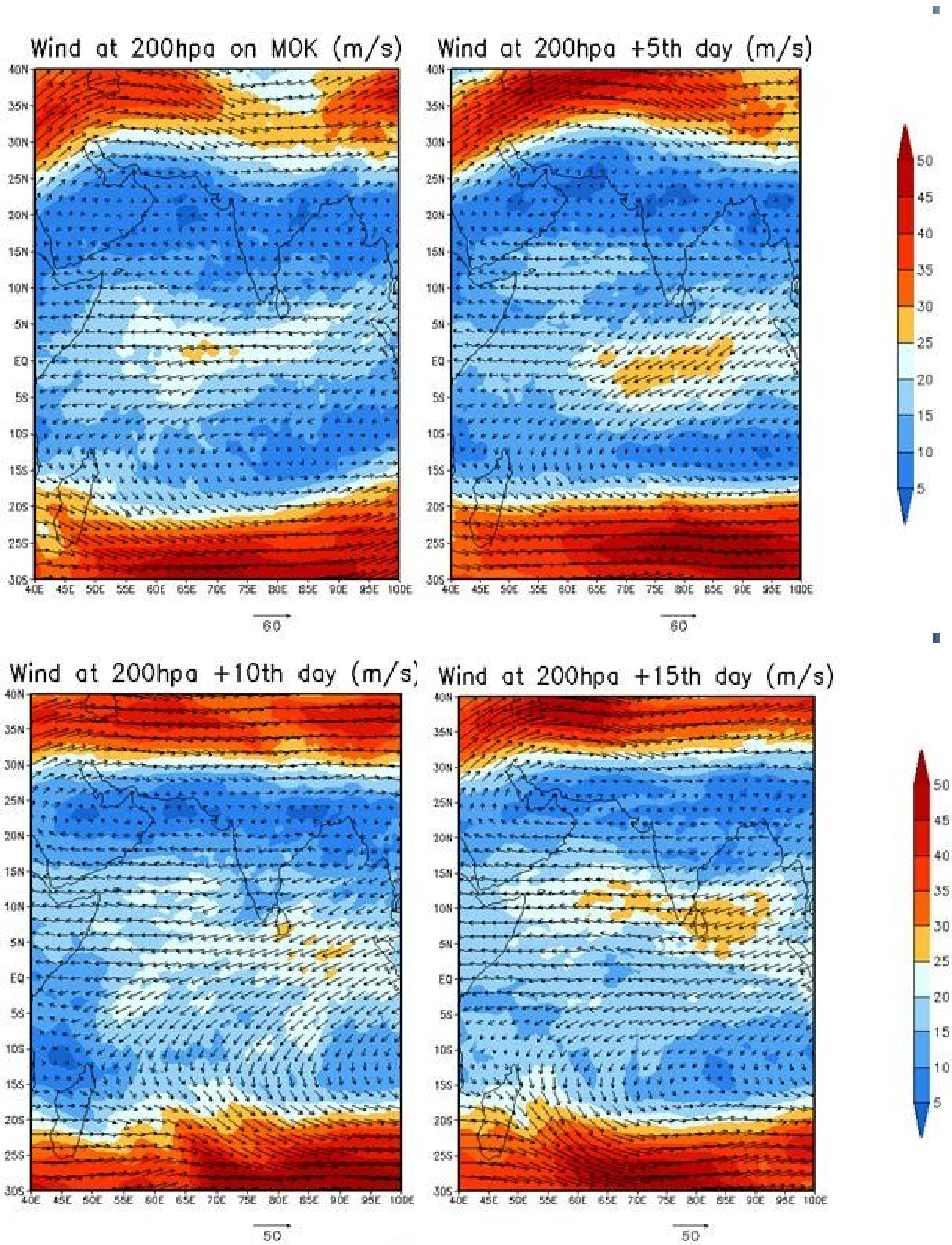


Fig.11. upper level wind pattern

The TEJ is a dominant feature of the Indian summer monsoon. TEJ shows a persistent intensity and the direction throughout the summer monsoon season. ts position fluctuates between 5° and 20°N. TEJ comes into existence quickly after the Sub tropical Jet stream has shifted to the north of the Himalayas (Early June). Somali jet, tropical easterly jet and the subtropical jet streams are playing a significant role in the establishment and advancement of Indian summer monsoon.

From fig.11. TEJ during the onset phase with a wind speed of 20ms-1 around the longitude 65 to 95E. It strengthens during this period. A gradual strengthening of TEJ in the west coast of Kerala is observing about 2 weeks before the MOK. Subtropical westerly wind at 30N on -15th day observed at a wind speed of more than 30 m/s, and it decreases by 10m/s on the monsoon onset of Kerala. Upper-tropospheric easterlies at the same time increase the speed of 10m/s.

4.3.4. Seasonal March of Wind

Fig.12. shows the seasonal march of winds at two levels such as at 850 hpa and 200 hpa over the Asian monsoon region 70ºE to 120ºE. With the development of Asian summer monsoon, the 850 mb wind from equator to 15 N is start to reverse in the April and maximum monsoon low-level westerlies observed in the July, this is coupled with the development of tropical easterly jet streams in the 200 hpa pressure level. At 25° N to 35° N the upper level westerly jet streams observed from Dec-feb but that migrates to northward when at April starts and it returns to original place associated with retrieval of south west monsoon. Vertically sheared flow established at equator to 20° N associated with lower level westerly's (LLJ) with a wind speed of about 10m/s and upper level easterlies(TEJ). Reversal of 850hpa winds from equator to 15ºN and subsequent build up of maximum low level westerlies indicates seasonal transition. Vertical

wind shear is at maximum at tropics at summer monsoon period when the easterly jet stream is its maximum speed. The 850 hPa zonal wind maximum is about 10m/s.

