Years of Service to the Nation
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NATIONAL METEOROLOGICAL OLYMPIAD

on
Weather & Climate Science for Society

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Content

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Chapter 1

Introduction to Weather & Climate System

1.1. Introduction to Weather and Climate

Weather and climate are fundamental components of Earth's environmental system, influencing all living organisms, human activities, agriculture, and water resources. Understanding the difference between weather and climate is essential for comprehending their impact on society and the natural world. Weather refers to the short-term atmospheric conditions in a specific place at a particular time, including temperature, humidity, precipitation, wind speed, and visibility. These conditions can change frequently, often within minutes, hours, or days. For example, a sunny morning can quickly turn into a rainy afternoon due to shifts in atmospheric pressure, temperature, and moisture levels. Climate, on the other hand, refers to the long-term patterns and averages of weather conditions in a region, typically measured over 30 years or more. It encompasses trends in temperature, humidity, wind, and precipitation over extended periods. For instance, a tropical climate is characterized by hot, humid conditions with significant rainfall throughout the year, while a polar climate is defined by persistently cold temperatures.

1.1.1. Importance of Weather and Climate

Weather and climate have far-reaching impacts on ecosystems, agriculture, infrastructure, human health, and economies. They control the distribution of water through rain, snow, and other forms of precipitation, which directly affects agriculture and freshwater availability. Extreme weather events such as droughts, floods, hurricanes, and heatwaves can lead to food shortages, water scarcity, property damage, and even loss of life. A notable example is the 1999 Odisha Super Cyclone in India, which resulted in nearly ten thousand deaths and displaced over a million people. Understanding and monitoring weather patterns are essential for disaster preparedness, while studying climate trends is critical for predicting long-term changes that influence natural resources, human health, energy supplies, infrastructure, and transportation systems. Changes in climate can alter agricultural productivity, biodiversity, and water availability, presenting significant long-term challenges for human societies and the environment.

1.1.2. Climate Impact on Society

Climate has a significant impact on our daily lives, natural resources, and ecosystems. Weather patterns influence the distribution of water on Earth, which is essential for the survival of all living organisms. The availability of fresh water for drinking and agriculture depends on weather patterns and seasonal changes. For example, droughts can devastate agricultural production, leading to food shortages and the loss of livelihoods. Historical records reveal that severe droughts have caused millions of deaths worldwide. Extreme weather events, such as hurricanes, tornadoes, floods, and heatwaves, profoundly affect human civilization. For instance, the Odisha Super Cyclone in 1999 resulted in nearly 10,000 deaths and displaced over a million people. These catastrophic events highlight the importance of understanding weather and climate to minimize their societal impact. Climate Change poses new challenges to society by impacting health, infrastructure, food and water security, and ecosystems. The frequency and intensity of natural disasters are increasing, emphasizing the need for society to adapt to changing weather patterns and mitigate its adverse effects.

1.1.3. Weather and Climate Services

To monitor and predict weather and climate patterns, scientists use advanced observational techniques and technologies. Data on atmospheric conditions such as temperature, humidity, pressure, wind speed, and precipitation are gathered globally through surface weather stations, satellites, weather radars, and upper-air measurements. These observations form the foundation for weather forecasts, climate research, and disaster preparedness. Surface observations are conducted at weather stations worldwide, which use instruments like thermometers (to measure temperature), barometers (for pressure), hygrometers (to measure humidity), anemometers (for wind speed), and rain gauges (to track precipitation). Upper air data is collected using pilot balloons and radiosondes, providing crucial information on temperature, humidity, and pressure at various altitudes, which is key to predicting weather patterns. Weather radars detect precipitation, storm intensity, and movement, offering real-time monitoring of hazardous weather phenomena such as heavy rainfall, thunderstorms, and cyclones, thereby facilitating timely warnings. Satellites provide a global perspective by monitoring land, oceans, and the atmosphere, collecting data on cloud formation, sea surface temperatures, rainfall, and upper atmospheric conditions. For instance, the INSAT series of satellites in India contributes significantly to weather forecasting and climate research by providing essential meteorological data.

1.1.4. Ancient Meteorology

The beginnings of meteorology in India can be traced to ancient times. Early philosophical writings of the 3000 B.C. era, such as the Upanishadas, contain serious discussion about the processes of cloud formation and rain and the seasonal cycles caused by the movement of earth round the sun. Varahamihira's classical work, the Brihatsamhita, written around 500 A.D. provides clear evidence that a deep knowledge of atmospheric processes existed even in those times. It was understood that rains come from the sun (Adityat Jayate Vrishti) and that good rainfall in the rainy season was the key to bountiful agriculture and food for the people. Kautilya's Arthashastra contains records of scientific measurements of rainfall and its application to the country's revenue and relief work. Kalidasa in his epic, 'Meghdoot', written around the seventh century, even mentions the date of onset of the monsoon over central India and traces the path of the monsoon clouds. Meteorologica written by Aristotle around 350 BCE is one of earliest treatise on meteorology.

Long before the development of modern scientific instruments, cultures around the world attempted to explain weather patterns through a combination of observation, mythology and rudimentary techniques. Many folklores developed in earlier periods hold good even today. Meteorology, as we perceive it now, may be said to have had its firm scientific foundation in the 17th century after the invention of the thermometer and the barometer and the formulation of laws governing the behaviour of atmospheric gases. It was in 1636 that Halley, a British scientist, published his treatise on the Indian summer monsoon, which he attributed to a seasonal reversal of winds due to the differential heating of the Asian land mass and the Indian Ocean.

India is fortunate to have some of the oldest meteorological observatories of the world. The British East India Company established several such stations, for example, those at Calcutta in 1785 and Madras (now Chennai) in 1796 for studying the weather and climate of India. The Asiatic Society of Bengal founded in 1784 at Calcutta. A disastrous tropical cyclone struck Calcutta in 1864 and this was followed by failures of the monsoon rains in 1866 and 1871. In the year 1875, the Government of India established the India Meteorological Department, bringing all meteorological work in the country under a central authority. Mr. H. F. Blanford was appointed Meteorological Reporter to the Government of India. The first Director of Bombay (now Mumbai), promoted scientific studies in meteorology in India. Captain Harry Piddington at Calcutta published 40 papers during 1835-1855 in the Journal of the Asiatic Society dealing with tropical storms and coined the word "cyclone", meaning the coil of a snake. In 1842 he published his monumental work on the "Laws of the Storms". In the first half of the 19th century, several observatories began functioning in India under the provincial governments.

1.1.5. India Meteorological Department (IMD)

A disastrous tropical cyclone struck Calcutta in 1864 and this was followed by failures of the monsoon rains in 1866 and 1871. In the year 1875, the Government of India (under British rule) established the India Meteorological Department, bringing all meteorological work in the country under a central authority, with its headquarters at Calcutta (now Kolkata). Mr. H. F. Blanford was appointed Meteorological Reporter to the Government of India. The IMD, is India’s primary agency for meteorological observations, and weather forecasting. Current national Headquarters of the IMD is located in New Delhi. It plays a critical role in monitoring weather patterns and issuing forecasts that aid agriculture, aviation, shipping, disaster management, and other sectors vital to the economy and public safety. IMD’s responsibilities include cyclone warnings, which help coastal regions prepare for storms, and monsoon forecasts, essential for agriculture and water management. Equipped with a network of weather stations, radars, and satellites, IMD continuously monitors atmospheric conditions, providing real-time updates to the public while supporting climate research. IMD provides its services up to village level through six Regions Meteorological Centres located at Delhi, Mumbai, Kolkata, Chennai, Guwahati, Nagpur and State Met Centres located at the state capitals.

IMD has also established itself as a global leader in weather science. It was among the first meteorological institutions to adopt telegraphy for weather communication, setting up observatories that contributed to international data sharing. Its historical focus on monsoon and cyclone forecasting has made IMD a key contributor to the World Meteorological Organization (WMO) and a pioneer in global weather science.

Monsoon forecasting is one of IMD’s most significant contributions. The Indian monsoon is crucial for the nation’s agriculture and water resources, and its impact extends globally, affecting the climate of the Indian Ocean region and Southeast Asia. IMD’s expertise in understanding atmospheric patterns, such as the El Niño-Southern Oscillation (ENSO), contributes to international efforts in climate prediction. The department also collaborates with initiatives like the Asian-Australian Monsoon Project, advancing global monsoon research.

Cyclone forecasting is another area where IMD excels. Using advanced numerical weather prediction (NWP) models and satellite observations, IMD accurately predicts the intensity and path of cyclones in the Bay of Bengal and the Arabian Sea. Its Regional Specialized Meteorological Centre (RSMC) provides cyclone advisories to neighbouring countries, helping to minimize the loss of life and property. This service is part of the global early warning system under the WMO framework.

IMD’s technological advancements have further enhanced global weather forecasting. The department utilizes India’s INSAT and Oceansat series of satellites, providing real-time weather data shared with international organizations. Its network of Doppler Weather Radars (DWRs) has improved short-term forecasts and monitoring of severe weather events. IMD also uses sophisticated NWP models like the Global Forecast System (GFS) and the Weather Research and Forecasting (WRF) model, contributing to global weather predictions.

In addition to its technological contributions, IMD collaborates with global organizations like the WMO and UNFCCC, providing technical assistance and training to regional meteorologists. It leads initiatives such as the South Asian Climate Outlook Forum (SASCOF), offering seasonal climate forecasts that support resilience in South Asia. IMD’s research contributions, especially in climate change studies, have been invaluable. Its long-term climate records are critical for analyzing trends in extreme weather events, and its work in developing climate adaptation strategies benefits global climate resilience efforts.

IMD also offers essential services to marine and aviation sectors, providing weather forecasts for maritime operations and real-time weather information for air travel safety. Its oceanographic data contributes to global programs like the Global Ocean Observing System (GOOS), while its aviation services are integral to both domestic and international flights.

Looking ahead, IMD continues to expand its role in global weather science, enhancing its forecasting capabilities through initiatives like the Monsoon Mission and exploring the use of artificial intelligence and machine learning. Its ongoing leadership in weather forecasting, climate research, and disaster management ensures that IMD will remain a key player in global meteorology for years to come.

Further details on evolution of India Meteorological department are described in Appendix-B

1.1.6. World Meteorological Organization (WMO)

The World Meteorological Organization (WMO), established in 1950, with its headquarters at Geneva (Switzerland) is a specialized agency of the United Nations that coordinates global efforts in weather, climate, and water resource monitoring. Its mission is to promote international cooperation in sharing meteorological data and information, ensuring standardized methods for observation and forecasting. WMO’s global network of observational systems forms the foundation of weather forecasting, climate research, and disaster risk reduction. This coordination helps improve weather predictions and supports international climate science efforts.

One of WMO's primary functions is to support climate change research by compiling and analyzing weather and climate data from around the world. This data is crucial for informing policymakers and assisting them in developing effective mitigation and adaptation strategies to address the impacts of climate change. The organization’s Global Framework for Climate Services (GFCS) ensures that climate-sensitive sectors, such as agriculture and disaster management, have access to reliable climate information.

WMO also plays a significant role in disaster risk reduction by enhancing early warning systems for extreme weather events like cyclones, floods, and droughts. Through initiatives such as the Multi-Hazard Early Warning Systems (MHEWS) and Regional Specialized Meteorological Centers (RSMCs), WMO provides timely warnings to vulnerable regions, helping to mitigate the impacts of these hazards.

In addition, WMO is involved in capacity building, particularly in developing countries. India has been an active member of the WMO since its inception. It provides training, resources, and technical support to strengthen national meteorological and hydrological services. This support helps improve local forecasting abilities and enhances preparedness for weather-related disasters. By fostering international collaboration and providing critical weather and climate services, WMO plays a vital role in addressing the global challenges posed by climate variability and extreme weather events.

1.2. The Earth in the Solar System

The Earth is one of the eight planets in our solar system, part of the vast Milky Way galaxy. Our solar system consists of the Sun, the eight planets (Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune), their moons, and other celestial objects like asteroids and comets (Figure 1.1). Earth is the third planet from the Sun and is unique because it supports life. This ability is due to several factors: its perfect distance from the Sun, the presence of liquid water, and an atmosphere that contains essential gases like oxygen. These features allow life to thrive in various forms, from microscopic bacteria to large mammals like elephants and whales.

The Earth is like a giant system made up of four main parts that work together to support life. The atmosphere is the layer of air that surrounds our planet, providing oxygen for us to breathe and protecting us from the Sun’s harmful rays. It also helps regulate the Earth's temperature. A conceptual diagram of the Earth system is shown in the figure 1.2. The biosphere includes all living things, like plants, animals, and humans, and it depends on the other parts of the Earth system to survive.

The lithosphere is the solid, outer layer of the Earth made up of rocks and soil. It forms mountains, valleys, and the land we live on. Lastly, the hydrosphere covers all the water on Earth, including oceans, rivers, lakes, and even the water in the air. These parts are connected, and any change in one can affect the others. Together, they create the perfect balance that makes life on Earth possible.

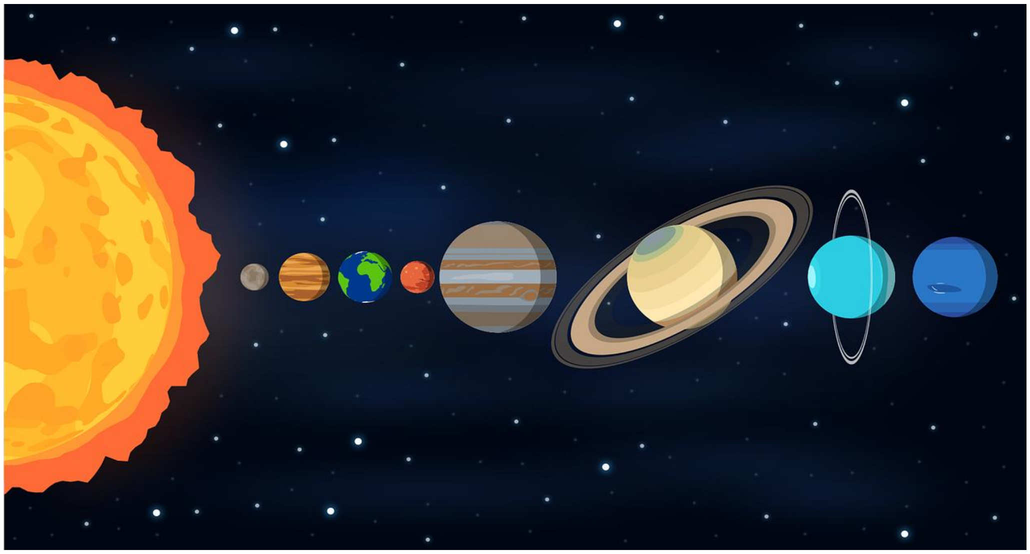


Figure 1.1: The Solar System (Image Credit: Pixabay)

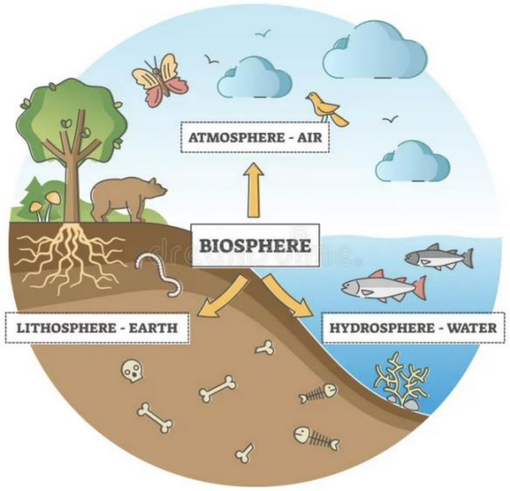


Figure 1.2: The Earth System (Image Credit: ID 210304128 © VectorMine| Dreamstime.com)

1.2.1. The Sun:

The Sun is a giant star at the center of our solar system. It is composed mainly of Hydrogen and Helium gases. The Sun's immense energy powers weather systems and climate patterns on Earth. The sunlight we receive is crucial for processes like photosynthesis, which allows plants to produce food and release oxygen—both vital for life.

