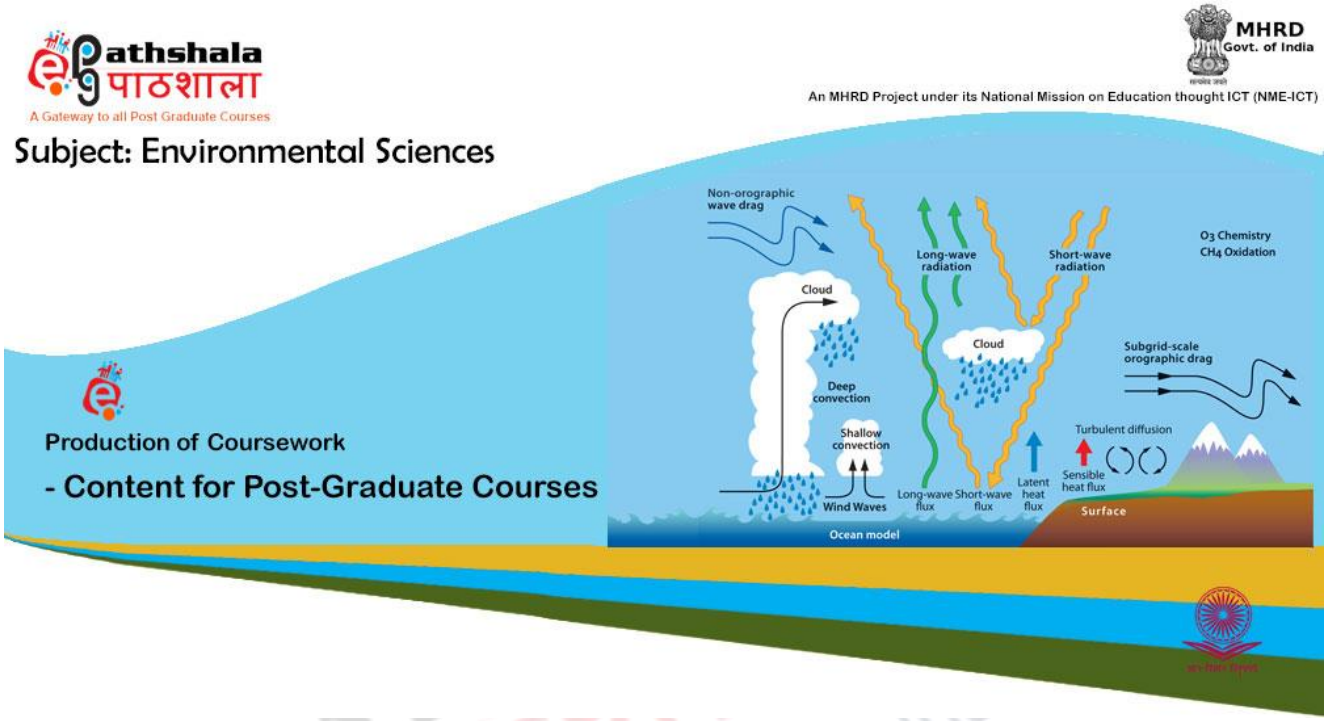

Paper No: 8 Atmospheric Processes

Module: 23 General Weather Systems and Indian Monsoon

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Description of Module	
Subject Name	**Environmental Sciences**
Paper Name	Atmospheric Processes
Module Name/Title	General Weather Systems and Indian Monsoon
Module Id	EVS/AP-VIII/23
Pre-requisites	
Objectives	• have a clear understanding about the climate of India • know about the origin and mechanism of monsoon system • know about pattern of onset, development, progress and withdrawal of monsoon in India • get the basic idea about different weather systems that affect Indian monsoon • develop an understanding about the western disturbances and local convective systems
Keywords	Monsoon origin, Monsoon trough, Monsoon Depression, Heat Low, Tibetan High, Local convective systems, Western disturbances

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1. *Learning outcomes*

After studying this module, you shall be able to:

- have a clear understanding about the climate of India
- know about the origin and mechanism of monsoon system
- know about pattern of onset, development, progress and withdrawal of monsoon in India
- get the basic idea about different weather systems that affect Indian monsoon
- develop an understanding about the western disturbances and local convective systems

2. *Introduction*

The weather systems are generally referred to as the synoptic systems of varying expanse which influence the weather/climate in short term or seasonal time scale. The most common meso-scale system that influences the climate of India is the monsoon. The weather systems during summer monsoon are interwoven with several synoptic systems. Besides that there are many weather systems developed during pre and post monsoon period which have significant influence on the seasonal characteristics of Indian climate. In this section the general weather systems of India including monsoon, its associated systems and other smaller scale weather systems during pre and post monsoon period.

3. *Indian Monsoon*

The term 'monsoon' stems from seasonal variations in winds but it now more generally applied to seasonal reversal in both the atmospheric circulation and associated precipitation largely confined to tropical and subtropical regions. Monsoon is a global phenomenon, mainly observed throughout the tropics and subtropics. The dominant monsoon systems in the world are the Asian-Australian, West-African and North and South American monsoons, although the latter did not clearly identify with wind reversals. In these sectors, the wet zone migrates from one hemisphere to the other following the sun, causing reversal of atmospheric circulation. The meteorologists describe monsoon as complete replacement of the dry hot air by the equatorial maritime air up to an altitude of three to five kilometers over the land and water surface. The physical processes governing monsoon involve dynamic interactions among the atmosphere ocean and land surface.

In India, monsoon circulation is generally described as southwest monsoon and northeast monsoon associated with seasonal reversal of wind at lower and upper atmosphere over Indian subcontinent. The term, southwest monsoon (or summer monsoon) is used for the phenomenon of rains associated with southwesterly surface winds that prevail for 2 to 4 months from June to September. The northeast monsoon, or Retreating Monsoon, on the other hand occurs during September to December is characterized by cold and dry wind flowing down from the Himalayas and Indo-Gangetic Plain towards the vast spans of the Indian Ocean south of the Deccan peninsula. However, the northeast monsoon has mild impact in the major part of the country due to presence of the Himalayas that act as a barrier to the cold wind blowing from north.

3.1. Origin and mechanism

3.1.1. Traditional theory (Thermal theory)

The traditional theory portrays the monsoon as a large-scale sea breeze. In 1686 Sir Edmund Halley, with trade and navigation on his mind, suggested that the monsoon was driven by differential heating between the Indian Ocean and the landmass of South Asia. During the north hemispheric summer, the massive landmass of the Indian Peninsula heats up faster than the surrounding seas, resulting in a pressure gradient from south to north. This causes the flow of moisture-laden winds from sea to land, popularly known as *southwest monsoon* or *summer monsoon* which is accompanied by wet weather and rainfall in major part of the country. During the winter, reverse wind blows from colder landmass toward the Indian Ocean in a north-easterly direction, causing the *northeast monsoon*. Only part of the northeast monsoon passing over the Bay of Bengal picks up moisture, causing rain in parts of Andhra Pradesh and Tamil Nadu during the winter months.

Many meteorologists argue that the monsoon is not a local phenomenon as explained by the traditional theory, but a general weather phenomenon along the entire tropical zone of Earth.

3.1.2. Dynamic theory (ITCZ theory)

The *dynamic theory* explains the monsoon on the basis of the annual shifts in the position of global belts of pressure and winds. The trade winds from both the hemispheres converge at the equatorial low pressure belt known as Inter Tropical Convergence Zone (ITCZ). However, the position of the ITCZ shifts north and south, toward the Tropics of Cancer and Capricorn during the summer of the Northern

and Southern hemisphere respectively, with change in solar declination. It is assumed that the monsoon is a result of the shift of the ITCZ.