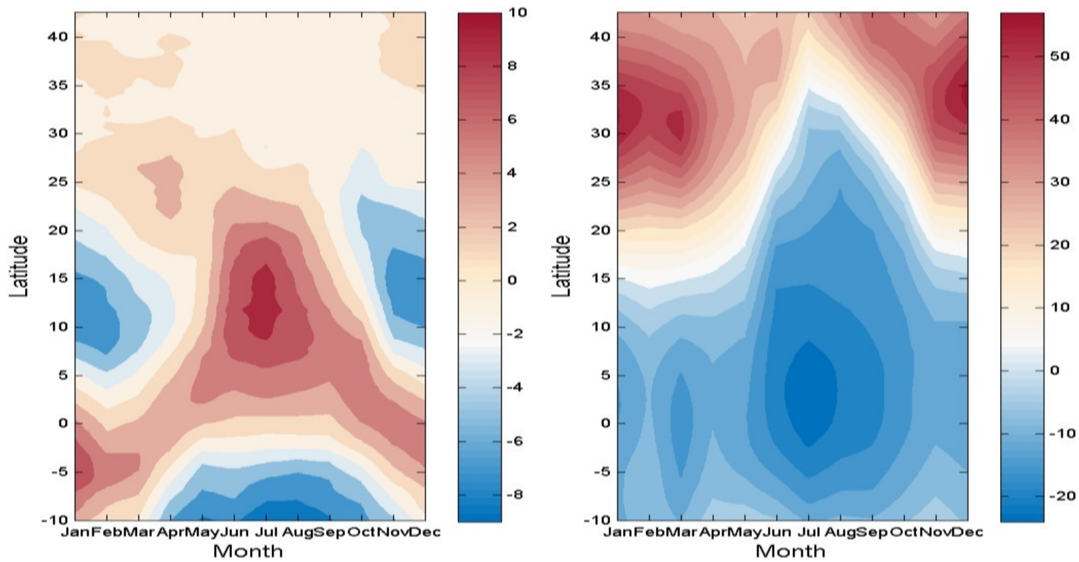


Fig.12. Time-Latitudinal variations 850 and 200hPa zonal wind (m/s-1) for the Asian summer monsoon region (70E-120E)

4.4. **Vertically Integrated Moisture Flux And Rainfall**

Fig.13. shows the graph of vertically integrated moisture flux in the primary axis and daily rainfall in the secondary axis. Time period in days is marked in the X-axis. At Kochi the daily rainfall shoot up from 1mm to 6mm (AWS data at ACCAR) on one day prior to the onset date. Vertically integrated moisture transport increases sharply with onset over Kerala. Moisture flux and rainfall shows a good correlation (cc=0.63). Moisture Flux is the product of a field of values and the wind speed is referred to as the flux of that field. Moisture flux means water vapour transport and it is integrated through the depth of troposphere to get the vertically integrated moisture flux.

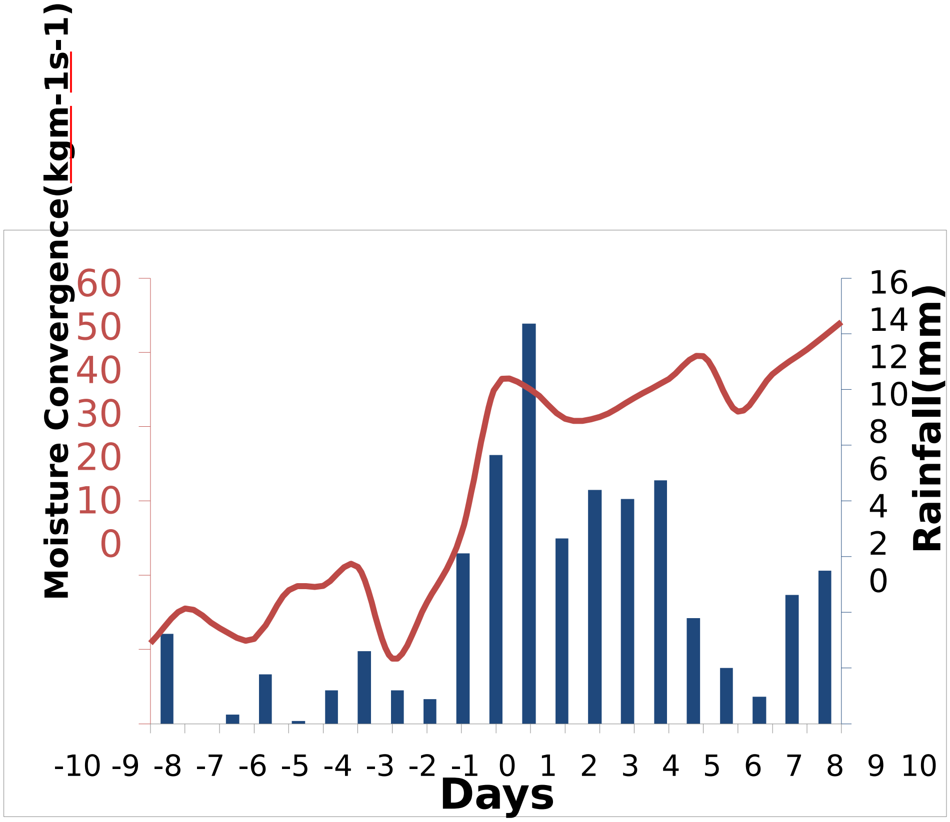


Fig .13.vertically integrated moisture flux

4.5. **Wind Shear**

Difference in the resultant (of zonal and meridional) wind velocities in different heights [corresponding to 850hPa and 200hPa; i.e. 1.44 km and 14.28 km respectively] were determined and plotted along with area averaged rainfall of Kerala obtained on those specific days. Plot shows there is a large correlation exist between the rainfall and wind shear(cc=0.67), that is monsoon onset is associated with a vertically sheared flow and a sharp increase in rainfall.