1.3. Origin and Evolution of our Atmosphere and Ocean

1.3.1. Origin of the Atmosphere:

The Earth's atmosphere was formed about 4.5 billion years ago during the planet's early development. Initially, the atmosphere was composed mainly of hydrogen and helium, captured from a cloud of gas and dust called the solar nebula. This primary atmosphere was lost because the Earth's gravity was too weak to hold onto these light gases, and the strong solar wind blew them away.

A new atmosphere, known as the secondary atmosphere, formed from gases released by volcanic eruptions, a process called volcanic outgassing. Volcanic eruptions released water vapor, carbon dioxide, ammonia, and methane into the atmosphere. These gases were crucial in creating an environment that could support life.

1.3.2. Evolution of the Atmosphere:

As the Earth cooled, water vapor in the atmosphere condensed to form liquid water, leading to the creation of oceans. This was a pivotal moment in Earth's history, as it allowed for the development of life. Early life forms, such as cyanobacteria, began using sunlight to make food through photosynthesis, a process that produces oxygen. Over millions of years, oxygen accumulated in the atmosphere, forming the ozone layer. The ozone layer is important because it protects life on Earth from the Sun's harmful ultraviolet (UV) rays, allowing more complex life forms to develop.

1.3.3. Formation of the Oceans:

The formation of oceans is closely linked to the atmosphere. Water vapor released by volcanic activity and possibly from icy comets that collided with Earth contributed to the early oceans. These bodies of water played a vital role in regulating the planet's climate and providing a habitat for early life. The oceans cover about 71% of the Earth's surface and play a crucial role in regulating the planet's climate. They absorb carbon dioxide from the atmosphere, helping to stabilize global temperatures. Oceans also support diverse ecosystems, ranging from tiny plankton to large marine mammals.

1.4. Composition and Structure of Atmosphere and Ocean

1.4.1. Composition of the Atmosphere:

The Earth's atmosphere is composed of several gases: nitrogen (78%), oxygen (21%), and trace amounts of other gases such as argon, carbon dioxide (0.04%), and neon. The presence of water vapor and greenhouse gases like carbon dioxide and methane is vital for maintaining the Earth's temperature.

Structure of the Atmosphere: The Earth's atmosphere consists of several layers, each with distinct characteristics. A conceptual diagram of the layers of atmosphere is shown in the figure 1.3.

- The **troposphere** is the lowest layer, extending up to about 12 kilometers (7.5 miles) above the Earth's surface. It is where all weather occurs and contains about 75% of the atmosphere's mass. In the troposphere, temperatures decrease as you go higher.
- The **stratosphere** is located above the troposphere and extends from 12 to 50 kilometers (7.5 to 31 miles) high. This layer contains the ozone layer, which absorbs and scatters UV radiation from the Sun. In the stratosphere, temperatures increase with altitude.
- The **mesosphere** extends from 50 to 85 kilometers (31 to 53 miles) above the Earth. In the mesosphere, temperatures decrease with altitude, and it is where most meteorites burn up upon entering the Earth's atmosphere.
- The **thermosphere** ranges from 85 to 600 kilometers (53 to 373 miles) above the Earth. It is characterized by very high temperatures due to the absorption of high-energy radiation from the Sun. The thermosphere is also where the auroras (northern and southern lights) occur.
- The **exosphere** is the outermost layer of the atmosphere, extending from the thermosphere into space. It is composed of very sparse particles that gradually escape into space.

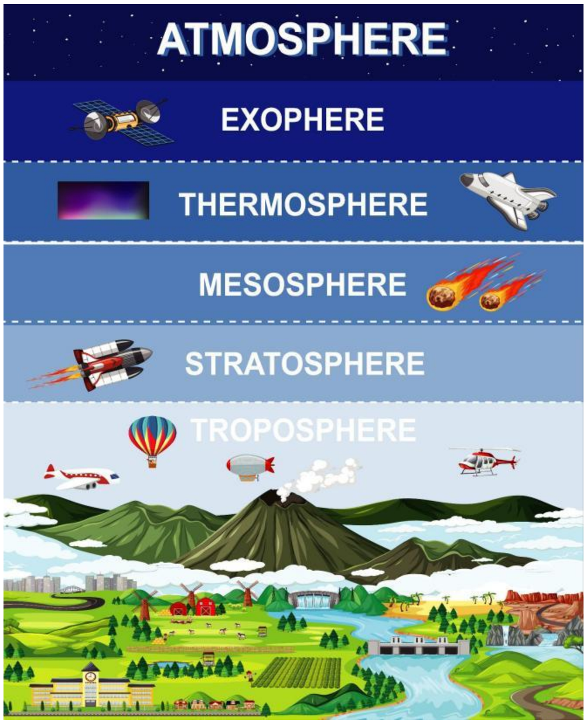


Figure 1.3: The Atmosphere (Image credit: Freepik images)

1.4.2. Composition of the Ocean:

The Earth's oceans cover about 71% of the planet's surface and contain 97% of the Earth's water. Ocean water is composed of 96.5% water and 3.5% dissolved salts, mainly sodium chloride.

1.4.3. Structure of the Ocean: The Earth's oceans are vast and deep, and they play a critical role in regulating the planet's climate and supporting life:

- The **surface layer** is the uppermost part of the ocean, extending to about 200 meters (656 feet). It is well-mixed by wind and waves, allowing sunlight to penetrate and support photosynthetic life, such as algae.
- The **thermocline** is a layer in the ocean where temperatures decrease rapidly with depth. The thermocline acts as a barrier between the warm surface waters and the cold deep ocean.
- The **deep ocean** extends from the thermocline to the ocean floor. It is characterized by cold temperatures, high pressure, and limited light. Despite the harsh conditions, it is home to a variety of life forms adapted to these environments.

1.5. Role of Atmosphere and Ocean

1.5.1. Role of the Atmosphere: The atmosphere regulates temperature by trapping heat through the greenhouse effect, which keeps the Earth's surface warm enough to support life. Without this effect, the planet would be too cold for most life forms. The atmosphere also distributes heat around the planet through wind and weather systems. This redistribution helps maintain a relatively stable climate across different regions. Finally, the atmosphere protects life from harmful solar radiation, particularly UV rays, through the ozone layer.

1.5.2. Role of the Oceans: The oceans are equally vital in maintaining the Earth's climate and supporting life. The oceans act as a heat reservoir by absorbing and storing solar energy. This stored heat helps moderate global temperatures and influence weather patterns. Ocean currents regulate climate by distributing heat around the globe, affecting regional climates. For example, the Gulf Stream carries warm water from the tropics to the North Atlantic, moderating the climate of Western Europe. The oceans support marine ecosystems by providing habitats and resources for a diverse range of marine life. They are also a source of food and oxygen, playing a crucial role in the Earth's biosphere.

1.6. Land, Air, Water, and Ecosystem

Land: The land includes various landscapes such as mountains, plains, and valleys, providing habitats and resources for terrestrial life. Landforms can affect weather patterns, such as mountains influencing wind and precipitation.

Air: The air is essential for respiration and photosynthesis, maintaining the balance of gases necessary for life. The air's composition includes nitrogen (78%), oxygen (21%), and trace gases.

Water: Water covers most of the Earth's surface and exists in various forms: liquid (oceans, rivers, lakes), solid (ice, snow), and gas (water vapor). Water is vital for life, weather, and climate systems.

Ecosystem: An ecosystem consists of living organisms interacting with their physical environment. Ecosystems include biomes such as forests, deserts, tundras, and aquatic systems, each supporting different life forms.

Chapter 2

Weather and Climate Processes

2.1 Principles of Weather and Climate Systems

Understanding the principles of weather and climate systems is vital for comprehending how these natural processes impact our daily lives and the planet as a whole. Weather and climate shape ecosystems, agriculture, water resources, and even human activities. By studying these processes, we can better prepare for weather changes and understand long-term climate trends, which is increasingly important in the context of climate change.

2.1.1 Weather: Short-Term Atmospheric Conditions

Weather refers to the short-term state of the atmosphere at a specific place and time. It encompasses various elements, including temperature, humidity, precipitation, wind, and visibility. Weather can change rapidly, often within minutes or hours, and is influenced by several factors such as atmospheric pressure, temperature differences, moisture levels, and the movement of air masses. Each of these elements plays a critical role in defining the weather of a particular area**:**

- **Temperature**: This measures how hot or cold the atmosphere is at a given place and time. Temperature is typically measured in degrees Celsius (°C) or Fahrenheit (°F). The Sun is the primary source of heat energy, warming the Earth's surface. When the Sun's rays hit the Earth, they warm the land, air, and water, resulting in varying temperatures across different regions. During the day, temperatures are generally higher because of direct sunlight, while at night, the absence of sunlight causes the temperature to drop.
- **Humidity**: Humidity refers to the amount of water vapor present in the air. It is usually expressed as a percentage, indicating how saturated the air is with moisture. For example, if the humidity is 100%, the air is fully saturated and cannot hold more water vapor, which often leads to the formation of clouds and precipitation. High humidity levels can make warm temperatures feel even hotter because the body's ability to cool itself through sweat evaporation is reduced. Humidity plays a crucial role in weather patterns, especially in tropical climates, where high humidity levels can lead to frequent rainfall.
- **Precipitation**: Precipitation includes all forms of water—liquid or solid—that fall from clouds to the ground. This includes rain, snow, sleet, and hail. Precipitation occurs when clouds, which are composed of tiny water droplets or ice crystals, become too heavy to remain suspended in the air. When this happens, gravity pulls the water down to Earth. Precipitation is essential for maintaining freshwater supplies and supporting plant and animal life.
- **Wind**: Wind is the movement of air from areas of high pressure to areas of low pressure. It is caused by the uneven heating of the Earth's surface by the Sun. Wind speed and direction are influenced by factors such as the Earth's rotation, pressure systems, and geographic features like mountains and oceans. Winds play a vital role in transporting heat, moisture, and even pollutants around the globe, influencing weather patterns. For example, sea breezes occur when cooler air from the sea moves toward the land, creating a refreshing breeze during the day.

- **Visibility**: Visibility is a measure of the distance one can clearly see. It is affected by weather conditions such as fog, rain, snow, or smoke. Reduced visibility can impact daily activities, such as driving and air travel, making it important for weather forecasts to include visibility reports.

- **Clouds: Formation, Categories, and Role in Rainfall**: Clouds play a crucial role in weather forecasting, as their types and patterns can provide early signs of changing weather conditions. Clouds form when warm, moist air rises and cools, causing the water vapor within it to condense into tiny droplets. These droplets cluster together to create clouds. Clouds are classified based on their appearance, height, and the weather they bring. There are three main types: cirrus, cumulus, and stratus. Cirrus clouds are high, thin, and wispy, often seen in fair weather. They are often seen ahead of a change in the weather, such as an approaching storm. Cumulus clouds are fluffy, white clouds with a flat base, typically indicating fair weather. However, when they grow larger, they can develop into cumulonimbus clouds, which are towering and dark, bringing thunderstorms, heavy rain, and sometimes even hail. Stratus clouds form low, gray layers that cover the sky, bringing overcast weather or light rain/drizzle. A graphical representation of different types of clouds based on its height is Figure 2.1.

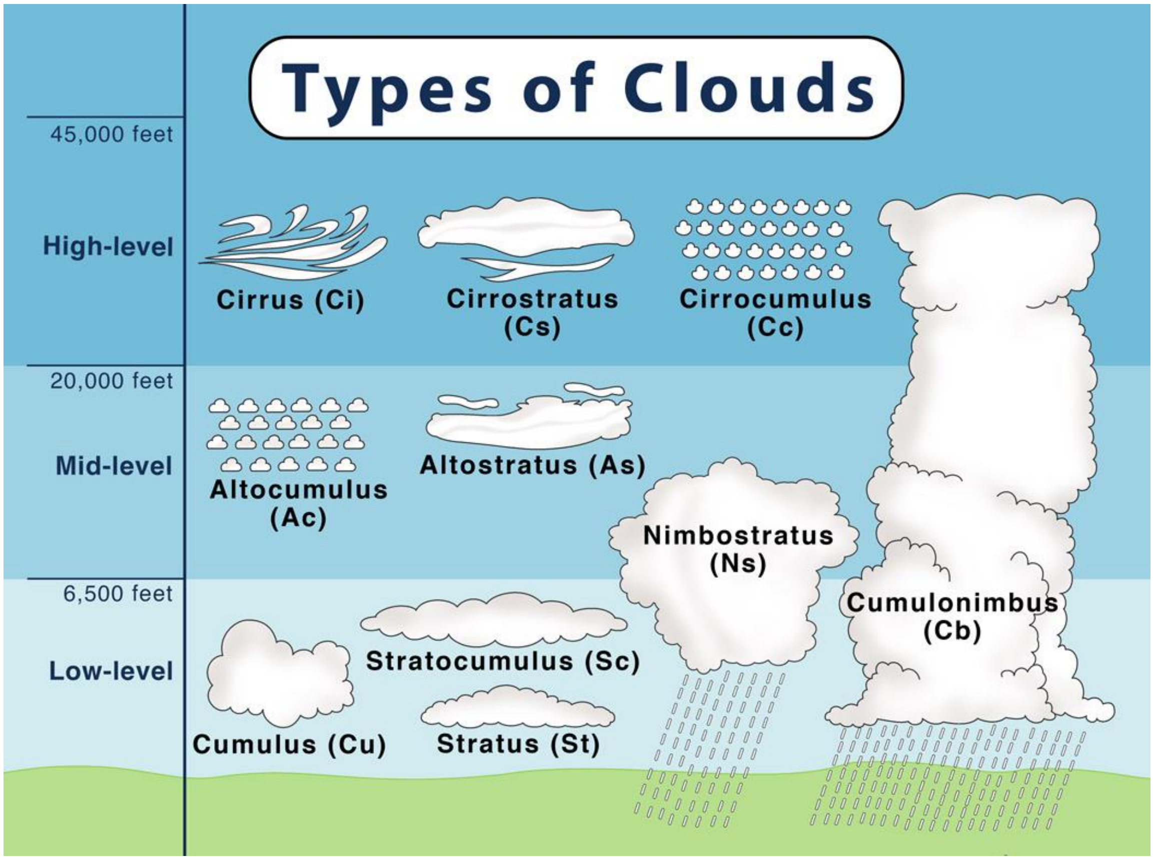


Figure 2.1: Cloud types (Image credit (Science Facts)

- **Weather phenomena**: Weather phenomena refer to various atmospheric events and conditions that occur naturally in the Earth's atmosphere and affect different regions around the globe. These phenomena are driven by complex interactions between temperature, humidity, air pressure, and wind patterns. Common weather phenomena include precipitation events such as rain, snow, sleet, and hail, as well as storms like thunderstorms, cyclones, tornadoes, and hurricanes. Lightning, thunder, and windstorms are also categorized under weather phenomena. Fog and mist, which reduce visibility, are other examples. Severe weather phenomena, like heatwaves, cold snaps, and droughts, can significantly impact human activities, agriculture, and the environment. Weather phenomena vary widely depending on geographic location and the season, and their study helps meteorologists forecast weather patterns and develop strategies for mitigating their effects on communities. Understanding these phenomena is crucial for safety, disaster preparedness, and efficient management of natural resources.

2.2 Weather and Climate forecasting process

Weather and climate forecasting involves using scientific principles and tools to predict atmospheric conditions over various time scales. Understanding the dynamics of the atmosphere and ocean is crucial for accurate forecasting. The forecasting system encompasses everything from seasonal predictions to real-time nowcasts, providing timely and accurate weather information for various sectors. Long Range Weather Prediction (LRF) focuses on seasonal patterns, such as the monsoon, months in advance by integrating oceanic, atmospheric, and land surface data to predict large-scale climate phenomena. Extended Range Weather Prediction (ERF) models provide forecasts ranging from 10 to 30 days, assisting in predicting trends like heatwaves and rainfall patterns. For medium-range forecasting (up to 10 days) and short-range forecasts (up to 3 days), Numerical Weather Prediction (NWP) models are utilized, enhancing accuracy through observed weather data from different sources. Nowcasting, which offers immediate forecasts (for the next 3 hours), employs high-resolution models and integrates radar, satellite, surface, and upper air observations to track weather events. A schematic diagram of IMD's operational forecasting system is provided in the Figure 2.2.