With the ITCZ near the Tropic of Cancer during summer, the southeast trade winds of the Southern Hemisphere have to cross the equator to reach it. The southeast trade winds while crossing equator are deflected east in the Northern Hemisphere under the Coriolis force, transforming into southwest wind. These deflected trade winds pick up moisture while travelling from sea to land and cause rainfall in the Indian Peninsula. This is known as southwest monsoon.

The dynamic theory explains the monsoon as a global weather phenomenon that occurs in the tropical regions around the globe rather than just a local one. However, monsoon development is not a slow and gradual process. Both Dynamic and Thermal theories fails to explain the sudden onset, break and withdrawal of monsoon.

3.1.3. Jet Stream theory

The modern theory of monsoon is based on the linkage of upper air circulation and jet streams with surface pressure and monsoon circulation. Jet stream is the latest theory regarding the origin of the monsoons and has earned worldwide acclaim from the meteorologists.

The jet streams are the systems of upper-air westerlies. A jet stream may be described as band of fast moving air from west to east usually found in the middle latitudes in the upper troposphere at a height of about 12 km (just below tropopause) over areas of steep pressure gradient on the surface. The wind speeds in a jet stream are commonly 150 to 300 kmph with extreme values reaching 400 kmph. The main types are the *polar jets*, the *subtropical westerly jets*, and the less common *tropical easterly jets*. They follow the principle of geostrophic winds.

Over India, a subtropical westerly jet develops in the winter season that causes high pressure over northern parts of the subcontinent during the winter. This results in the north-to-south flow of the winds in the form of the northeast monsoon. With the northward shift of the vertical sun, this jet shifts north, too. The intense heat over the Tibetan Plateau as well as Central Asia, coupled with associated terrain features of the Himalayas, generate the tropical easterly jet over central India. This jet creates a low-pressure zone over the northern Indian plains, influencing the wind flow toward these plains and assisting the development of the southwest monsoon.

The sudden onset of the southwest monsoon is explained by the fact that the northward shift is not a slow and gradual process, as expected for most changes in weather pattern. As the Tibetan Plateau heats up, the low pressure created over it pulls the westerly jet north. But the westerly jet's movement is inhibited by the lofty Himalayas,. But with continuous dropping pressure, sufficient force is created for the movement of the westerly jet across the Himalayas after a significant period. As such, the shift of the jet is sudden and abrupt, causing the bursting of southwest monsoon rains onto the Indian plains. The reverse shift happens for the northeast monsoon wind leading to a second, minor burst of rainfall over the eastern Indian Peninsula during the Northern Hemisphere winter months.

The jet stream theory also explains the variability in timing and strength of the monsoon. A timely northward shift of the subtropical westerly jet at the beginning of summer is critical to the onset of the southwest monsoon over India. If the shift is delayed, so is the southwest monsoon. An early shift results in an early monsoon. The strength of the southwest monsoon is determined by the strength of the easterly tropical jet over central India. A strong easterly tropical jet results in a strong southwest monsoon over central India, and a weak jet results in a weak monsoon.

3.2. Onset and progress of south west monsoon

The period of activities of southwest monsoon in India is generally limited to the beginning of June to the end of September. The summer monsoon rainfall first arrives in the south-western state of Kerala between late May and early June every year. The monsoon crosses the Western Ghats with heavy rainfall and with at least 3 mm day^{-1} over the southern and eastern parts of India by 5 June. The monsoon gradually advances across the rest of India during June, and almost all of India experiences rainfall by 1 July. The withdrawal of the summer monsoon starts by 20 September when much of India experiences less intense rainfall, and the withdrawal of the monsoon is almost complete by 28 September

Monsoon winds beyond south Kerala progress in the form of two branches viz. the Arabian Sea branch and the Bay of Bengal branch. Arabian Sea branch of the monsoon is much powerful than the Bay of Bengal branch because the entire Arabian Sea current advances towards India, whereas only a part of the Bay of Bengal current enters India, the remainder proceeding to Myanmar, Thailand and Malaysia.