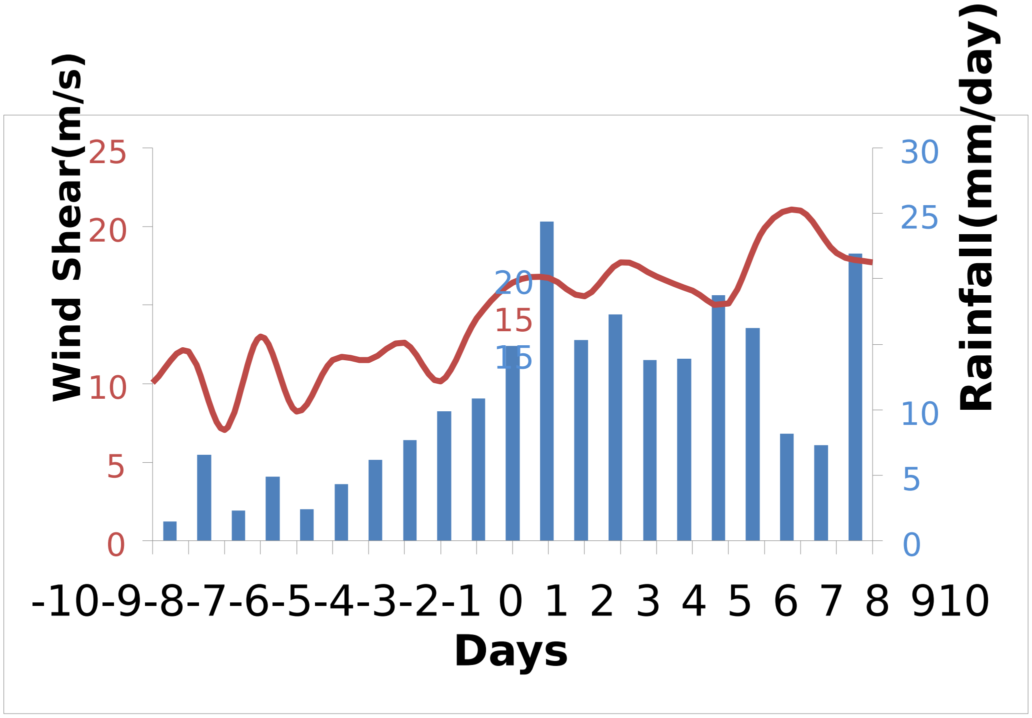


Fig.14. Vertical wind shear (U200-U850)and rainfall

4.6.**RELATIVE HUMIDITY**

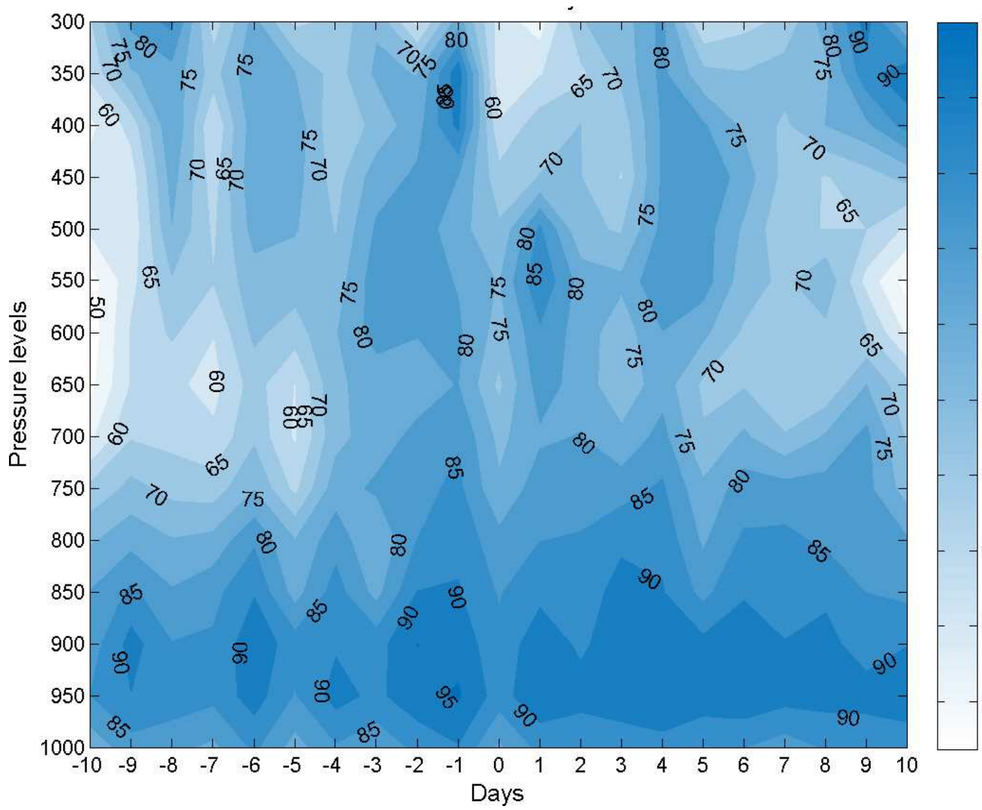
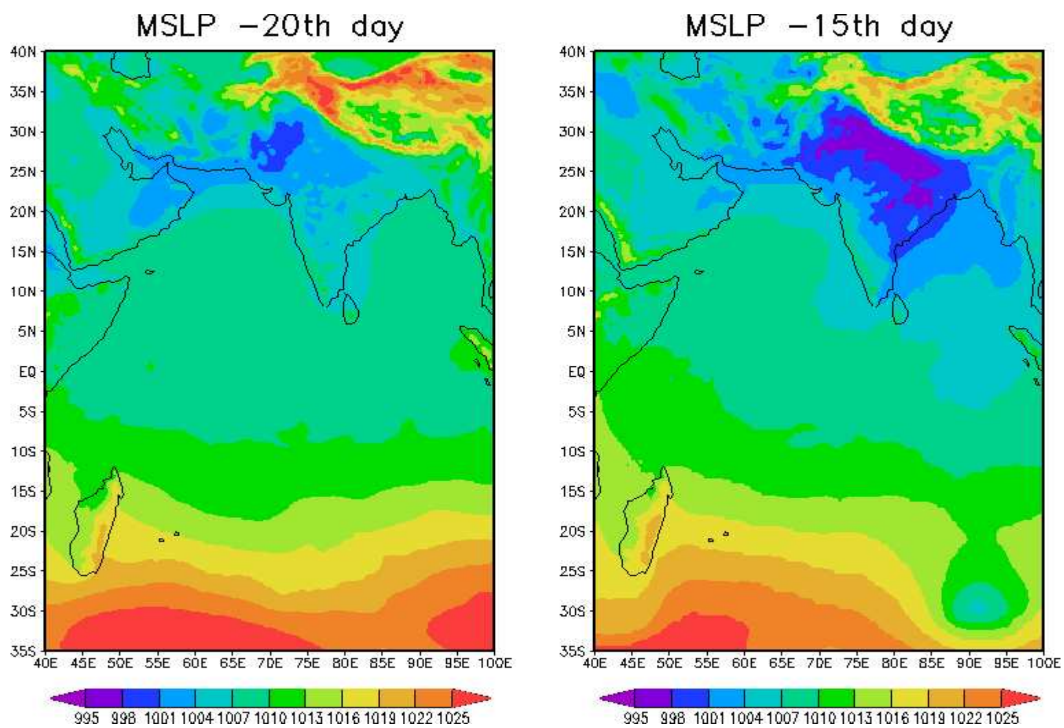