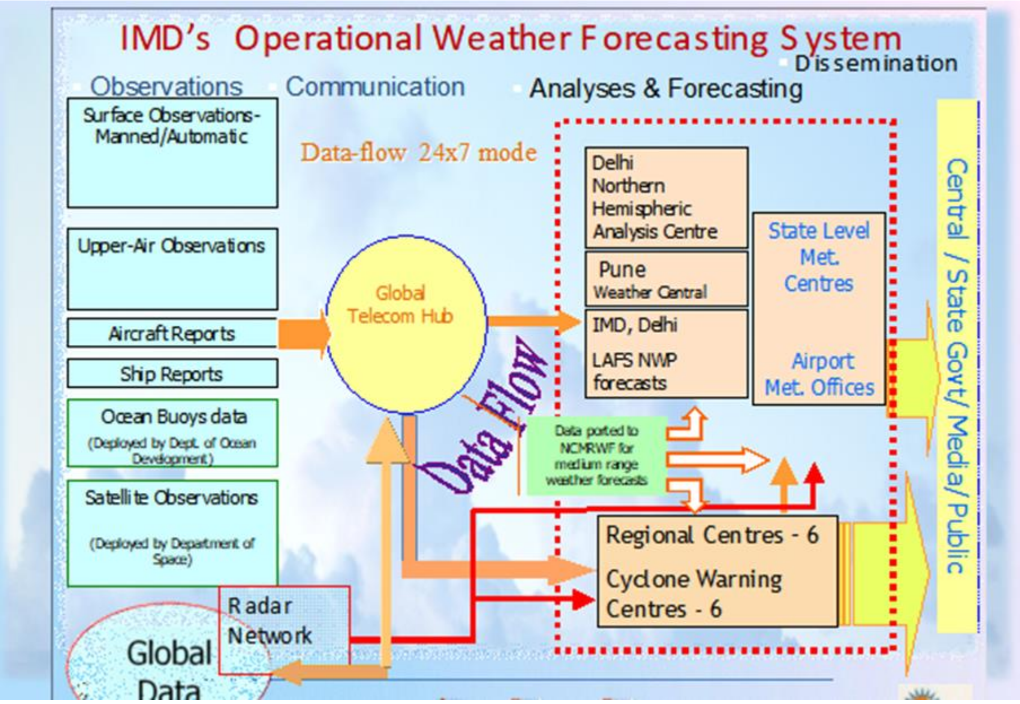


Figure 2.2: IMD's Weather Forecasting System

2.2.1 Data Observations

Weather forecasting begins with the collection of meteorological data, and the IMD has established a comprehensive network to gather this data from across the country, as well as global data through various collaborations. A map of integrated observing system is provided in the Figure 2.3.

The data collection methods include:

- **Surface Observatories**: IMD operates around 206 meteorological observatories (synoptic stations) across India, which collect essential weather parameters like temperature, humidity, pressure, wind speed/direction, clouds, and rainfall, etc. These observatories form the backbone of IMD's data network, ensuring continuous monitoring of weather patterns. In addition, IMD has also deployed around 735 automatic weather stations (AWS) (Figure 2.4a) and 1350 automatic rain gauge (ARG) stations, which are equipped with sensors to measure various weather parameters without the need for human intervention. These stations provide real-time data, particularly in remote areas where manual observations might be limited.
- **Upper Air Observation:** IMD conducts upper air observations using radiosondes (Figure 2.4b) and pilot balloons to measure atmospheric conditions at various altitudes. Currently, the India Meteorological Department (IMD) conducts radiosonde launches from 56 locations and pilot balloon launches from 62 locations across India. These upper air data include critical parameters like temperature, humidity, wind, and pressure at different heights, which are essential for accurate weather forecasting, particularly in tracking large-scale weather systems and cyclonic developments.
- **Satellites:** Satellite data plays an indispensable role in modern meteorological predictions. IMD utilizes the Indian Space Research Organization (ISRO)'s INSAT-3D, INSAT-3DR, INSAT-3DS, and Oceansat-3 satellites, which provide a continuous feed of meteorological data, including cloud cover, atmospheric temperature, humidity, sea surface temperatures, rainfall, wind speed & direction, clouds, cloud temperature, ocean surface wind, cyclone position, cyclone tracking, etc. Satellite image of cyclone "Mocha" captured from INSAT-3D satellite is shown in Figure 2.5. These satellites deliver real-time data crucial for weather forecasting and disaster warnings. IMD also utilizes weather satellites of foreign nations

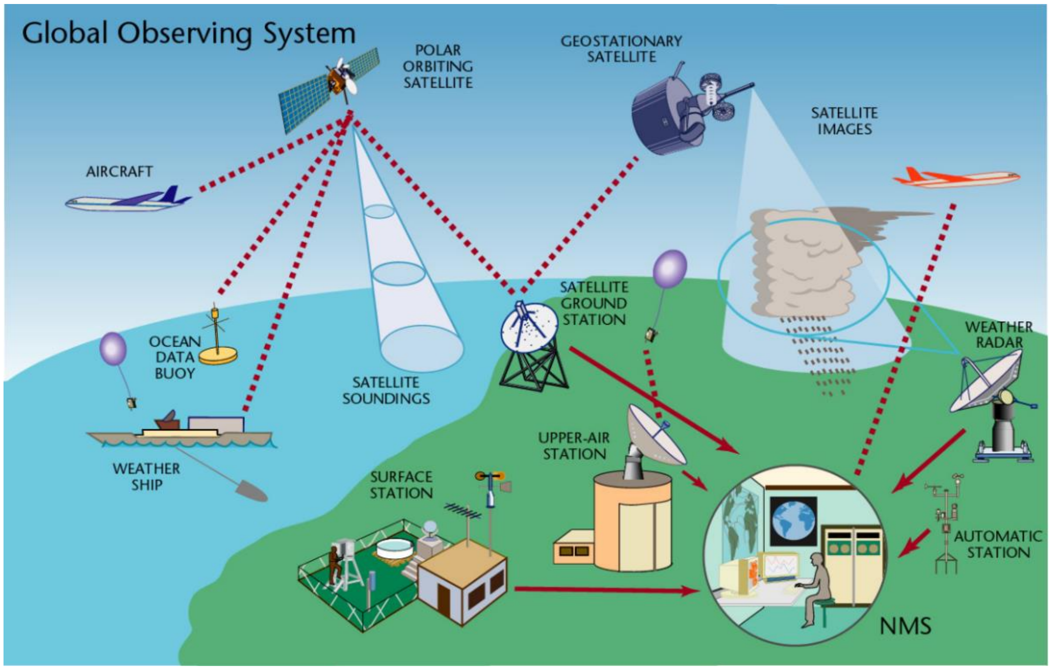


Figure 2.3: Integrated Observing System

(a) IMD Surface observatory (b) Radiosonde

Figure 2.4: IMD Surface Observatory and Radiosonde

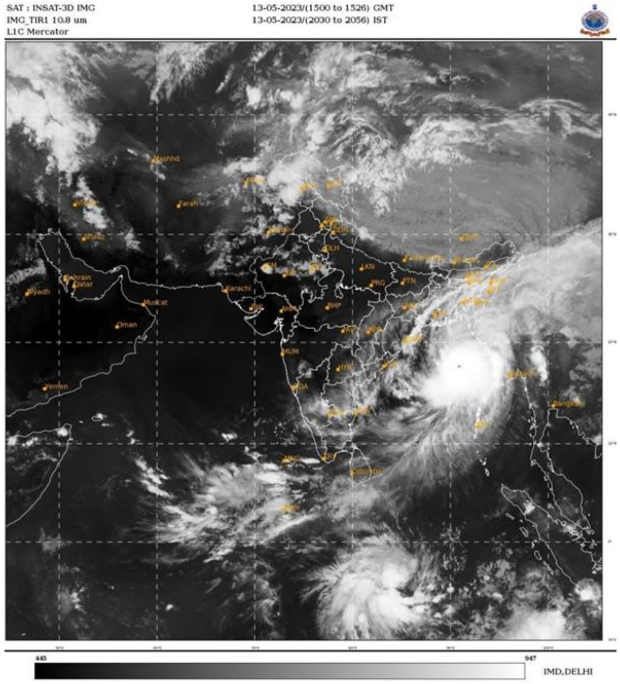


Figure 2.5: Satellite Image of Cyclone “Mocha”

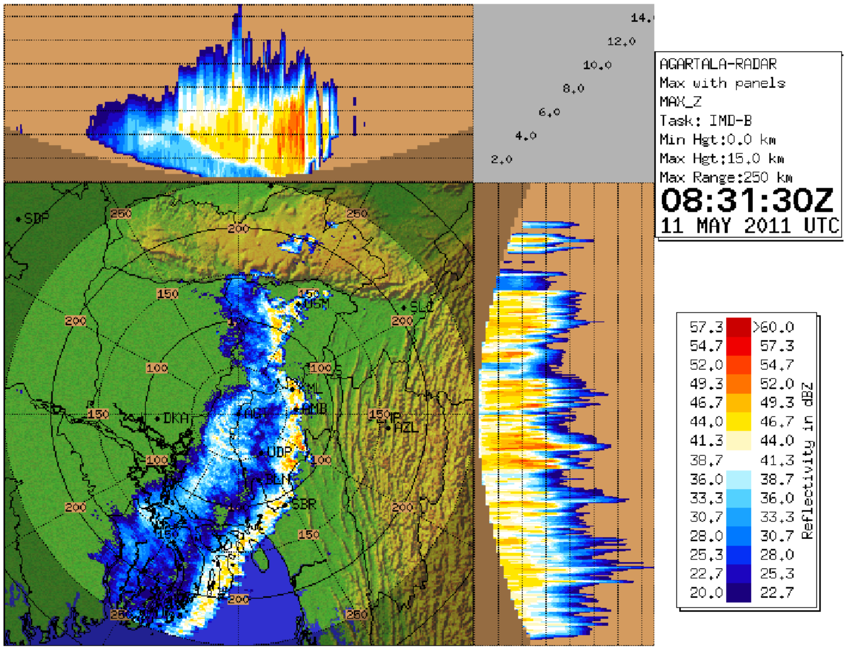


Figure 2.6: A Squall line observed by Doppler radar at Agartala on 11 May 2011.

- **Doppler Weather Radars (DWR):** The Doppler Weather Radar network is a crucial component of IMD’s forecasting infrastructure. These radars provide real-time information on rainfall intensity, storm structure, wind patterns, and the movement of cyclonic storms. IMD’s Doppler radars are particularly vital in predicting short-term weather phenomena like thunderstorms and severe storms.

A Squall line (narrow band of thunderstorms that can produce strong winds, heavy rain, and severe weather) observed by Doppler radar at Agartala on 11 May 2011 is shown in Figure 2.6.

- **Global Data Networks:** In addition to domestic data, IMD is part of global data-sharing networks facilitated by the World Meteorological Organization (WMO). This ensures that IMD has access to global weather data, which is essential for long-term forecasting and understanding broader weather patterns.

2.2.2 Climate: Long-Term Atmospheric Patterns

Weather is a short-term phenomenon, often varying from day to day. For instance, it might be sunny in the morning and rainy by afternoon, or warm today and cold tomorrow. Understanding weather elements and how they interact helps meteorologists predict short-term weather patterns, allowing people to prepare for immediate changes. Climate, on the other hand, refers to the long-term average of weather patterns in a specific region, typically measured over 30 years or more. While weather is what happens in the atmosphere on a day-to-day basis, climate is the overall trend and pattern of these conditions over an extended period. Climate is influenced by several key factors:

- **Latitude:** This is the distance of a place from the equator, measured in degrees. Latitude plays a crucial role in climate because it affects the amount of solar energy a region receives. Areas near the equator receive direct sunlight year-round, resulting in warm, tropical climates. In contrast, regions near the poles receive less direct sunlight, leading to colder, polar climates. For example, equatorial regions like the Amazon rainforest experience hot and humid conditions, while the Arctic has a frigid polar climate.
- **Altitude:** Altitude is the height of a place above sea level. Higher altitudes tend to have cooler temperatures because the atmosphere becomes thinner, and air pressure decreases as you go higher. This is why mountainous regions, even those near the equator, can have colder climates than surrounding lowlands. For instance, the Himalayan mountains in Asia have snow-covered peaks year-round despite being in a tropical region.
- **Ocean Currents:** Ocean currents are large-scale movements of seawater that play a significant role in regulating climate. Warm currents, such as the Gulf Stream, carry heat from the tropics toward higher latitudes, influencing the climate of nearby coastal areas. For example, the Gulf Stream warms the climate of Western Europe, making it milder than other regions at similar latitudes. Conversely, cold currents can lower temperatures along coastlines, as seen in the cool waters off the west coast of South America.
- **Human Activities:** Activities such as deforestation, urbanization, and the burning of fossil fuels release greenhouse gases into the atmosphere, contributing to climate change. These human-induced changes can alter climate patterns by increasing the Earth's overall temperature, causing shifts in weather, sea level rise, and more frequent extreme weather events like hurricanes and droughts.

Understanding climate is essential because it helps predict long-term changes and their potential impacts on the environment and human societies. For example, knowing that a region has a tropical climate with a rainy season helps farmers plan their planting and harvesting schedules.

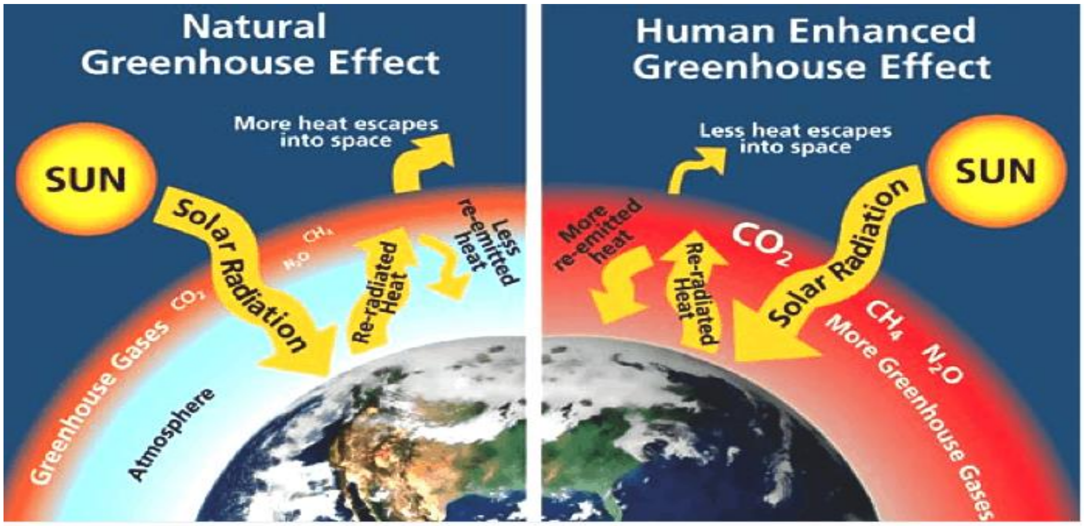
2.2.3 Solar Radiation and Heat Balance:

The Earth receives energy from the Sun in the form of solar radiation. This energy is absorbed, reflected, and emitted by the Earth's surface and atmosphere. The balance between incoming and outgoing radiation determines the Earth's temperature and climate. Factors such as greenhouse gases, albedo (reflectivity), and cloud cover influence this heat balance.

- **Greenhouse Gases:** These gases, such as carbon dioxide, methane, and water vapor, trap heat in the atmosphere and keep the Earth's surface warm.
- **Albedo:** This is the reflectivity of the Earth's surface. Surfaces like ice and snow have high albedo and reflect most of the sunlight, while darker surfaces like oceans and forests have low albedo and absorb more heat.
- **Cloud Cover:** Clouds can both reflect sunlight back into space and trap heat the atmosphere influencing the Earth’s’ heat balance.

Greenhouse Effect and Greenhouse Gases (GHGs)

The greenhouse effect is a natural process that warms the Earth's surface. When the Sun's energy reaches Earth, some of it is reflected back into space, while the rest is absorbed and re-radiated by greenhouse gases. This effect is crucial for life on Earth, as it keeps the planet warm enough to sustain most forms of life. The natural greenhouse effect maintains the Earth's average surface temperature at around 15°C (59°F). Without it, the average temperature would be about -18°C (0°F), making the planet too cold for most life forms. This process is vital for sustaining life on Earth by maintaining a temperature suitable for habitation.