The *Arabian Sea Branch* of the Southwest Monsoon first hits the Western Ghats of the coastal state of Kerala, India, that marks the onset of the Southwest Monsoon. The climatological mean date of onset of the monsoon over Kerala is 2 June with a standard deviation of 8 days. The Arabian Sea branch of the southwest monsoons is divided into three distinct streams on arriving in the mainland of India. The first stream strikes the west coast of India perpendicular to Western Ghats causing heavy Orographic Rainfall (400 to 500 cm annual rainfall) on the windward side. Rainfall is drastically reduced to about 30 to 50 cm on the leeward side of the crest. There is a narrow belt of marked aridity on the immediate leeward side of the Western Ghats. The amount of rainfall increases further east. The second stream enters Narmada—Tapi troughs (narrow rift valley) and reaches central India. It does not cause much rain near the coast due to the absence of major orographic obstacle across the rift. Some parts of central India receive rainfall from this stream. The third stream moves parallel to the Aravali Range without causing much rainfall. Consequently the whole of Rajasthan is a desert area. However, some orographic effect is occurs on the southeastern edge of the Aravali Range. Mt. Abu gets about 170 cm rainfall while the surrounding plains have only 60 to 80 cm rainfall.

The *Bay of Bengal Branch* of Southwest Monsoon flows over the Bay of Bengal between Srilanka to Sumatra Island heading towards North-East India and Bengal, picking up more moisture from the Bay of Bengal. The normal date of its arrival at Kolkata is 7th June. The Bay of Bengal Branch of the southwest monsoon is divided into two distinct streams. The northern stream crosses the Ganga-Brahmaputra delta and reaches Meghalaya. Here that the orographic effect results in intense rainfall. Mousinram (Cherrapunji) located on the southern slopes of the Khasi hills at the northern end of a deep valley running from south to north receives an annual rainfall of about 1100 cm, major portion of which occurs from June to August. The northern current spreads rather rapidly over most of Assam. The second stream of the Bay of Bengal branch moves along Himalayan foothills as they are deflected to the west by the Himalaya and brings widespread rainfall to Ganga plain. The rainfall by this stream decreases as monsoon progresses from east to west up the plain. Furthermore, the Himalayan foothill receives more rainfall due to orographic influence.

The Arabian Sea and Bay of Bengal branches merge mostly around Delhi to form a single current which extends to west Uttar Pradesh, Haryana, Punjab, Rajasthan and finally to Himachal Pradesh and Kashmir. By the end of June the monsoon is usually established over most parts of the

country. By mid-July, the monsoon extends into Kashmir and the remaining parts of the country. By this time it reaches Kashmir, it has shed most of its moisture.

The monsoon accounts for 80% of the rainfall in India. The rainy season persists through July and August and into the beginning of September with active and break periods. The withdrawal of the summer monsoon starts by 20 September when much of India experiences less intense rainfall, and the withdrawal of the monsoon is almost complete by 28 September

Indian agriculture is heavily dependent on the rains, for growing major crops like rice, oilseeds, cotton and coarse grains. The irregularity of monsoon with respect to date of onset, mid season break or localized excess rainfall causes drought or flood in different part of the country.

3.3 North east Monsoon

Towards September, with southward shift of the position of sun, the northern part of India begins to cool off rapidly and the air pressure begins to build over northern India, the Indian Ocean and its surrounding atmosphere still holds its heat. The cold winds sweep down from the Himalayas and Indo-Gangetic Plain towards the vast spans of the Indian Ocean south of the Deccan peninsula. This is known as the Northeast Monsoon or Retreating Monsoon. The northeast monsoon is dry in most part of the country. However, while travelling towards the Indian Ocean, the dry cold wind picks up some moisture from the Bay of Bengal causes some amount of rainfall in part of peninsular India and parts of Sri Lanka. The Indian state, Tamil Nadu receives about 50 to 60% of the annual rainfall from Northeast Monsoon.