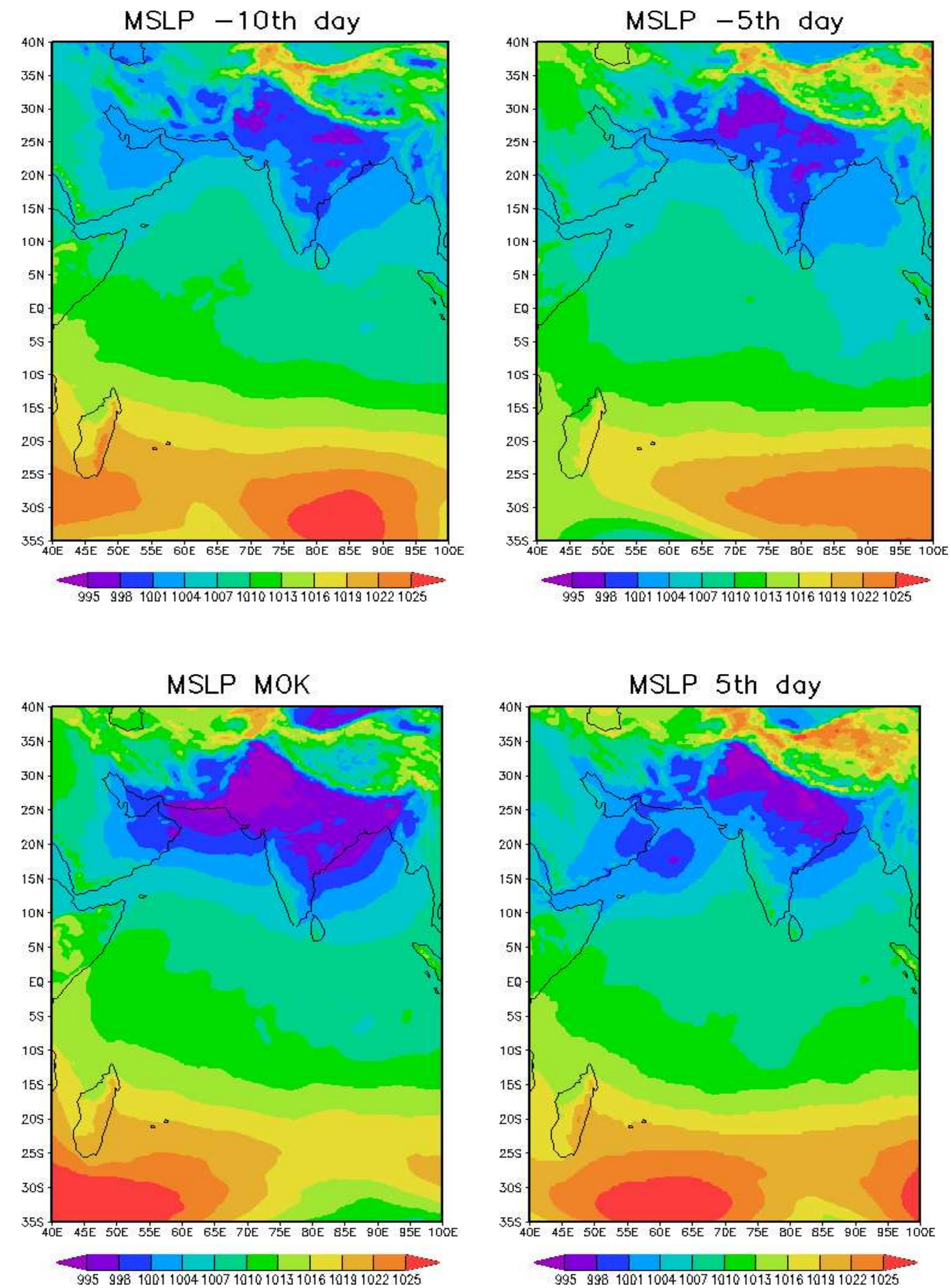
Fig .15.vertical structure of evolution of relative humidity

Composite vertical analysis of Relative humidity shows a sharp increase before 2 days of onset. Humid layer deepens before few days of local onset .70 %line sharply rises towards 300hpa levels before 2 days of onset. Build up of moisture occurs before 5 days ago of onset in Kochin indicates the arrival of southwest monsoon.

4.7.**Mean Sea Level Pressure Pre-Monsoon And Monsoon Period**

During April- May corresponding to the heating of land mass a heat trough is developed over the central Indian region and this is different from the TCZ that established in this region associated with monsoon onset . Thus the transition from spring to the summer monsoon season involves a transition from this heat trough to a dynamic trough/TCZ (Pai and Rajeevan, 2009). The pressure difference between the two major elements of the summer monsoon such as Mascarene high and the monsoon trough over northeast India clearly observed.





MSLP −10th day
MSLP −5th day
MSLP MOK
MSLP 5th day
40N 35N 30N 25N 20N 15N 10N 5N EQ 5S 10S 15S 20S 25S 30S 35S
40E 45E 50E 55E 60E 65E 70E 75E 80E 85E 90E 95E 100E
995 998 1001 1004 1007 1010 1013 1016 1019 1022 1025

Fig .16. Mean sea level pressure Preonset day to post onset days

In this figure the meridional pressure gradient along the asian summer region in premonsoon to monsoon transition phase is showing. Ocean–continent pressure gradient, which is the main driving force of the Asian summer monsoon, is larger. A deep low pressure area developed in the west Asian summer monsoon region as a result of pre-monsoon heating is known as heat low, and this helps to establish a meridional pressure gradient force and drives the monsoon circulation. The Monsoon Trough (MT) is an elongated area of a low pressure running parallel to the Himalayan Mountains in a west to east direction. It extends up to 5-6 km tilting southwards with height. From plot at -20th day a low pressure is developed at NW India. This high-pressure region located between 25°S-35°S and 40°E-90°E near the Mascarene Islands in the southern Indian Ocean is a source of Southwest monsoon in India. Since, it is a high pressure is, it is also known as Mascarene high. A stronger high pressure will produce stronger monsoon circulations. By the first half of May whole of central India is heated up and a low pressure area created.