(Source: Center for Climate and Energy Solutions)

Figure 2.7: Source Centre for climate and energy solution

Key greenhouse Gases

Greenhouse gases trap heat in the Earth's atmosphere and contribute to global warming (Fig 2.7)**.** The most significant GHGs are:

1. Carbon Dioxide (CO_2): Released by burning fossil fuels (coal, oil, natural gas) and deforestation.
2. Methane (CH_4): Emitted during the production of coal, oil, and natural gas; also released by livestock and other agricultural practices.
3. Nitrous Oxide (N_2O): Mainly from agricultural activities, such as the use of fertilizers.
4. Water Vapor (H_2O): Naturally occurring but amplifies the warming effect.
5. Ozone (O_3): Exists naturally in the stratosphere, but human-made ozone at ground level is a pollutant.

The Greenhouse Effect: The greenhouse effect is a natural process where greenhouse gases trap some of the sun's heat in the form of terrestrial radiations, keeping Earth warm enough to support life. However, human activities have intensified this effect, leading to global warming.

2.2.4 Weather and Climate: Differences and Similarities

Both weather and climate are influenced by similar processes, such as atmospheric pressure, solar energy, and the Earth's rotation, but they operate on different timescales. Weather is concerned with short-term changes in the atmosphere, while climate focuses on the long-term trends and averages of these weather patterns. Studying both is crucial for understanding the Earth's atmospheric behaviour and how it affects ecosystems, agriculture, and human activities.

2.3 Dynamics of Atmosphere and Ocean

The dynamics of the atmosphere and ocean play a crucial role in shaping weather patterns and influencing climate variability. Atmospheric dynamics focuses on the movement of air, which is influenced by forces such as pressure gradients, the Coriolis effect, friction, and gravity. Solar radiation and Earth's energy balance drive atmospheric circulation patterns, including Hadley, Ferrel, and Rossby cells, which in turn create wind patterns like trade winds and the jet stream. These circulations impact air masses and fronts, leading to cloud formation and precipitation processes.

Ocean dynamics involves the movement of water driven by ocean currents, wind stress, temperature and salinity gradients, and Earth's rotation (Coriolis effect). The interaction between the atmosphere and the ocean is key to understanding larger-scale weather systems, such as El Niño and La Niña, which have global climate impacts. Together, the interplay of these atmospheric and oceanic forces shapes the Earth's weather and climate.

Atmospheric Dynamics: This refers to the study of the motion of air in the atmosphere, influenced by various forces, such as:

Pressure gradients, Coriolis effect, Friction, Gravity.

Ocean Dynamics: The movement of ocean water is affected by:

Ocean currents, Wind stress, Temperature and salinity gradients, Earth's rotation (Coriolis effect).

The interaction between the atmosphere and ocean is vital in understanding weather patterns and climate variability.

2.3.1 Atmospheric Circulation

One of the main drivers of both weather and climate is atmospheric circulation. The Earth's rotation and the uneven heating of its surface cause air to move, creating wind patterns that transport heat and moisture around the globe. This circulation is responsible for the movement of air masses and the formation of weather systems. A diagram of which represents atmospheric circulation is provided in the Figure 2.8. Key features of atmospheric circulation include:

- **Trade Winds**: Steady winds that flow from east to west between 30 degrees latitude and the equator in both hemispheres. These winds are crucial for moving warm ocean waters and influencing weather patterns in tropical regions. For example, they play a key role in bringing moisture-laden air to coastal areas, leading to rainfall.
- **Westerlies**: Winds that blow from west to east between 30 and 60 degrees latitude in both hemispheres. The westerlies influence weather patterns in the mid-latitudes, where many major cities are located. For instance, they bring warm air from the tropics to Europe, moderating its climate.
- **Polar Easterlies**: Winds that blow from east to west near the poles. They contribute to the formation of polar weather systems, which are characterized by extremely cold temperatures. These winds play a part in shaping weather patterns in regions like Antarctica and the Arctic.

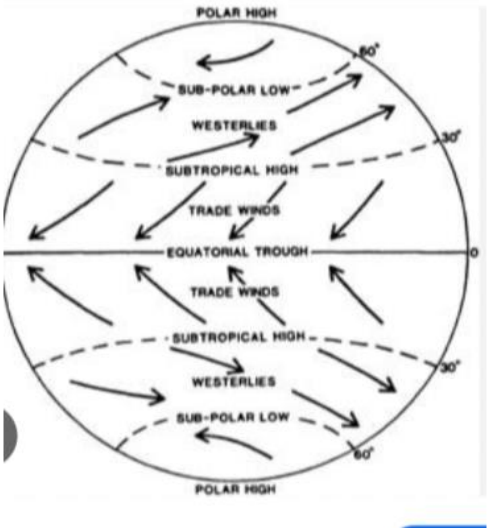


Figure 2.8: Atmospheric Circulation

Atmospheric circulation not only dictates daily weather but also contributes to the long-term climate of a region. For example, the steady flow of trade winds helps create tropical rainforests near the equator, while the westerlies contribute to the temperate climates found in parts of North America and Europe.

2.3.2 Weather Systems:

Weather systems, such as cyclones, anticyclones, and frontal systems, are formed by the interaction of air masses with different temperatures and humidity levels. These systems bring changes in weather conditions, including precipitation, wind, and temperature variations. Major weather affecting India is shown in Figure 2.9.

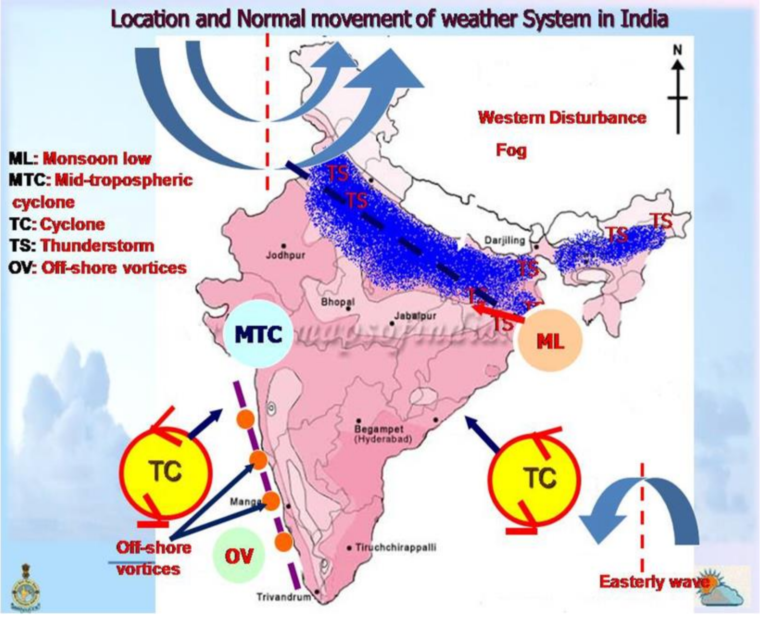


Figure 2.9: Weather System and Extreme Weather in India

- **Cyclones:** Low-pressure systems characterized by inward spiraling winds and often associated with stormy weather. In the Northern Hemisphere, they rotate counterclockwise, while in the Southern Hemisphere, they rotate clockwise (Details in Chapter 3).
- Anticyclones: High-pressure systems characterized by outward spiraling winds and typically associated with calm and clear weather. In the Northern Hemisphere, they rotate clockwise, while in the Southern Hemisphere, they rotate counterclockwise.
- **Frontal Systems:** Boundaries between two air masses of different temperatures and humidity levels. They can cause dramatic weather changes, including storms and heavy precipitation.

2.3.3 Climate Systems:

Climate systems are influenced by long-term factors such as ocean currents, volcanic activity, solar radiation variations, and human activities. These factors interact in complex ways to shape regional and global climate patterns. Understanding these interactions is crucial for predicting future climate changes and their potential impacts.

- **Ocean Currents:** Large-scale movements of seawater that distribute heat around the globe. For example, the Gulf Stream carries warm water from the tropics to the North Atlantic, moderating the climate of Western Europe.

- **Volcanic Activity:** Volcanic eruptions can release large amounts of ash and gases into the atmosphere, affecting climate. For example, the eruption of Mount Pinatubo in 1991 caused global temperatures to drop temporarily.
- **Solar Radiation Variations:** Changes in the amount of solar energy reaching the Earth can influence climate. For example, periods of reduced solar activity, such as the Maunder Minimum, have been associated with cooler global temperatures.
- **Human Activities:** The burning of fossil fuels, deforestation, and industrial processes release greenhouse gases into the atmosphere, contributing to global warming and climate change.

2.3.4 Climate Classification

Climate classification is a system used to categorize the world’s different climate types based on various factors like temperature, rainfall, and seasonal patterns. It helps scientists, farmers, and policymakers understand and predict the climate conditions of a particular region. By grouping areas with similar weather patterns, climate classification makes it easier to study global climate systems and how they affect agriculture, ecosystems, and human activities. For example, the Köppen Climate Classification divides climates into groups like tropical, dry, temperate, continental, and polar, based on temperature and precipitation. Similarly, the Thornthwaite Classification focuses on moisture availability and how water is used and stored in an area. The map of Indian climatic zones is depicted in Figure 2.10. Overall, climate classification helps us make informed decisions about water management, farming, and preparing for weather changes.

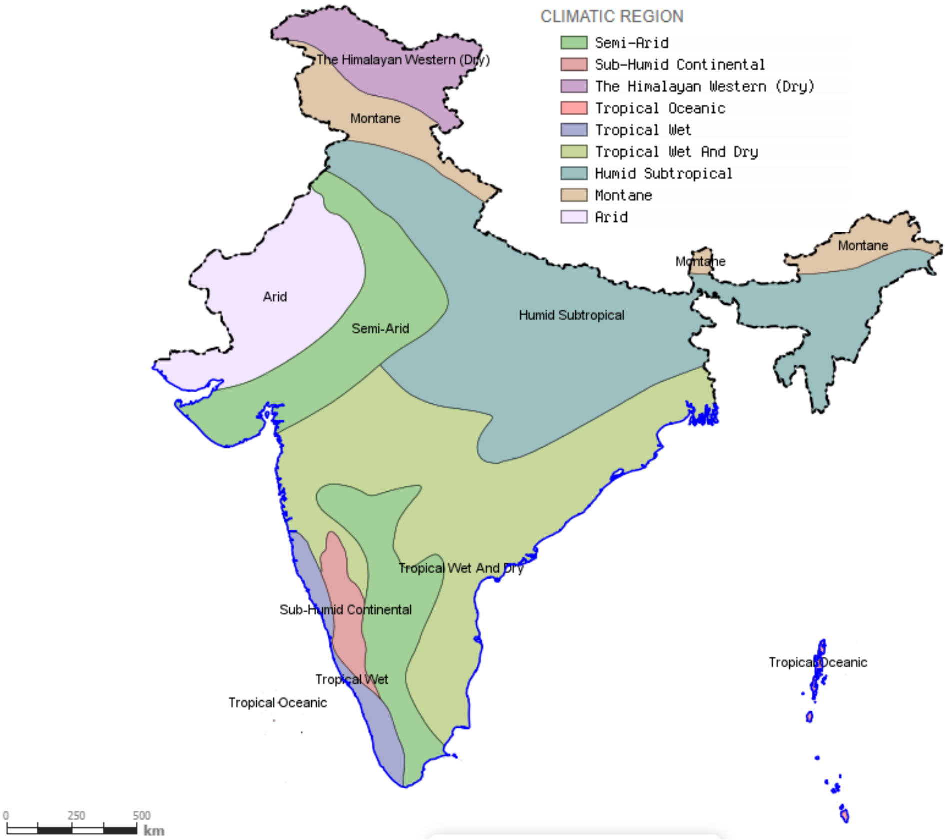


Figure 2.10: The map of Indian climatic zones.

2.4 Seasons

- **Winter:** Winter occurs when a hemisphere is tilted away from the Sun, resulting in shorter days and cooler temperatures. In India, winter typically lasts from December to February. The weather is generally dry and cold, with occasional rain brought by Western Disturbances in northern regions. Snowfall occurs in mountainous areas. The Indo-Gangetic Plains (IGP) of northern India frequently experience fog and poor air quality, especially during the winter months. Fog occurs when cooler air traps moisture near the surface, leading to reduced visibility. This phenomenon is particularly common from November to January, when cooler temperatures and high humidity contribute to dense fog formation. The situation is exacerbated by human activities such as vehicular emissions, industrial pollution, and agricultural burning, particularly the practice of stubble burning in states like Punjab and Haryana. These pollutants, combined with the stagnant air, contribute to severe air pollution, forming a toxic mixture of fog and smog, often called "smog episodes." The lack of wind and atmospheric circulation traps pollutants close to the surface, leading to hazardous air quality. Poor air quality over the IGP not only disrupts transportation and daily activities due to reduced visibility but also poses significant health risks, including respiratory problems and other chronic conditions, affecting millions of people across densely populated areas.
- **Pre-Monsoon (Summer):** The pre-monsoon season, also known as summer, spans from March to May. During this time, temperatures rise significantly, especially in inland regions. Hot winds, known as "loo" in northern India, blow across the plains. This period also marks the buildup to the monsoon, with increased humidity and occasional thunderstorms.
- **Southwest Monsoon (Rainy Season):** The southwest monsoon season extends from June to September. Moist winds from the Indian Ocean and the Arabian Sea blow towards the land, bringing heavy rainfall across much of India. This rain is crucial for agriculture, replenishing water sources and supporting crop growth. However, excessive monsoon rains can lead to floods and landslides, especially in coastal and hilly regions.
- **Post-Monsoon (Autumn):** The post-monsoon season, or autumn, occurs from October to November. During this period, the southwest monsoon withdraws, and the weather becomes more stable. Temperatures begin to cool, and the skies are generally clear. This season is also known as the retreating monsoon, as the winds shift direction, leading to sporadic rainfall in certain regions like the southeastern coast of India.

2.5 Rainfall and Monsoons

The monsoon is a seasonal wind system that plays a crucial role in shaping the climate and weather patterns of India and many other regions in South Asia. In India, the monsoon is divided into two primary phases: the Southwest Monsoon and the Northeast Monsoon, each with distinct characteristics and effects on the subcontinent. The climate and rainfall of India and its neighbourhood to a large extent is determined by the geographic location. India is an extension of the great Asiatic continent with the vast expanse of the Indian ocean to the south and the loftiest Himalayas to the north. The rainfall over India and neighbourhood is dominated by two monsoons - Southwest monsoon and Northeast monsoon.

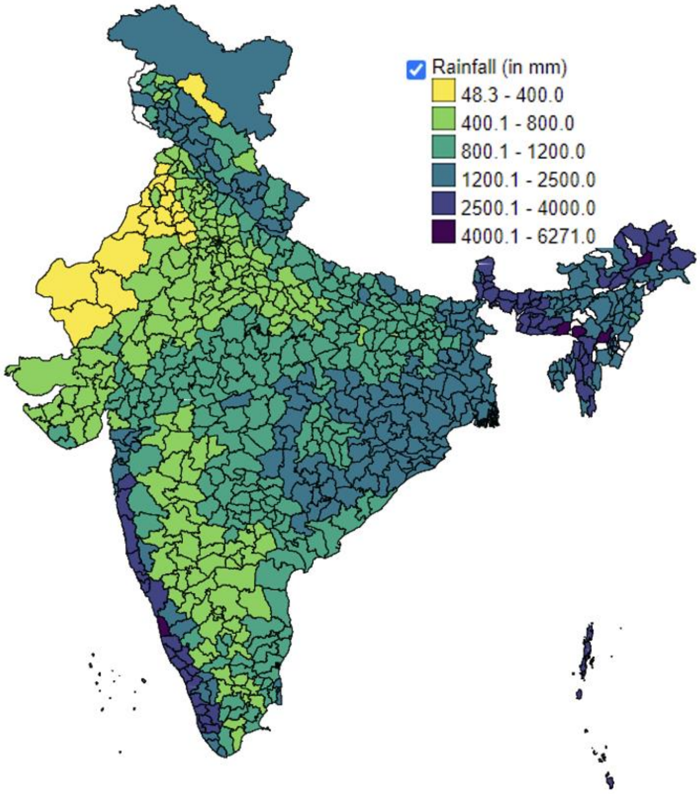


Figure 2.11.: All India District wise annual rainfall normal using the data during 1971-2020.