3.4. Weather systems associated with monsoon

The weather systems associated with summer monsoon could be bracketed under two major categories: semi-permanent systems and transient rain producing systems. The semi-permanent systems are present during the monsoon seasons on most of the days and remain more or less in the same location in a quasi-permanent state. These include, Heat Low, Monsoon Trough, Tibetan High, Tropical Easterly Jet and Mascarene High. The transient rain bearing systems, on the other hand, are generally migratory and may not be present on every day. They influence the monsoon in short/medium time scales. 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.

3.4.1. Heat Low (HL)

Due to the intense heating of the Indian sub-continent in pre monsoon months a low pressure belt develops over the Afro-Asian continent running from north Africa to northwest India through Arabia and Pakistan. The deepest low pressure area over Pakistan and adjoining northwest India is known as the heat low. The heat low is shallow and extends upto only 1.5 km amsl. Weather is hot, dry and cloudless over the heat low. Aloft it is overlain by a high pressure cell. The intensity of heat low is a good indicator of the continental heating and land-sea contrast which drives the monsoon. A deep heat low will usually associate with strong north-south pressure gradient and enhances monsoon activity. The heat low usually develops in March and is maintained by blocking of cold air from the north by the Himalayas, by the subsiding air warmed by the release of latent heat in the monsoon rain systems to the east and advected westwards by the easterly jet. The heat low withdraws gradually in June with the onset of southwest monsoon.

The region of heat low itself receives very little rainfall, during summer monsoon. Multan in Pakistan (71.3"E, 30.2"N, Elevation 123m amsl) in the heat low region, receives normal rainfall of 97mm only during June-September. But the intensity of heat low is positively correlated with the rainfall of certain region of India and Bangladesh.

3.4.2. Monsoon Trough (MT)

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 amsl tilting southwards with height. In the lower troposphere, the temperature decreases with latitude to the south of the trough. The Monsoon Trough becomes clearly defined in July and August. From September, its position is gradually shifted southward and the western end gets diffused The monsoon trough is regarded as the equatorial trough of the northern summer over India and adjacent territories. Recent studies have shown that the monsoon trough is closely linked to the radiation balance of lower troposphere i.e., by the feedback mechanism generated by changes in cloud distribution and conditions at the earth's surface.

The monsoon trough has a vital bearing on the day to day monsoon activity over India. The normal position of the axis of monsoon trough lies roughly along Kolkata – Ganganagar via Allahabad and it shows a periodic shift in north-south direction. A well marked – southerly position of monsoon

trough is normally associated with good monsoon activity over most parts of India while northward shift (close to the Himalayan foothills), is associated with considerable decrease in rainfall in central parts of India and increase in rainfall over north India along the foothills of Himalayas. This is known as *monsoon break*. When the eastern end of the monsoon trough swings southwards and dips into the northern most Bay of Bengal, conditions become favourable for the formation of a monsoon depression.

3.4.3. Tibetan High (TH)

The Tibetan High is a dominant feature of summer monsoon. The Tibetan plateau is an extended region of 2000 km length in east-west direction and width of about 600 to 1000 km with an average height of 4 km. The heating of this extensive high land generates powerful thermal convection. The ascending air rapidly spreads outward both to the north and to the south of the plateau. The divergence of the air leads to formation of anticyclone over a Tibet around 300 or 200 hPa, popularly known as Tibetan high. This feature is being maintained by the radiation balance over the Himalayas.

It has even been suggested by some researchers that the thermal effects of the plateau might be responsible for the northward extension of easterly monsoon current over India. A well distributed rainfall over India is associated with well-pronounced Tibetan high. Southward shift of this high from its normal position as a result of the protrusions of the mid-latitude westerlies, is seen accompanied with reduction in monsoon activity over India and neighborhoods. The westward shift may cause monsoon to extend further westward into Pakistan and in extremes cases into north Iran. Sometimes upper air westerly troughs intrude to lower latitudes, bisecting the TH. This normally results in monsoon breaks. It has also been suggested that the snow cover over the Tibetan plateau in the winter may extend till the summer and a large snow albedo in the winter may weaken the summer monsoon.