4.8. **Meridioanal Pattern Of Tropospheric Temperature**

Pre-monsoonal heating over the Indian land mass results a formation of meridional gradient of TT, which drives the monsoon circulation because a meridional tropospheric temperature gradient will results a meridional pressure gradient force and an establishment of a monsoon circulation (Xavier et al., 2007). Tropospheric temperature of the north of the equator starts to increases in the end of May and in the June, July, August month’s high temperature is observed over 25-35 degree latitude. At this time tropospheric temperature at the latitude of the south Indian Ocean shows very low temperature. A temperature gradient is formed between souths and north of equator which is mainly drives the monsoonal circulation. In the end of September the temperature pattern reverses as like in the pre-monsoon months. From October to February tropics is comparatively and subtropics is cooler than tropics.

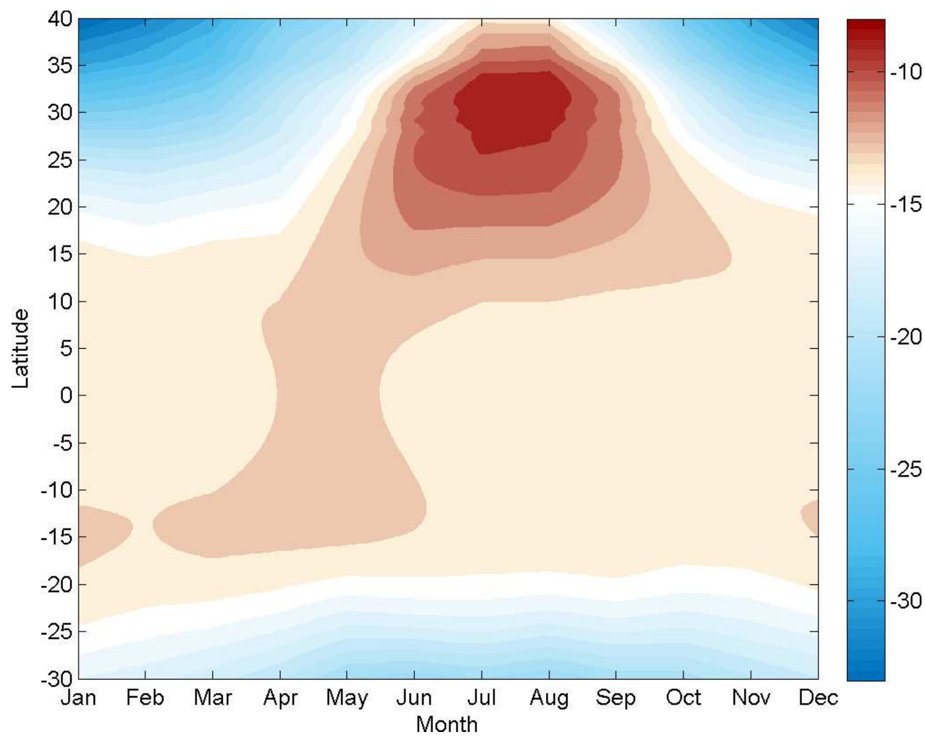
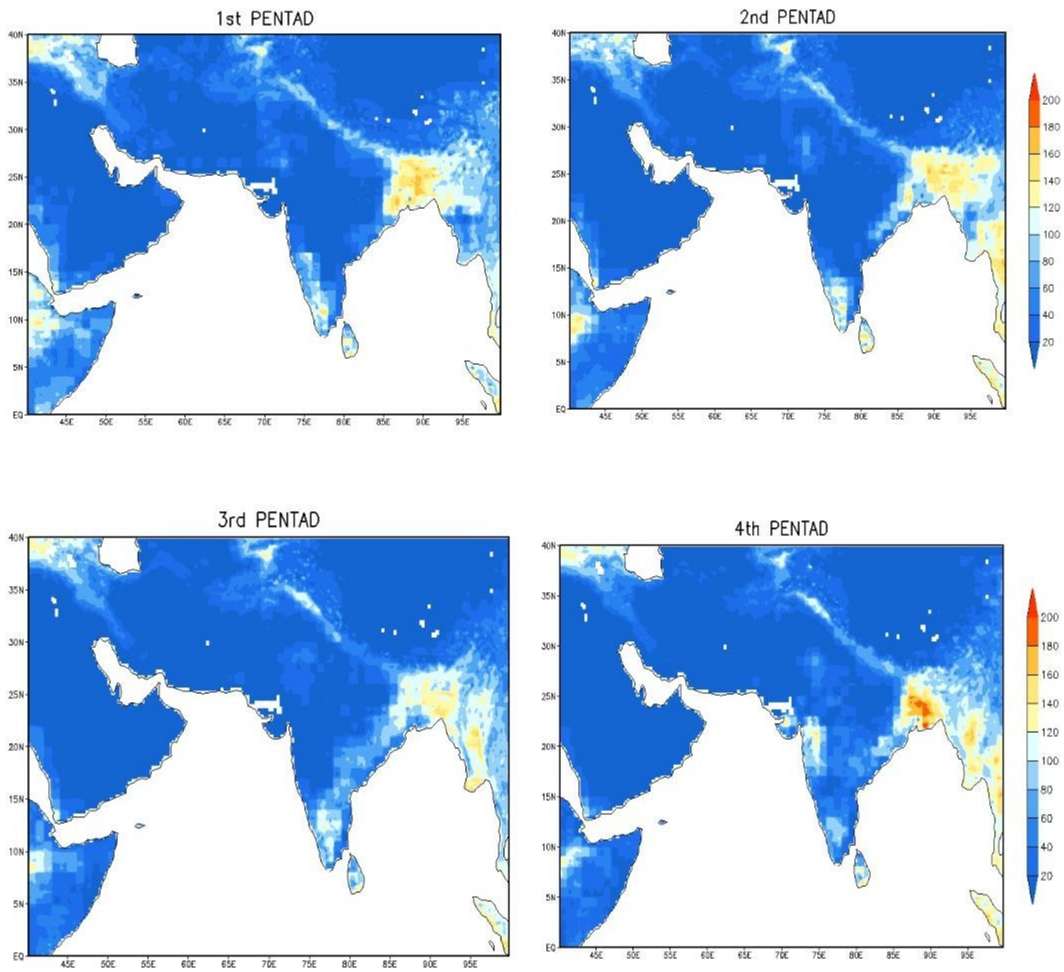


Fig.17.time –latitude variation of tropospheric temperature(degree celcius),(700hpa-200hpa)over a longitude of 70-100E indian summer monsoon region.