All India normal rainfall is 118 cm of which 75% (86.8 cm) rainfall takes place in the monsoon season. Rainfed agriculture in India covers 68% of the net sown area. Rainfall monitoring and forecast for rainfed agriculture areas is important as it accounts for almost 40% of the country's food production. Figure 2.11 shows the district-wise annual normal rainfall map of India, generated using data from 1971 to 2020.

2.5.1 Southwest Monsoon (June to September)

The Southwest Monsoon is the most significant monsoon season in India, responsible for around 70-90% of the country’s annual rainfall. It occurs from June to September and is crucial for the country's agriculture, economy, and water resources.

1. **Mechanism**: The Southwest Monsoon is driven by the differential heating of land and water. During summer, the Indian landmass heats up more quickly than the surrounding oceans, creating a low-pressure zone over the northern plains. At the same time, the Indian Ocean remains cooler, generating a high-pressure zone. This difference in pressure causes moist winds from the southwest, originating over the Arabian Sea and the Bay of Bengal, to move towards the Indian subcontinent.

2. **Onset**: The monsoon generally makes landfall over the Kerala coast around June 1st. It progresses northwards, reaching the central and northern parts of India by mid-July. The winds carry moisture from the ocean, which condenses as they move over land, leading to widespread

rainfall. The normal dates for onset of southwest monsoon over different part of the country is illustrated in the Figure 2.12.

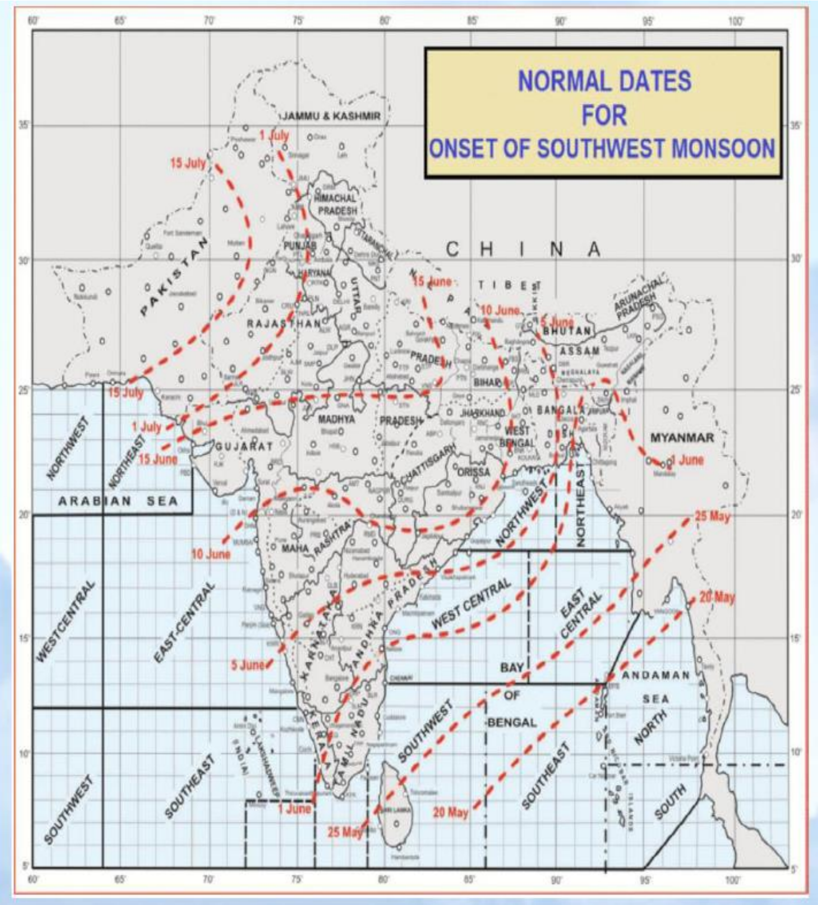


Figure 2.12.: Map of Onset of Southwest Monsoon in India (Image Credit: IMD)

Rainfall Distribution: The Western Ghats and northeastern states receive the heaviest rainfall due to the orographic effect, where mountains force the moisture-laden air to rise, cool, and release rain. States like Kerala, Karnataka, Maharashtra, and the northeastern regions experience significant downpours. Central and northern India also benefit from the monsoon rains, which are vital for crops like rice, cotton, and sugarcane. Figure 2.13 shows the district-wise normal rainfall map of India during southwest monsoon season, generated using data from 1971 to 2020.

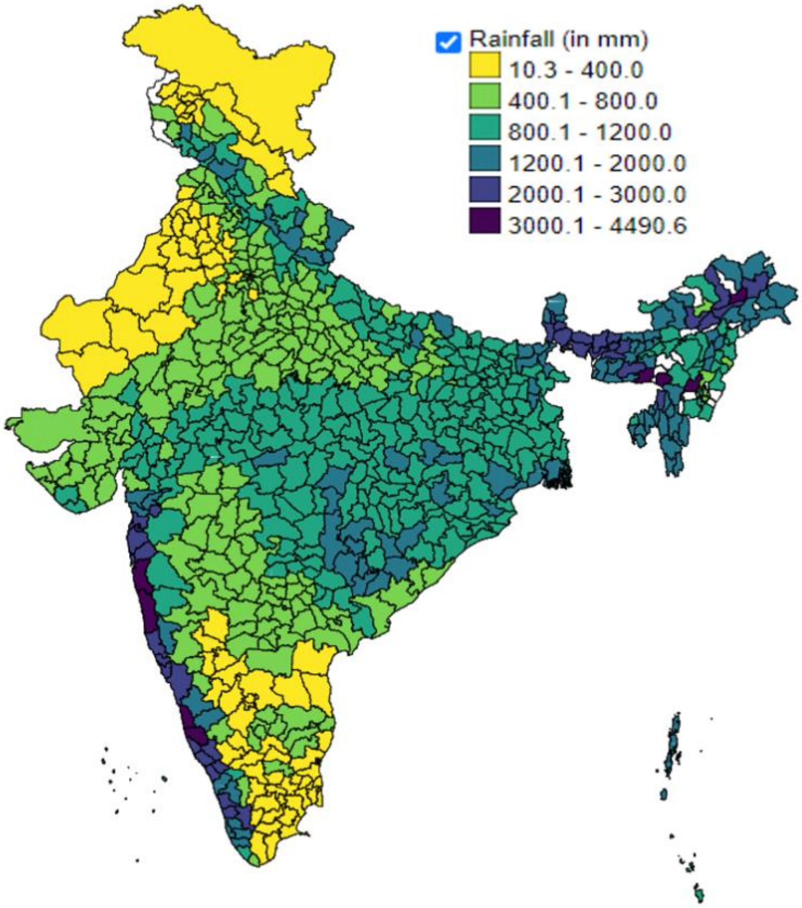


Figure 2.13: Map of All India District-wise Rainfall Normals using the data during 1971-2020 for the southwest Monsoon season (June to September) (Image Credit: IMD)

The 4 zones of rainfall throughout India are categorized below.

a). Insufficient Rainfall Zone (less than 50cm of rainfall): This rainfall zone is found in Andhra Pradesh, some regions of Karnataka as well as regions of Maharashtra, Ladakh, and a vast area of Rajasthan. Jaisalmer is an area in Rajasthan that counts for receiving the least rainfall in India.

b). Low Rainfall Zone (50cm – 100cm of rainfall): This rainfall zone is found in Maharashtra, some areas in Gujarat, some places in Karnataka, Tamil Nadu, Andhra Pradesh, Madhya Pradesh, Punjab, Haryana, and sparsely in Western Uttar Pradesh.

c). Medium Rainfall Zone (100cm – 200cm of rainfall): The various zones of abundant rainfall in India are geographically separated from each other. First, the Western Ghats have a thin strip that runs North-to-South across the Ghats' entire length. The frequency of rainy seasons rises as one travels South. For example, the North has 4 rainy periods between June and September whereas the Midlands have 5 rainy months ranging from June to October.

d). High Rainfall Zone (200cm – 300cm of rainfall) : The most notable rainfall occurs on the West side, in the Western Ghats, including the sub-Himalayan areas of the upper East along Meghalaya's slopes. The North-Eastern region and also the windward portion of the Central Highlands receive an average of 400cm of rain every year. Rain in the Brahmaputra Valley and its surrounding hills experience less than 200cm of rainfall. This zone includes locations that receive 200cm-300cm of rain each year. This zone is primarily found in Eastern India.

3. **Impact**: The Southwest Monsoon is essential for the Kharif crop season, and the livelihood of millions of farmers depends on its timely arrival and adequate distribution. However, the monsoon can also cause challenges such as flooding, landslides, and waterlogging, especially in regions prone to heavy rainfall like Assam, Bihar, and parts of Maharashtra.

2.5.2 Northeast Monsoon (October to December)

The Northeast Monsoon, also known as the retreating monsoon, occurs from October to December and mainly affects the southeastern part of India, particularly Tamil Nadu, Andhra Pradesh, and parts of Karnataka and Kerala.

1. **Mechanism**: The Northeast Monsoon is caused by the reversal of wind patterns as the Indian subcontinent begins to cool after the intense heat of summer. By October, the low-pressure zone over the northern plains weakens, and a high-pressure zone forms over the landmass as temperatures drop. Cold, dry winds from the northeast blow toward the ocean, but as they pass over the Bay of Bengal, they pick up moisture and bring rainfall to southeastern India.

2. **Onset**: The Northeast Monsoon typically begins in October and continues until December. Unlike the Southwest Monsoon, which covers most of India, the Northeast Monsoon affects a smaller region, primarily the southeastern coastal areas.

3. **Rainfall Distribution**: Tamil Nadu receives about 50-60% of its annual rainfall from the Northeast Monsoon. Coastal areas like Chennai, Puducherry, and other parts of Tamil Nadu and southern Andhra Pradesh benefit from this monsoon. The rainfall is generally less intense compared to the Southwest Monsoon but is vital for the Rabi crops grown in these regions. Figure 2.14 shows the district-wise normal rainfall map of India during northeast monsoon season, generated using data from 1971 to 2020.

4. **Impact**: The Northeast Monsoon is important for replenishing water reservoirs and supporting agriculture in the southeastern states. However, it can also cause localized flooding, especially in low-lying areas and coastal cities like Chennai.

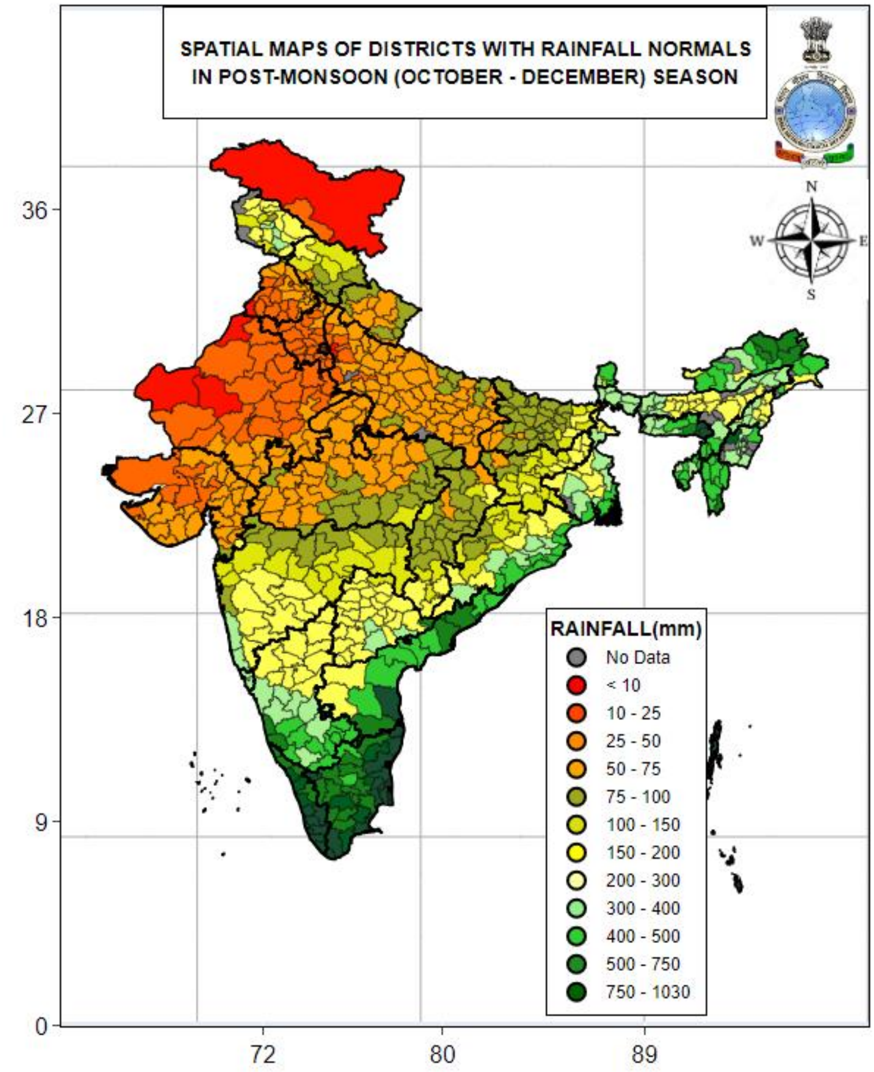


Figure 2.14.: District-wise Post Monsoon Season Rainfall (Image Credit: IMD)

2.5.3 Importance of Monsoons in India

Monsoons play a critical role in India’s agrarian economy, determining water availability for agriculture, drinking water, and hydropower generation. The timely arrival and adequate spread of the monsoons are vital for the country’s food security. However, the monsoons also present challenges, as both excessive and deficient rainfall can lead to floods, droughts, and economic losses. Understanding and predicting monsoon patterns is therefore crucial for disaster preparedness, agricultural planning, and water resource management in India.

Chapter 3

Natural Hazards and Disasters

3.1. Introduction to Natural Hazards

3.1.1. Overview of Natural Hazards on Earth

Natural hazards are naturally occurring events that can pose significant threats to human life, property, and the environment. These hazards are caused by different Earth processes, including atmospheric, geological, and hydrological phenomena. They vary in type, scale, and impact, ranging from localized events like landslides to widespread disasters like hurricanes or earthquakes. While natural hazards themselves are inevitable, their effects can be mitigated through preparedness, early warning systems, and effective disaster management strategies.

3.1.2 Types of Natural Hazards

Natural hazards can be broadly categorized into Hydrometeorological hazards and Geological hazards:

(i) Hydrometeorological Hazards

These are hazards associated with weather and climate processes. They often stem from atmospheric conditions and include the following:

Cyclones: Cyclones are large-scale storm systems characterized by low pressure at the center and strong winds rotating around it. These storms can cause extensive flooding, damage to infrastructure, and loss of life.

Thunderstorms: A localized storm often accompanied by lightning, thunder, and heavy rainfall. Thunderstorms can cause flash floods, landslides, and damage due to strong winds and lightning strikes.

Heavy Rainfall: Excessive rain over a short period of time can lead to urban flooding, river overflows, landslides, and soil erosion, severely impacting communities and agriculture.

Heat Waves: Prolonged periods of excessively high temperatures can lead to health crises, particularly affecting vulnerable populations like the elderly and those with pre-existing conditions.

Cold Waves: Periods of unusually low temperatures can cause severe cold stress on humans and animals, damage crops, and disrupt energy systems.

Fog: Dense fog can reduce visibility, leading to transportation accidents, particularly in aviation and road traffic. It also poses health risks, especially for respiratory conditions.

3.1.3 Geological Hazards

Geological hazards arise from Earth’s internal processes and include the following:

Landslides: Landslides refer to the downward movement of soil, rock, or debris due to gravity, often triggered by factors such as heavy rainfall, earthquakes, or human activities like deforestation. They can block roads, damage buildings, and cause fatalities.