3.4.4. Tropical Easterly Jet (TEJ)

The south of the sub-tropical ridge over Asia, the strong easterly flow (60 to 80 knots) concentrates into a jet stream in the higher troposphere at 150-100 hPa levels with its central region passing roughly along 13.5^0N over the Indian sub-continent. This stream is called Tropical Easterly Jet (TEJ) which is formed due to the south to north temperature gradient over India during southwest monsoon in all the levels of the troposphere. The TEJ makes its appearance at the time of monsoon onset over Kerala and disappears in October, when the summer monsoon has retreated from the most parts of the region.

The TEJ runs from the east coast of Vietnam to the west coast of Africa. Over Africa its location is around 10^0N latitude. A stronger TEJ is normally associated with good monsoon and weak TEJ with poor monsoon. However, this relation is not one to one and may manifest better in seasonal means rather than in the daily features of monsoon.

3.4.5. Mascarene High (MH)

The Mascarene High is a high pressure cell at the surface level observed over Western Indian Ocean, east or southeast of Madagascar. The outflow from this high travels northwards, gathers moisture over Indian Ocean and Arabian Sea, and arrives at west coast of India and thereafter at southeast coast of Bangladesh as the southwesterly monsoon current. MH influences the low level westerly jet in the Arabian Sea and thereafter in the Bay of Bengal. An intense Mascarene High is expected to be associated with active monsoon over India, Bangladesh and neighbourhoods. The position of the MH oscillates in longitudinal and latitudinal direction around its mean position during summer monsoon.

3.4.6. Monsoon Depression (MD)

Monsoon depressions are the synoptic features that cause most of the monsoon rains. Weaker systems with wind speeds less than 17 kt, are called lows and are referred to as depressions when surface winds are upto 33 kt (while over the sea) and cyclonic storms.

A major part of the South West Monsoon rainfall is generated by depressions originating in the Arabian Sea and Bay of Bengal. Some depressions develop over land also. About 3 to 4 depressions are formed per month from June to September. Almost all of them are sucked inward through the deltas of great rivers, the Ganga, the Mahanadi, the Godavari, the Krishna and the Cauvery and cause heavy rain in these areas. The location of depressions strongly coincide with the latitudinal position of ITCZ.

4. Weather systems formed during pre and post monsoon period

4.1. Local convective systems

During the hot weather period i.e., from March to May the Eastern and Northeastern states of the subcontinent like West Bengal, Bihar, Assam, Orissa (parts) and Bangladesh experience dramatic appearance of a special type of violent thunderstorm known as Nor'wester. In Bengal it is known as 'KalBaisakhi' or calamity of the month of Baisakh (15-April to 15-May). Nor'wester is a Local

Convective Storm (LCS), characterized by violent conditions, squall lines and sometimes hail storm. A squall line is a group of storms arranged in a line, often accompanied by "squalls" of high wind and heavy rain. A large number of these thunder squalls strike from northwest for which they are called nor'westers. The LCS is caused by thermal instability coupled with moisture inflow from the Bay of Bengal, enhanced by a south-west wind intensification at 950 hPa (approx. 500 m above ground level), a temperature increase, due to westerly winds, across the region at 800 hPa (approx. 2 km above ground level), leading to a trough and an enhancement of cold advection at 550 hPa (approx. 5 km AGL) from the north west.

On an average the hot weather season experiences about 15 such thunder squalls. However, the frequency of their occurrence and distribution are highly variable from year to year. Most of the times these thunder squalls occur in the afternoon and evening. In a nor'wester the wind speed varies from 55 to 80 km per hour and may exceed 140 km per hour in some cases. On the approach of the squall, generally, the temperature drops by 2 to 4 ^{0}C and pressure rises suddenly due to descending cold air from aloft. The amount of rainfall is also highly variable. Hail from the towering cumulonimbus cloud occurs during the early part of the season and decreases gradually along with the progress of the season due to gradual rise of the freezing level as a result of increasing surface heating. Duration of 'KalBaisaki' over a station varies from a few minutes to about an hour.