4.9.**Geographical Distribution Of Latent Heat Flux**

There is a large importance in the diabatic heating over the Eurasian continent as a whole in establishing the summer monsoon circulation.(Raju et al., 2005). intensity and duration of heating of Tibetan Plateau has a direct bearing on the amount of rainfall in India by the monsoons. Establishment and maintainance of a summer monsoon circulation is greatly influenced by the latent heat release and diabatic heating over the Asian summer monsoon region. Sustanance of the daibatic heat source is very important and the strong moisture convergence and convective cloud formation release latent heat and maintan the summer monsoon circulation. (Agnihotri et al., 2020). surface moisture flux increases as a result of the increase of the low-level wind and the moisture content of the air increases and reaches a level sufficient to produce deep cumulus convection and latent heat release. The whole circulation is maintained through a positive moisture feedback.


1st PENTAD
2nd PENTAD
3rd PENTAD
4th PENTAD
40N
35N
30N
25N
20N
15N
10N
5N
EQ
45E
50E
55E
60E
65E
70E
75E
80E
85E
90E
95E
200
180
160
140
120
100
80
60
40
20

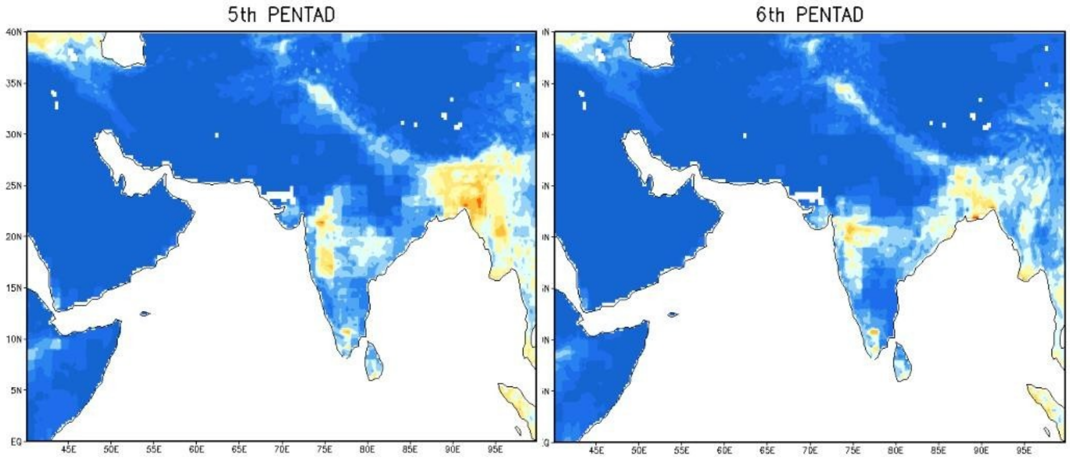


Fig.18. Spatial pattern of latent heat flux

Plot showing the geographical distribution of latent heat energy the value is increases with the advancement of monsoon. Here mean latent heat of a pentad is calculated from -15th day to +15th day. In the west coast of Kerala the value is high compared to other region. In the 3rd pentad the latent heat flux of the whole southern peninsula is high which represents the high level of convection and cloud formation. Strong vertical motion of moist air parcel, get condensed when reaches a saturation level and cloud formation is occurs and latent heat is released from this cloudy region. (Maggagi and Barrows., 2004). Latent heat peak in the lower troposphere (<600 hPa) is convective rain. Latent heat in the upper troposphere (300 hPa) is significantly released, and the maximum cooling is in the case of stratiform rain between 700 and 800 hPa. The ability to distinguish between these two heating profiles is important, because the difference in the vertical structure of latent heat reflects the spatial organization of tropical mesoscale circulation and large-scale dynamics, especially in the case of convective systems, showing great spatial variability (Luo,Yanai.,1984, Subhrahmanyam et al., 2011).

DISCUSSION

The basic meteorological fields observed and analyze for the study includes Vertical and spatial structure of zonal and meridional wind pattern, evolution of OLR field, vertically integrated moisture convergence, evolution precipitation, Abrupt increase in kinetic energy and Relative humidity during monsoon transition.

A rapid northward shift of rain-belt to the northern position seen around late May to early June and rapidly it returns to the equator in September, this also portrays the monsoon onset. Dramatic changes in the daily precipitation rate are known to occur during the monsoon onset; to investigate this feature of monsoon onset composite of area averaged rainfall over Kerala for the years 2017-18 is calculated and which shows a sharp increase in precipitation rate.

To examine the two-dimensional evolution of monsoon circulation, the composite of daily OLR in a five day interval from 10 days prior to the 10 days after the onset for the years 2017-20, is plotted. At the onset the south-west coast and the north east Arabian sea becomes the high convective activity areas. Major convective areas have an OLR value below 200w/m2.

In next section, the vertical structure of monsoon circulation is analyzed in detail. The mean altitude structure of the synoptic-scale southwest monsoon winds is studied using the radar data. Major circulation features like LLJ and TEJ are clearly observed from the radar data and its evolution during the transitional phase is very clear and it can be treated as a potential predictor to declare the onset date. Zonal wind is mainly northwesterly at the west coast of kerala its depth and strength increases during the onset phase which is clearly plotted in a graph. The LLJ shows an vertical extent up to a 2.5 to 3 km. There is a sudden increase in kinetic energy of low-level westerlies from 20-30 J/kg to 100 J/kg before onset and this is maintained during the upcoming days. Vertically integrated moisture transport increases sharply with

onset over Kerala. Moisture flux and rainfall shows a good correlation (cc=0.63)