Earthquakes: Sudden shaking or movement of the Earth's crust due to the release of energy along fault lines. Earthquakes can lead to severe structural damage, ground rupture, and secondary hazards like tsunamis and landslides.

Volcanic Eruptions: When magma from beneath the Earth's surface is ejected through a volcano, causing pyroclastic flows, ash clouds, lava flows, and volcanic gases. Volcanic eruptions can devastate communities, ecosystems, and infrastructure.

3.2 Hydro-meteorological hazards over India

India is prone to a variety of hydro-meteorological hazards that vary by season and region, significantly impacting the lives and livelihoods of its population. During the monsoon season, which typically lasts from June to September, heavy rainfall leads to flooding in many states, often resulting in loss of life and property. In contrast, the pre-monsoon months of April and May witness severe heatwaves affecting northern and central India, with states like Rajasthan, Gujarat, Uttar Pradesh, Haryana, Delhi and Madhya Pradesh experiencing soaring temperatures that can lead to heat-related illnesses and agricultural losses. The winter months, particularly from December to February, bring dense fog to northern plains, disrupting transportation and posing risks to travellers. Additionally, the coastal regions of India, including Tamil Nadu, Odisha, West Bengal, Gujarat and Andhra Pradesh, are frequently impacted by cyclones, particularly during April to June and September to December, leading to storm surges, heavy rainfall, and widespread destruction. Furthermore, regions like Uttarakhand and Himachal Pradesh are vulnerable to landslides triggered by heavy rains, especially during the monsoon. Overall, the diverse climatic conditions across India create a complex landscape of hydro-meteorological hazards that necessitate comprehensive disaster management strategies to mitigate their impacts.

3.3 Cyclones

3.3.1. Formation and Structure of cyclones

Cyclones typically form over warm tropical waters where sea surface temperatures exceed 26.5°C, as warm water provides the energy needed to fuel the cyclone. In addition to warm water, other favorable conditions include high humidity in the atmosphere, low vertical wind shear (where wind speeds and directions do not change drastically with height), and a pre-existing disturbance, such as a low-pressure area. A cyclone is a large-scale air mass that rotates around a strong center of low atmospheric pressure, characterized by inward spiraling winds.

Cyclones are classified based on their location and intensity, with tropical cyclones (hurricanes or typhoons) forming over warm ocean waters and featuring strong winds, heavy rainfall, and storm surges. Cyclones form due to the Coriolis effect, which causes the wind to rotate in a counterclockwise direction in the Northern Hemisphere and clockwise in the Southern Hemisphere.

When all the favorable conditions combine, they create the perfect environment for cyclones to develop and grow in strength. However, these powerful storms can lead to significant damage and pose serious threats to life and property. In the Indian Ocean, particularly the Bay of Bengal and the

Arabian Sea, cyclones are common during pre-monsoon (April-June) and post-monsoon (October-December) seasons.The shape of a tropical cyclone is typically circular or spiral, characterized by a well-defined central core called the eye (Figure 3.1). Surrounding the eye is the eye wall, a ring of towering thunderstorms where the most intense winds and heavy rainfall occur. The cyclone's outer structure consists of spiral rainbands, which are bands of clouds and precipitation that spiral outward from the center. These rainbands contribute to the storm's overall spiral shape, resembling a massive, rotating system when viewed from above. The symmetrical structure is maintained by the Coriolis force, which causes the cyclone to rotate, and the storm's energy is driven by warm ocean waters.

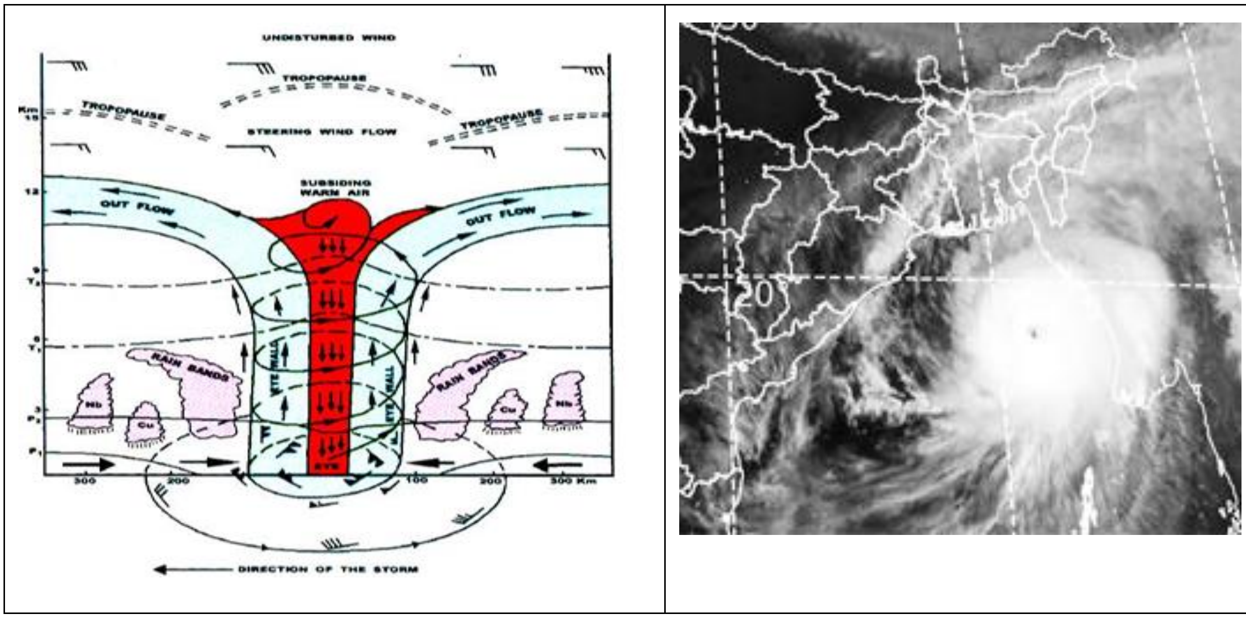


Figure 3.1. (Left) Vertical structure of tropical cyclone; (Right) Image of the cyclone Mocha captured from satellite with eye of the cyclone visible.

Cyclones are intense low pressure areas - from the center of which pressure increases outwards. The amount of the pressure drop in the center and the rate at which it increases outwards gives the intensity of the cyclones and the strength of winds. The criteria followed by the India Meteorological Department (IMD) to classify the low pressure systems in the Bay of Bengal and in the Arabian Sea as adopted by the World Meteorological Organisation (W.M.O.) are given in Table 3.1.

Table 3.1. Criteria for classification of cyclonic disturbances over the North Indian Ocean

Type of disturbance	**Associated maximum sustained wind**
1. Low Pressure Area	Not exceeding 17 knots (<31 kmph)
2. Depression	17 to 27 knots (31-49 kmph)
3. Deep Depression	28 to 33 Knots (50-61 kmph)
4. Cyclonic Storm	34 to 47 Knots (62-88 kmph)
5. Severe Cyclonic Storm	48 to 63 Knots (89-117 kmph)
6. Very Severe Cyclonic Storm	64 to 90 Knots (118-167 kmph)
7. Extremely Severe Cyclonic Storm	91 to119 Knots (168-221 kmph)
8. Super Cyclonic Storm	120 Knots and above (≥222 kmph)

3.3.2 Climatology of tropical cyclone

The climatology of tropical cyclones involves the study of their frequency, distribution, and intensity across various ocean basins. . Cyclones are more prevalent in certain regions, like the North Atlantic, Eastern Pacific, and Western Pacific, with seasonal peaks often between June and November.The storms are call Hurricanes in North Atlantic and North-east Pacific oceans. These are called Typhoons over East Pacific ocean. In the Indian Ocean, tropical cyclones typically form between April to June and September to December, affecting South Asian nations, particularly India, Bangladesh, and Sri Lanka. The Bay of Bengal sees more intense cyclones compared to the Arabian Sea, largely due to geographic and climatic factors. Indian Ocean cyclones often have severe impacts, causing storm surges and heavy rainfall, which lead to widespread flooding and devastation along coastal regions. Their tracking and prediction are crucial for disaster preparedness. The India Meteorological Department (IMD) has significantly improved its accuracy in predicting tropical cyclones, using advanced tools such as satellite data, Doppler radars, and numerical models. This enhanced forecasting has reduced the lead time for warnings, enabling timely evacuations and minimizing loss of life and property, especially during major cyclones in the Indian Ocean.

3.3.3 Impacts of cyclones on human life and property

Cyclones have severe effects on human life and property, especially in India's coastal regions, where densely populated areas face risks of flooding, destruction of homes, and infrastructure damage. Coastal states like Odisha and Andhra Pradesh experience agricultural losses, displacement, and fatalities. Fishing activities and ecosystems are also affected, leading to long-term economic and environmental damage. Figure 3.2 shows cyclone-prone districts in India, based on cyclone frequency, severity, and related hazards like maximum wind speeds, storm surges, and precipitation.

Winds: Cyclone winds cause widespread damage, particularly near the eye-wall where gusts are strongest. Rapid wind direction changes twist structures and vegetation. Over land, friction amplifies wind gusts, damaging buildings, especially roofs and communication networks. Tall buildings face resonant motions, while coastal roads are obstructed by debris and fallen structures.

Rainfall: Heavy rainfall, often exceeding 30 cm in 24 hours, leads to flooding and infrastructure damage. It disrupts relief efforts, erodes soil, and weakens embankments. Restoring water systems and repairing damaged infrastructure are significant challenges post-cyclone.

Storm Surge: Storm surges cause sudden coastal flooding as seawater is pushed inland by strong winds and pressure gradients. Areas like the Bay of Bengal experience intensified surges due to shallow waters and coastal shapes. The surge damages buildings, erodes foundations, and worsens when combined with high tide.

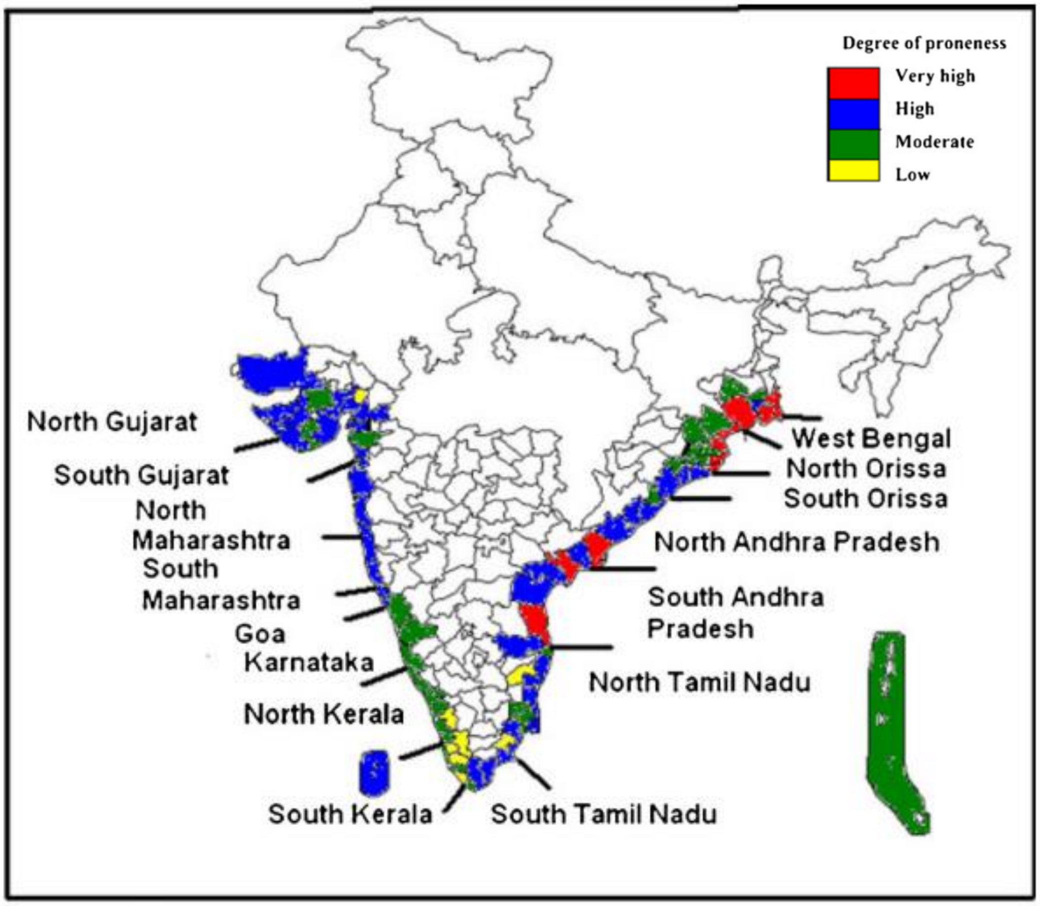


Figure 3.2: Cyclone hazard prone districts of India based on frequency of total cyclones, total severe cyclones, actual/estimated maximum wind, probable maximum storm surge associated with the cyclones and probable maximum precipitation for all districts (Mohapatra et al. 2012).

3.4 Thunderstorm and Lightning

A thunderstorm is a type of weather phenomenon characterized by the presence of lightning and thunder, typically accompanied by strong winds, heavy rain, and sometimes hail. These storms develop from towering cumulonimbus clouds, which form when warm, moist air rises rapidly into cooler layers of the atmosphere. Lightning is an electrical discharge caused by the imbalance between storm clouds and the ground, or within the clouds themselves. Thunder, the sound created by the sudden expansion of air heated by lightning, always follows. Thunderstorms are often intense and localized, capable of producing dangerous conditions such as flash floods, high winds, and lightning strikes, which pose significant risks to both life and property.

3.4.1. Thunderstorms: Structure and Life Cycle

Thunderstorms (TS) occur over different parts of the globe with large spatial & temporal as well as diurnal, seasonal and annual variability. Over Indian region thunderstorms occur throughout the year during different seasons. Its frequency varies from region to region. Thunderstorm activities

during monsoon, post-monsoon and winter seasons are mainly governed by the large scale synoptic weather systems with some alterations caused by local topographical effects. However, the highest frequency and the most severe thunderstorm events occur in general during the pre-monsoon season (March to May) throughout the length and breadth of the country. In India hundreds of people die due to phenomena associated with thunderstorms like lightning strikes, squalls and hails etc
The entire process in the life cycle of thunderstorm from the developing stage to dissipating stage can take place quickly, sometimes over a period of one hour or less.

The following conditions are present for most thunderstorms:
•Warm, humid air at the surface
•Unstable atmosphere (determined by lifting surface parcels)
•Trigger to move air upward to the unstable level, e.g., mountains, weather fronts, surface convergence and/or upper level divergence, or surface heating and free convection.

A single-cell thunderstorm typically goes through three stages in about an hour (Figure 3.3).

1. Cumulus Stage: Warm, humid surface air rises, cooling as it ascends, forming clouds. Latent heat enhances the buoyancy, creating updrafts.
2. Mature Stage: Precipitation begins, causing downdrafts as falling droplets evaporate and cool the air. This phase has both updrafts and downdrafts, making the storm most powerful.
3. Dissipating Stage: Downdrafts dominate, cutting off the storm’s energy, causing it to weaken. Gust fronts may trigger new storms or dust storms.

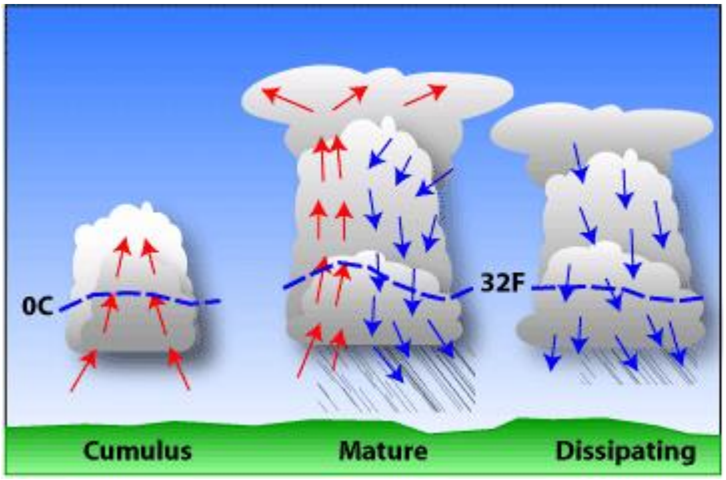


Figure 3.3 Simplified model depicting the life cycle of an ordinary thunderstorm that is nearly stationary. (Arrows show vertical air currents. Dashed line represents freezing level, 0°C isotherm.)