Apart from its destructive effects like sudden rise in wind speed, lightning, thunder and hail the rainfall associated with the storm although small in amount, is extremely helpful for the pre-kharif crops like jute, Aus paddy, summer till and a large number of vegetables and fruits in the eastern states of the country. The sudden drop in temperature due to Nor'wester also gives relief after unbearable midday heat.

4.2. Western Disturbances

Western Disturbance is an extratropical storm originating in the Mediterranean region that brings sudden winter rain to the northwestern parts of the Indian subcontinent. This is a non-monsoonal precipitation pattern driven by the Westerlies. The moisture in these storms usually originates over the Mediterranean Sea and the Atlantic Ocean. Extratropical storms are a global, rather than a localized phenomena with moisture usually carried in the upper atmosphere (unlike tropical storms where it is

carried in the lower atmosphere). These storms are residual frontal cyclones which move at the height of 2000 meters from the mean sea level. On an average, 4 to 6 cyclonic waves reach northwestern India between October and April each year. The frequency of WDs abruptly decreases from winter to the pre-monsoon season.

The arrival of these temperate storms of western disturbances causes precipitation leading to an abrupt decrease in air temperature over Northwest India. Western Disturbances also bring heavy snowfall in the Himalayan Region and a cold wave to north Indian plains. The weather becomes clear after the western disturbances passes away. After the passage of the disturbance, widespread fog and cold waves lowering the minimum temperature by 5° to 10°C below normal are experienced. Fog lowers visibility and causes great inconvenience for transportation.

The western disturbances affect weather conditions during the winter season up to Patna (Bihar) and give occasional rainfall which is highly beneficial for the standing rabi crops, (wheat, barley, mustard, gram, lentil, etc.).

5. Summary

- Monsoon is the most common meso-scale system that influences the climate of India. The monsoon circulation is generally described as southwest monsoon (summer monsoon) during June to September and northeast monsoon (winter monsoon) during September to December associated with seasonal reversal of wind at lower atmosphere and upper atmosphere
- Traditionally monsoon is considered as a large-scale sea breeze originated from wide land-sea contrast between Indian Ocean and the landmass of South Asia. The seasonal shifts in the position of Inter Tropical Convergence Zone (ITCZ) and the associated trade winds with change in solar declination and the influence of upper air circulation and jet streams more comprehensively explain the surface pressure and monsoon circulation.
- The monsoon accounts for 80% of the rainfall in India a major part of it being received between June and September from southwest monsoon. The large scale variations monsoonal rainfall is largely governed by relief, mountain barrier, distance from the sea and weather

systems like monsoon trough as well depressions originating from Bay of Bengal and Arabian sea. The rainless interval during south west monsoon season is known as 'breaks'.

- The northeast monsoon is mostly dry. The Indian state, Tamil Nadu receives about 50 to 60% of the annual rainfall from Northeast Monsoon.
- The weather systems during summer monsoon are interwoven with several synoptic systems that include, Heat Low, Monsoon Trough, Tibetan High, Tropical Easterly Jet and Mascarene High.
- Some transient features of irregular and migratory nature also influence the monsoon in short/medium time scales. They are known as monsoon disturbances. The major transient rain producing systems are: Monsoon Depression (MD), Cyclonic storms (CS), Mid Tropospheric Cyclones (MTC), Low level jet (or Somali Jet) and Offshore Troughs /Vortices.
- The Nor'wester is a Local Convective Storm (LCS), characterized by violent thunderstorm, rain, squall lines and sometimes hail storm that occurs during March to May in the Eastern and Northeastern states like West Bengal, Bihar, Assam and Orissa (parts). The low amount of rainfall due to Nor'wester is extremely helpful for pre-monsoon crops in this region.
- Western Disturbances are extratropical storms originating in the Mediterranean region that bring sudden rain to the northwestern parts and heavy snowfall in the Himalayan region of the Indian subcontinent. On an average, 4 to 6 cyclonic waves reach northwestern India between October and April each year. The occasional rainfall due to the western disturbances is often beneficial to the winter crops.