CHAPTER 5

SUMMARY AND CONCLUSIONS

The mean circulation features, dynamics, and energetic of the pre-monsoon to monsoon transition phase are discussed mainly using Wind profiler radar data over Cochin and other secondary data sets. Cochin, in Kerala, being the gateway of monsoon to advance towards the rest of the country, is the perfect place to collect data regarding the changes in the atmospheric circulation features associated with the south west monsoon onset. In this study radar data used for the years 2017-20 to analyze the characteristics of monsoon circulation and to observe the gradual strengthening and changes associated with the onset at the entry point of southwest monsoon. The radar provides a unique amount of information on the transition phase of monsoon circulation. It observed that LLJ and TEJ are evolved at the end of May in lower and upper levels respectively, and after onset, these two features intensified. Core speed and core height of LLJ show an abrupt increment in the onset phase, and variability of LLJ is strongly correlated with rainfall over the station. The spatial pattern of wind is plotted using the ERA-interim dataset shows many characteristics large-scale circulation features over the summer monsoon region during the monsoon transition period. Gradual strengthening of cross-equatorial flow and and intense westerlies over the Arabian Sea are important low-level feature associated with the onset of summer monsoon over India, and northward migration of subtropical westerly jet and is strengthening of TEJ are on the other hand an important upper level characteristics associated with MOK. Radar data analysis has shown that these parameters can be used as predictors for monitoring the monsoon onset over Kerala. Wind profiler observations can be used for verifying the monsoon onset features and to develop objective criteria for declare MOK. Strong cross-equatorial flow and intense westerlies over the Arabian Sea are the characteristic low-level features in the evolution process of the summer monsoon over India. On the other hand, the westerly jet migrates towards the north, and the TEJ is strengthened during the onset period and it is intensified in the post-onset period. Latent heating profiles suggests more intense convective activity.

CHAPTER 6

REFERENCES

Agnihotri, G., Gouda, K. C., & Das, S. (2020). *Characteristics of pre-monsoon convective systems over south peninsular India and neighborhood using tropical rainfall measuring mission's precipitation radar. Meteorology and Atmospheric Physics.*, 133(D24)doi:10.1007/s00703-020-00740-7

Ananthakrishnan, R., and Thiruvengadathan, A. (1968). Thermal changes in the troposphere associated with seasonal transitions over india. *Current Science.*,37(7) pp. 184-186. https://www.jstor.org/stable/24084611

Ananthakrishnan, R., Rajan, C.K.(1987).some features of the south-west monsoon rainfall of cochin and minicoy. *journal of climatology.*,7(4):355-372. https://doi.org/10.1002/joc.3370070404

Bollasina, M. A., Ming, Y., & Ramaswamy, V. (2013). Earlier onset of the Indian monsoon in the late twentieth century: The role of anthropogenic aerosols. *Geophys. Res. Lett.*, *40*(14), 3715-3720. doi:https://doi.org/10.1002/grl.50719

Chakraborty, A., and Agrawal, S. Role of west Asian surface pressure in summer monsoon onset over central India (2017) *Environ. Res. Lett.* 12(7):074002
DOI:10.1088/1748-9326/aa76ca

Deshpande, S. M., Raj, P.E.(2008). Mean vertical motions and their time-height variations in the lower troposphere obtained from a UHF wind profiler at Pune, a tropical Indian station. *Journal of geophysical research*, VOL. 113, D07104, doi:10.1029/2007JD008704, 20

Fasullo, J., Webster, P. J. (2003). A hydrological definition of indian monsoon onset and withdrawal. *J.Climate.*,16 (19): 3200–3211.

https://doi.org/10.1175/1520-0442(2003)016<3200a:AHDOIM>2.0.CO;2

Gadgil, Sulochana (2018). *The monsoon system: Land–sea breeze or the ITCZ?. Journal of Earth System Science, 127(1), 5–*. doi:10.1007/s12040-017-0916-x

Ghosh, S., Vittal, H., Sharma, T., Karmakar,S., Kasiviswanathan, K,S., Dhanesh, Y. (2016) .Indian Summer Monsoon Rainfall: Implications of Contrasting Trends in the Spatial Variability of Means and Extremes. *PLoS ONE* 11(7): e0158670.doi:10.1371/journal.pone.0158670.

Joseph, P ,V., Sijikumar, S.(2004).Intraseasonal variability of the low-level jet stream of the Asian summer monsoon. *J. Climate*.VOL(17)..https://ui.adsabs.harvard.edu/link_gateway/2004JCli...17.1449J/doi:10.1175/1520-0442(2004)017%3C1449:IVOTLJ%3E2.0.CO;2

Joseph, P., Eischeid, J., & Pyle, R. (1994). Interannual Variability of the Onset of the Indian Summer Monsoon and Its Association with Atmospheric Features, El Niño, and Sea Surface Temperature Anomalies. *Journal of Climate, 7*(1), 81-105. http://www.jstor.org/stable/26197829

Joseph, S., Sahai, A. K., Abhilash, S., Chattopadhyay, R., Borah, N., Mapes, B. E., Kumar, A. (2015). *Development and Evaluation of an Objective Criterion for the Real-Time Prediction of Indian Summer Monsoon Onset in a Coupled Model Framework. Journal of Climate, 28(15), 6234–6248.* doi:10.1175/jcli-d-14-00842.1 .sci-hub.se/10.1175/jcli-d-14-00842.1

Lau, K. M., Yang. S.(1994).Seasonal variation abrupt transition, and intraseasonal variability associated with the Asian summer monsoon in the GLA GCM. *J. Climate.*Vol, 9(5):965-985. http://www.jstor.org/stable/26200323

Lim, E. S.; Wong, C. J.; Abdullah, K.; Poon, W. K. (2011). *Relationship between outgoing longwave radiation and rainfall in South East Asia by using NOAA and TRMM satellite. , (),785790.*

doi:10.1109/chuser.2011.6163843

Luo, H and Yanai, M.(1984). The Large-Scale Circulation and Heat Sources over the Tibetan Plateau and Surrounding Areas during the Early Summer of 1979. Part II: Heat and Moisture Budgets. *Monthly weather review.*112:966.989.DOI:https://doi.org/10.1175/15200493(1984)112<0966:TLSCAH>2.0.CO;2

Magagi, R and Barros, A. P. (2014). Estimation of latent heating of rainfall during the onset of the Indian monsoon using trmm and radiosonde data. *Journal of applied meteorology and climatology*.43:328-349.DOI:https://doi.org/10.1175/1520-0450(2004)043<0328:EOLHOR>2.0.CO;2