3.4.2. Thunderstorm Climatology in India

Intense and high frequency thunderstorm activities during the pre-monsoon season generally occur in East and Northeast India followed by southwest Peninsular India. The thunderstorm associated with dust storm mostly occurs over Northwest India. Thunderstorm climatology of India based on data from 1981-

2020 is shown in Figure 3.4, and tnumber of lightening days in annual over India based on the data of the period 1969-2019 is shown in Figure 3.5.

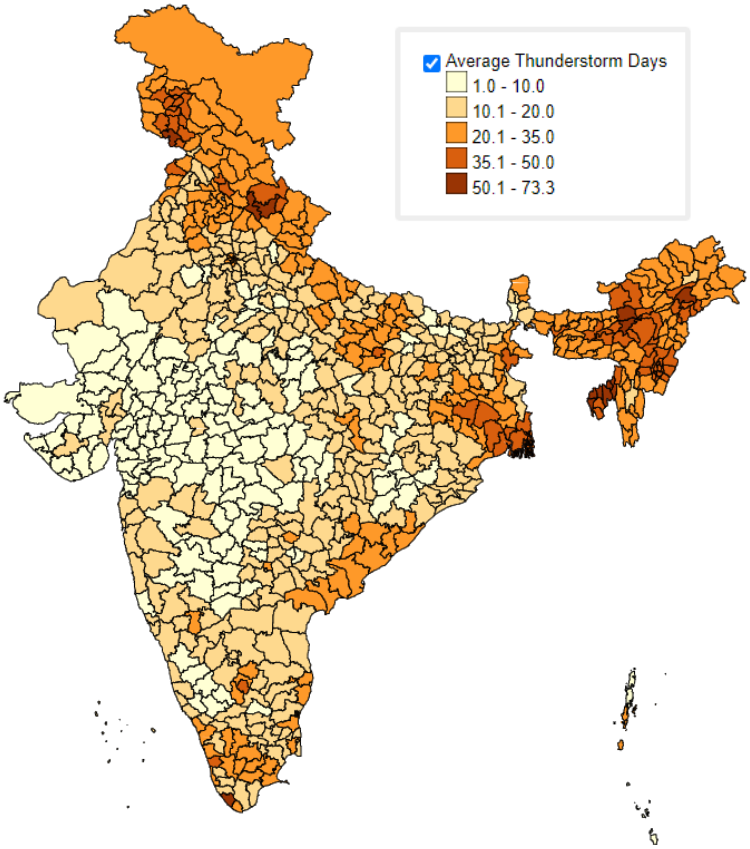


Figure 3.4: Annual thunderstorm climatology (average number of thunderstorm days) over India based on the data of the period 1981-2019 (Image Credit: IMD).

3.4.3 Thunderstorm associated Hazard

Thunderstorms are powerful atmospheric disturbances characterized by intense lightning, heavy rainfall, and strong winds. They can pose significant hazards, including deadly lightning strikes, which are a leading cause of storm-related fatalities, especially in open areas. Strong winds during thunderstorms can exceed 100 km/h, causing extensive damage to trees and buildings, while microbursts produce sudden gusts that threaten aviation safety during take-off and landing.. The associated squally winds damage the property like Kachcha houses, thatched huts and asbestos houses, telephone and electric poles and other structures amounting to crores of rupees every year. Apart from standing crops which get severely damaged, it also affects transport sector like Highways, railways and aviation resulting in human and revenue losses.

Heavy rainfall can lead to flash floods, particularly in urban areas, while soil erosion and landslides are concerns in hilly regions. Additionally, turbulence during thunderstorms can create hazardous conditions for aircraft, leading to passenger discomfort and structural stress. On the ground, sudden turbulent gusts can compromise the stability of structures such as cranes and scaffolding, increasing the risk of collapses. Proper awareness and preparedness are essential to mitigate these risks.

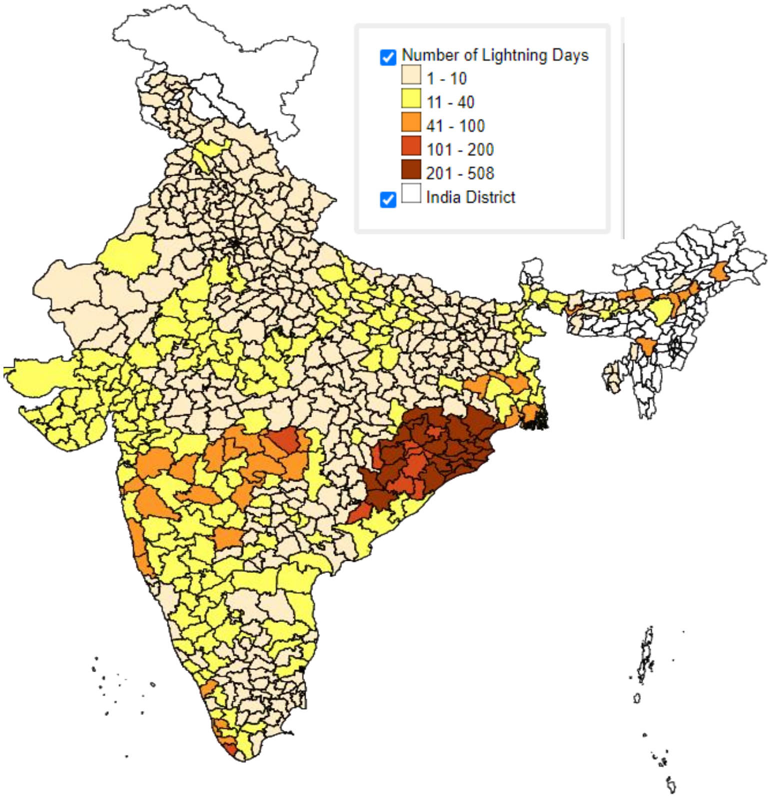


Figure 3.5: Total number of lightening days in annual over India based on the data of the period 1969-2019 (Image Credit: IMD).

Further details on Thunderstorms are given in Appendix-A

3.4.4 Safety measures for thunderstorms and lightning

- If outdoors, seek shelter from lightning.
    - The best shelter is a building.
    - If no buildings are available, seek protection in a cave, ditch, car, hard-top automobile, or a canyon.
    - Avoid trees as they attract lightning.
- If no shelter is available:
    - Avoid the tallest object in the area.
    - If only isolated trees are nearby, crouch in the open for better protection.
- If you hear thunder:
    - Avoid going outside unless absolutely necessary.
    - To estimate the distance from a lightning strike: count the seconds between a lightning flash and thunder, then divide by 3 (in kilometres).
- Stay away from anything that conducts electricity:
    - Avoid radios, toasters, hairdryers, and unplug electronic equipment before the thunderstorm arrives. This also includes fireplaces, radiators, stoves, metal pipes, sinks, and phones.
- Stay away from windows, doors, and verandas.
- Avoid contact with plumbing and metal pipes:

  - Do not wash your hands, take a shower, wash dishes, or do laundry during a thunderstorm.
- Stay away from: TVs, sinks, tubs, radiators, and stoves.
- Get out of water: This includes small boats on the water, pools, lakes, and other water bodies.
- If you feel an electric charge (hair standing up or tingling skin):
  - Drop to the ground immediately, as lightning may be about to strike.
- Protect livestock:
  - Livestock often gathers under trees during thunderstorms, making them vulnerable.
  - Move animals into a shelter, preferably one with a lightning protection system.

3.5 Heat Waves and Cold Waves

3.5.1 Heat Wave

Heatwaves have emerged in many parts of the world as one of the deadliest natural hazards which has caused more deaths than any other natural hazards like cyclones, floods, Thunderstorms, lightning. Heat waves are silent killers unlike Cyclones, In August 2003 Heat Wave in Europe killed more than 70,000 people. Because of ongoing global warming, significant increase in the frequency, intensity, duration and geographical spread of heatwaves has been observed.

A heat wave is a period of very hot weather that lasts for several days. A severe heat wave is even worse, with temperatures so high that they can be dangerous to people, animals, and plants. It can make people feel very uncomfortable and can even be dangerous if they don’t stay cool and drink enough water.

There is no universal definition of heatwave as it depends on climatic condition of the region, For example in Rajasthan 40 degree centigrade does not meet heatwave criteria whereas in hilly areas heatwave may occur at 35 degree centigrade

3.5.2 Climatology of heat waves

Heat waves typically occur during the pre-monsoon months of April to June, when temperatures soar, particularly in the northwestern, central, and eastern regions. These extreme heat events are driven by factors such as dry continental air masses, prolonged clear skies, and high solar radiation. The Thar Desert and Deccan Plateau often experience the most intense heat waves, with temperatures exceeding 45°C in some areas. Climate change has also contributed to an increase in the frequency and intensity of heat waves in recent years, posing significant health risks and impacting agriculture. Figure 3.6 showing total heat wave days based on the data during the period 1969 to 2019.

3.5.3 Cold Waves:

Cold Wave: A cold wave is a period of very cold weather that lasts for several days. It can make it very chilly outside and can be dangerous if people don’t stay warm and protect themselves from the cold. A severe cold wave is an extreme version of a cold wave, where the temperatures drop even lower and become much colder than usual.

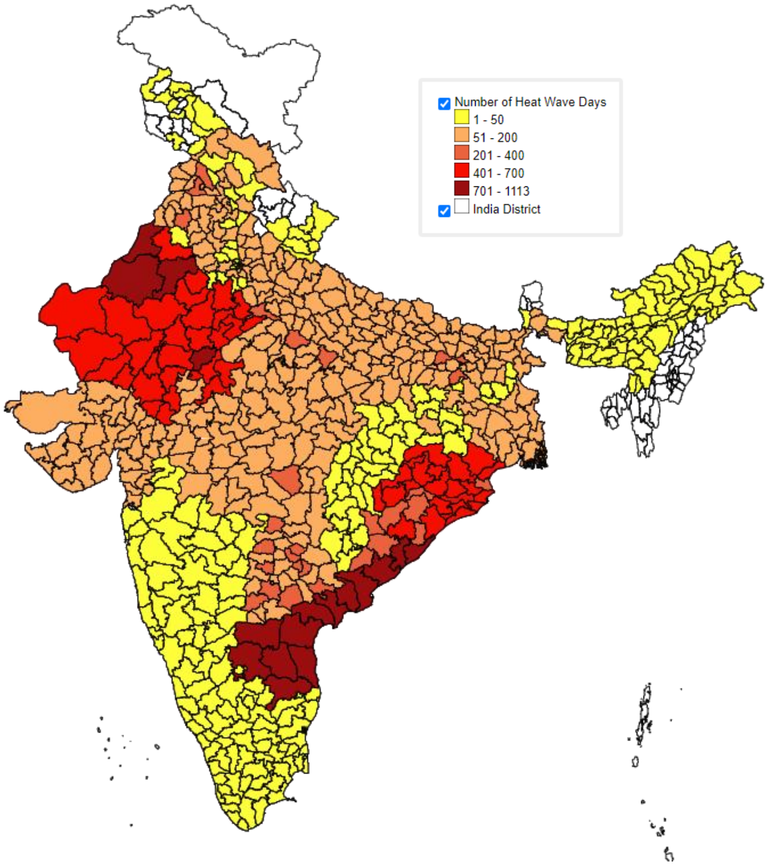


Figure 3.6 Total heat wave days (Total Number of Disasterous Heat Wave Days) using the data during the Period from 1969 to 2019 (Image Credit: IMD).

3.5.4 Climatology of cold waves

The climatology of cold waves over India is primarily influenced by the winter season, typically from December to February, when cold, dry winds from the Himalayas sweep across northern and central parts of the country. Cold waves are most intense in northern states like Punjab, Haryana, Delhi, Uttar Pradesh, and Bihar, where temperatures can drop significantly, sometimes below freezing in extreme cases. These cold spells are driven by large-scale high-pressure systems over northern latitudes and the penetration of polar air masses into the subcontinent. The occurrence of cold waves varies from year to year, but climate variability and changing weather patterns can sometimes intensify these events, leading to frost, crop damage, and health impacts, particularly among vulnerable populations. Figure 3.7 showing annual cold wave climatology based on the data during the period 1969 to 2019.

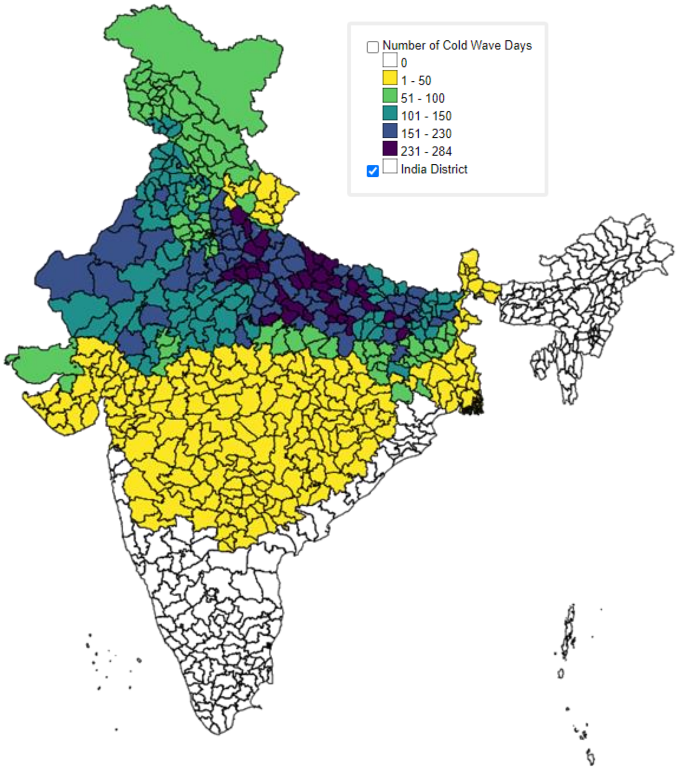


Figure 3.7 Total cold wave days (Total Number of Disasterous Heat Wave Days) using the data during the Period from 1969 to 2019 (Image Credit: IMD).

3.5.5 Impact of heat waves and cold wave on health and the environment

- *Health Impacts:*

Hypothermia and Frostbite: Prolonged exposure to cold can lead to severe health conditions such as hypothermia and frostbite.

Cardiovascular Diseases: Cold weather can trigger cardiovascular issues, including heart attacks and strokes.

Respiratory Issues: Lower temperatures increase the risk of respiratory problems, such as pneumonia and bronchitis.

Increased Risk of Infections: The cold can elevate the risk of influenza and other infections.

Mental Health Concerns: Cold waves can lead to mental health issues, including Seasonal Affective Disorder and depression.

- *Environmental Impacts:*

Disruption of Ecosystems: Cold waves can disrupt ecosystems and wildlife habitats, affecting biodiversity.

Increased Energy Consumption: Demand for heating rises, leading to increased energy consumption and greenhouse gas emissions.

Infrastructure Damage: Frozen water pipes and other infrastructure can sustain damage, leading to costly repairs.

Transportation Disruptions: Severe cold can cause transportation issues, including road closures and flight cancellations.

Crop Damage: Cold weather can result in agricultural losses due to frost damage.

Common Factors Exacerbating Heat and Cold Waves:

Climate Change: Global warming contributes to the frequency and intensity of heat and cold waves.

Urbanization: The urban heat island effect exacerbates temperature extremes in cities.

Aging Infrastructure: Old infrastructure may struggle to cope with extreme temperature variations.

Population Growth and Density: Higher population density can lead to increased vulnerability during temperature extremes.

Poor Air Quality: Degraded air quality can amplify health risks associated with heat and cold waves.

3.5.6 Mitigation and Adaptation Strategies for Extreme temperature Events

Mitigation and adaptation strategies are essential in addressing extreme temperature events such as heat waves and cold waves. Mitigation strategies include early warning systems, public education campaigns, infrastructure adaptations like green roofs, and climate-resilient agriculture to reduce vulnerabilities. Health sector preparedness, such as stockpiling medications, also enhances community resilience.