Overpeck, J., Anderson, D., Trumbore, S., and Prell, W.(1996). The southwest Indian Monsoon over the last 18000 years. Climate Dynamics. 12: 213–225. DOI:https://link.springer.com/article/10.1007/BF00211619

Pai, D.S., Nair, R. M. (2009). Summer monsoon onset over Kerala: new definition and prediction. *J Earth SystSci*., 118, 123–135.

https://doi.org/10.1007/s12040-009-0020-y

Parthasarathy, B., Kumar, K,R., and Deshpande, K, R.,(1991), Indian summer monsoon rainfall and 200-mbar meridional wind index: application for long-range prediction. *International journal of climatology*, VOL. 11, 165-176 551.577.32(540):551.557.36551.553.21:551.509.331

Patwardhan.S., Kulkarni.A. and Kumar.K.K.(2014). Impact of Climate Change on the Characteristics of Indian Summer Monsoon Onset. International Journal of Atmospheric Sciences.Volume 2014, Article ID 201695, 11.pages.http://dx.doi.org/10.1155/2014/201695

Prasad, V, S., and Hayashi, T. (2005). Onset and withdrawal of Indian summer monsoon. *Geophys. Res.lett*, VOL. 32, L20715, doi:10.1029/2005GL023269.

Prodhomme, Chloé & Terray, Pascal & Masson, Sébastien & Izumo, Takeshi. (2013). Factors controlling the Indian summer monsoon onset in a coupled model. Clim Dyn. DOI 10.1007/s00382-014-2200-y

Raju, P, V, S., Mohanty, U, C., and Bhatla, R.(2005).Onset characteristics of the southwest monsoon over India. Int. J. Climatol. 25: 167–182 .DOI: 10.1002/joc.1121

Ruchith, R, D., Deshpande, S, M and Raj, P, E.(2015). UHF wind profiler observation of low level jet and its association with rainfall over a tropical Indian station. *Atmósfera 29(1), 1-9 (2016).doi: 10.20937/ATM.2016.29.01.01*

Sahana, A.S.,Ghosh, S., Ganguly, A., and Murtugudde, R. (2015). SHIFT IN INDIAN SUMMER MONSOON ONSET DURING 1976/1977. *Environ.Res.Lett*.10054006

doi:10.1088/1748-9326/10/5/054006

Samson, T, K. et al.,(2016). Technical Aspects of 205 MHz VHF Mini Wind Profiler Radar for Tropospheric Probing. *Ieee geoscience and remote sensing letters*, VOL. 13, NO. 7.

Soman, M. K., Kumar, K, K .(1993). Space-time evolution of meteorological features associated with the onset of Indian summer monsoon .*Mon. Wea. Rev.* 121 (4): 1177–1194.https://doi.org/10.1175/1520-0493(1993)121<1177:STEOMF>2.0.CO;2.

Shukla, J., Misra, B. N.(1977). Relationships between sea surface temperature and wind speed over the Central Arabia Sea and monsoon rainfall over India. *Mon. Wea. Rev*.105: 998-1002. DOI: https://doi.org/10.1175/1520-0493(1977)105<0998:RBSSTA>2.0.CO;2

Subrahmanyam, M.V., Dong-xiao.W. (2011).Impact of latent heat flux on Indian summer monsoon during el niño/la niña years. *Journal of tropical meteorology.*Vol.17No.4. ID: 1006-8775(2011) 04-0430-11

Tyagi,A., Mazumdar,A.,B., Khole,M., Gaonkar, S, B., Devi, S., and Ramanathan, RM, A, N.(2011), Re-determination of normal dates of onset of southwest monsoon over India**.** *Mausam*, **62**, 321-328. 551.553.21 : 551.585.3 (540)

Varikoden, H., Revadekar, J.V., Kuttippurath, J. *et al.(2019).* Contrasting trends in southwest monsoon rainfall over the western ghats region of India. *ClimDyn* 52, 4557–4566 https://doi.org/10.1007/s00382-018-4397-7.

Viswanadhapalli, Y.B., Dasari,H.P., Dwivedi,S., Madineni,V.R., Langodan,S., Hoteit,I. (2019). Variability of monsoon low-level jet and associated rainfall over India. *International journal of climatology.,40(2),* 1067-1089.https://doi.org/10.1002/joc.6256

Wang, B., Ding, Q., Joseph, P.V. (2009). Objective definition of the Indian summer monsoon onset. *J. Climate.*22 (12): 3303–3316.https://doi.org/10.1175/2008JCLI2675.1

.

Xavier, P. K., Marzin, C., and Goswami, B. N.(2007). An objective definition of the Indian summer monsoon season and a new perspective on the ENSO–monsoon relationship. *Q. J. R. Meteorol. Soc.* 133: 749–764 (2007). DOI: 10.1002/qj.45.

CHAPTER 7

ABSTRACT

A wind profiler radar at the VHF range of 205 MHz is operational since January 2017, at Cochin University of Science and Technology (10.04◦N; 76.33◦E) in Cochin, a region lying on the west coast of Southern Peninsular India, which also is the entry point of the Indian summer monsoon. Using the wind Profiler radar, vertical structure of zonal and vertical wind pattern is studied in detail to investigate the pre-monsoon to monsoon transition of atmospheric conditions. The circulation pattern of the atmosphere is examined during the onset phase, which is shown to be a potential predictor for declaring the monsoon onset over Kerala in an objective manner. Monsoons are a dominant feature of the tropical and subtropical climate in many regions of the world, characterized by rainy summer and drier winter seasons, and companied by a seasonal reversal of the prevailing winds. Monsoon onset over Kerala is the crucial meteorological phenomenon over India and a major event related to India's agriculture and economy. Monsoon onset over Kerala (MOK) has been considered the beginning of India's rainy season. The monsoon low level jet (LLJ) and tropical easterly jet (TEJ) have a crucial role in the declaration of onset over Kerala; and these essential features are obtained from the radar. The purpose of the study is to understand the changes of atmospheric thermodynamic and dynamic characteristics in the troposphere and lower stratosphere associated with Indian Summer Monsoon Onset, with the help of data acquired from the Stratosphere-Troposphere Radar, the Automated Weather Station (AWS) located in the Advanced Center for Atmospheric Radar Research (ACARR), CUSAT. In order to understand the large-scale monsoon circulation, spatial pattern of wind and other crucial meteorological parameters are studied using secondary datasets.

S