Adaptation strategies focus on heat-resistant materials for construction, creating green spaces, and ensuring climate-resilient water management. Specific early warning systems for cold waves and community-based initiatives can further enhance preparedness.

In North India, temperature fluctuations during Western Disturbances (WDs) and anticyclonic formations influence cold wave conditions. The sinking motion caused by jet streams also contributes to cold waves.

Safety measures involve staying hydrated, using proper heating and cooling devices, and avoiding outdoor exposure during extreme temperatures. Community measures include opening cooling and warming centers, protecting vulnerable populations, and public awareness campaigns.

Finally, technology plays a key role, with mobile apps, social media alerts, and advanced weather monitoring systems providing real-time updates to help manage extreme weather events.

3.6. Floods and Droughts:

3.6.1: Floods

Floods are a recurrent natural disaster in India, caused by heavy rainfall, river overflow, dam breaks, or storm surges. They can lead to significant economic losses, destruction of infrastructure, and loss of life, particularly in vulnerable communities. India’s diverse geography, with its numerous rivers and monsoon climate, makes it especially susceptible to flooding. In recent years, the increasing trend of urban floods has become a major concern, especially in cities like Mumbai, Delhi, and Chennai. Rapid urbanization, inadequate drainage systems, and the loss of natural water bodies have worsened the situation, making urban areas highly vulnerable to flash floods, which occur in a short time (usually less than six hours) after heavy rainfall or dam failure.

Flood, Be Prepared !

BEFORE FLOODS

- Ignore rumours, Stay calm, Don't panic
- Keep your mobile phones charged for emergency communication: use SMS
- Listen to radio, watch TV, read newspapers for weather updates
- Keep cattle/animals untied to ensure their safety
- Prepare an emergency kit with essential items for safety and survival
- Keep a First Aid kit with extra medication for snake bite and diarrhoea ready
- Keep your documents and valuables in water-proof bags

AFTER FLOODS

- Do not allow children to play in or near flood waters
- Don't use any damaged electrical goods, get them checked
- Watch out for broken electric poles and wires, sharp objects and debris
- Do not eat food that has been in flood waters
- Use mosquito nets to prevent malaria
- Don't use the toilets or tap water if the water lines/sewage pipes are damaged.

DURING FLOODS

- Don't enter flood waters. In case you need to wear suitable footwear
- Stay away from sewerage lines, gutters, drains, culverts, etc.
- Stay away from electric poles and fallen power lines to avoid electrocution
- Eat freshly cooked or dry food. Keep your food covered
- Drink boiled/chlorinated water
- Use disinfectants to keep your surroundings clean

IF YOU NEED TO EVALUATE :

- Raise furniture, appliances on beds and tables
- Put sandbags in the toilet bowl and cover all drain holes to prevent sewage back flow
- Turn off power and gas connection
- Move to a higher ground/safe shelter
- Take the emergency kit, first aid box and valuables with you
- Do not enter deep, unknown waters: use a stick to check water depth
- Come back home only when officials ask you to do so

Figure 3.8: A Comprehensive Guide for Do's and Don'ts During Flood

Causes of Floods:

Floods can be triggered by various factors, both natural and human-induced. The primary causes include:

(i) Heavy Rainfall: (ii) River Overflow:

(iii) Storm Surges and Coastal Flooding: (iv) Dam Failure:

(v) Urbanization:

Effects of Floods:

(i) Loss of Life and Property: (ii) Damage to Agriculture:

(iii) Waterborne Diseases: (iv) Displacement of Populations:

(v) Environmental Impact:

A Comprehensive Guide of Do's and Don'ts During a Flood, which can be found in Figure 3.8. This guide offers essential safety instructions not only for actions to take during a flood but also for preparations before and necessary steps to follow after the flood. It covers crucial details on how to safeguard lives and property, minimize damage, and ensure proper recovery once the floodwaters recede.

3.6.2 Climatology of Floods in India

Flooding in India is influenced by the monsoon climate, particularly during the southwest monsoon season from June to September. Intense and prolonged rainfall leads to river overflow, primarily in the Ganges, Brahmaputra, and Godavari basins. Additionally, cyclonic storms can exacerbate flooding in coastal regions. Factors such as deforestation, urbanization, and inadequate drainage systems further increase flood risks. The interplay of topography, rainfall patterns, and human activities shapes the climatology of floods, making comprehensive flood management strategies essential for disaster risk reduction. The Number of flood events over India during the period 1969 to 2019 is provided in the Figure 3.9 (left).

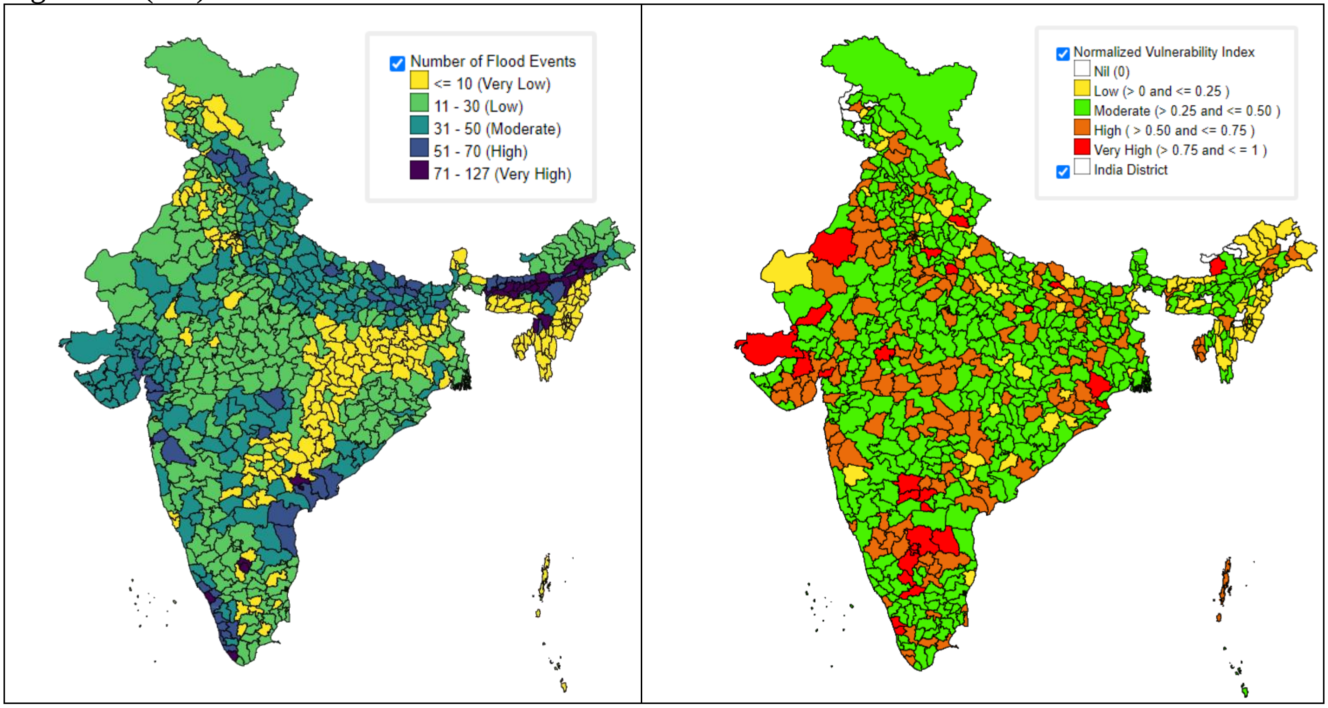


Figure 3.9 (Left): Total Number of Flood Events during the Period from 1969 to 2019. (Right) All Categories (Moderate, Severe and Extreme) Drought Normalized Vulnerability Index over India based on Standardized Precipitation Index (Image Credit: IMD).

3.6.3 Drought:

Drought is the consequence of a natural reduction in the amount of precipitation over an extended period of time, usually a season or more in length, often associated with other climatic factors (viz. high temperatures, high winds and low relative humidity) that can aggravate the severity of the drought event. There are four types of droughts:

(i) Meteorological Drought (ii) Hydrological Drought (iii) Agricultural Drought, and (iv) Socio-Economic Drought

Meteorological Drought: According to India Meteorological Department, meteorological drought over an area is defined as a situation when the seasonal rainfall received over the area is less than 75% of its long-term average value. It is further classified as "moderate drought" if the rainfall deficit is between 26-50% and "severe drought" when the deficit exceeds 50% of the normal.

Hydrological Drought: Hydrological Drought can be defined as a period during which the stream flows are inadequate to supply established use of water under a given water management system.

Agricultural Drought: It occurs when available soil moisture is inadequate for healthy crop growth and cause extreme stress and wilting.

Socio-economic drought: Abnormal water shortage affects all aspects of established economy of a region. This in turn adversely affects the social fabric of the society creating unemployment, migration, discontent and various other problems in the society. Thus, meteorological, hydrological and agricultural drought often leads to what is termed as Socio-economic drought.

Causes of Droughts:

Droughts occur due to a prolonged lack of rainfall, but several factors can contribute to their development:

(i) Lack of Precipitation:
(ii) Climate Change:
(iii) Overuse of Water Resources:
(iv) Deforestation and Land Degradation:
(v) Poor Water Management:

Effects of Droughts:

(i) Water Shortages:
(ii) Agricultural Losses:
(iii) Increased Wildfire Risk:
(iv) Economic Losses:
(v) Environmental Degradation
(vi) Health Impacts:

3.6.4 Climatology of Drought in India

Drought in India is primarily influenced by the variability of monsoon rainfall, with significant impact on agricultural productivity. Regions like Rajasthan, Gujarat, and parts of Maharashtra frequently experience prolonged dry spells. Factors such as climate change, deforestation, and inefficient water management exacerbate drought conditions. The Indian Meteorological Department employs indices like the Standardized Precipitation Index (SPI) to monitor and predict drought severity. Effective drought management strategies are crucial for mitigating its impacts on food security and rural livelihoods. Based on the SPI, the Drought Normalized Vulnerability Index for all Categories (Moderate, Severe and Extreme) are presented in the Figure 3.9 (right).

3.7 Fog

Fog is a major weather hazard over north India during the winter season. It impacts various sectors resulting in disruption and economic losses. Fog can be defined as a suspension of water droplets in the atmosphere with the base at the earth's surface. As per WMO, fog reduces the horizontal visibility to less than 1000 m at the surface of Earth.

3.7.1 Classification of Fog Type

Fog can be categorized into four distinct types—shallow, moderate, dense, and very dense—based on the range of general visibility. The visibility range for each fog type is summarized in the table below.

Fog Type	General Visibility Range (in meters)
Shallow	Visibility fall up to 500 m
Moderate	Up to 200 m
Dense	Up to 50 m
Very dense	< 50 m

3.7.2 Fog Formation

On the basis of formation process there are different categories of fog, including radiation fog and advection fog. Radiation fog is formed when the heat is radiated from ground surface, in turn cooling the surface and the air just above to its saturation temperature. If a sufficiently thick layer of moist air exists close to the ground, the humidity will reach 100%, leading to the formation of fog. This type of fog forms under calm wind and clear sky condition usually at night. This type of fog can result in near zero visibility. Advection fog, also an outcome of condensation, forms by the horizontal movement (advection) of warm and moist air mass moves over cold surface. Fog conditions observed over snow or sea surface can be an example of advection fog.

3.7.3 Climatological Characteristics and Trends of Fog in India

In India, dense fog spells occur primarily during December and January across the Indo-Gangetic Plains (IGP), with occasional fog in November and February. These fog episodes are linked to large-scale wind and temperature patterns. The December-January fog is widespread, lasts longer, and combines radiation and advection types, while November-February fog is localized, shorter (1-2 mornings), and primarily radiation fog, forming after western disturbances and rain, under calm winds and clear skies.

The IGP is highly prone to fog, with rapid formation, extensive coverage, and prolonged duration compared to other regions globally. Dense fog (<200 m visibility) typically lasts 6-7 hours in December-January, affecting densely populated areas. Fog also occurs in northern, central, eastern, and northeastern India. Figure 3.10 shows an image of Delhi on a foggy day, while Figure 3.11 illustrates a fog blanket extensively covering a large part of the Indo-Gangetic plains, as detected by the INSAT-3D satellite at 08:30 hours on January 5, 2018.

3.7.4 Impact of Fog

Depending on the thickness, fog impacts various sectors, leading to disruptions and economic losses. In transportation, it reduces visibility, causing flight delays, cancellations, and increased road accidents. Rail and road traffic are also affected by reduced speed and safety concerns. In agriculture, fog slows down photosynthesis, reduces crop yields, and creates excess moisture, which can promote fungal diseases. Health is another affected sector, as fog traps pollutants, worsening air quality and leading to respiratory issues such as asthma and bronchitis. Solar power generation is diminished due to reduced sunlight, while the demand for heating rises, increasing energy consumption. Additionally, tourism suffers as fog hampers visibility at landmarks, discouraging travel and affecting the hospitality industry.

Data indicates that around 159 lives were lost in extreme fog season (Dec – Jan) of 2017 – 18. Fog also affects different stage of crop growth such as flowering and seed formation stage.

Figure 3.10 An image depicting parts of Delhi on a foggy day.

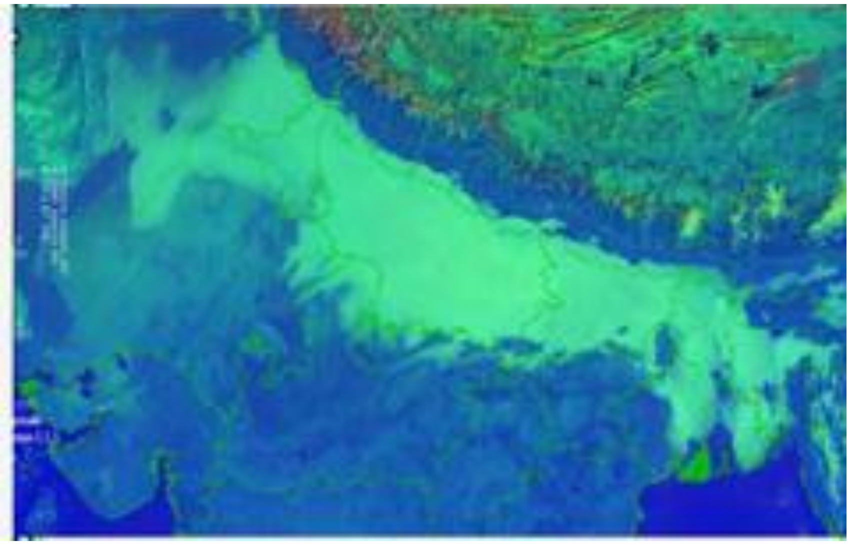


Figure 3.11 Fog blanket extensively covering a large part of the Indo-Gangetic plains, as detected by the INSAT-3D satellite at 08:30 hours on January 5, 2018

Chapter 4

Hazard Prediction, Warning Systems, and Disaster Management

4.1 Prediction of Natural Hazard

4.1.1 Early warning system of different Hazards

A natural hazard refers to a natural event, such as earthquakes, floods, landslides, cyclones or other weather extremes, that has the potential to cause significant harm to people, property, or the environment. Predicting such hazards is crucial to mitigating their adverse effects. Hazard assessment plays a critical role in this process by determining the likelihood and potential impact of a hazardous event. Through careful analysis of historical data, environmental factors, and technological tools, scientists and disaster management authorities can assess the probability and intensity of these hazards. This assessment informs preparedness plans, allowing communities to take preventive measures to reduce the risk and damage from impending natural hazards.

4.1.2 Early Warning Systems and its components

Early warning systems are designed to detect and predict hazardous events, providing timely information that enables individuals, communities, and authorities to take preventive action. Key components include:

Risk Knowledge: Understanding the types of hazards, their frequency, potential impacts, and vulnerable areas is crucial. This information comes from historical data, hazard mapping, and scientific research.

Monitoring and Forecasting: Advanced technologies like satellites, radar systems, seismographs, and numerical weather prediction models help detect and monitor hazards in real time. Continuous monitoring allows for forecasting the likelihood and intensity of events.

Communication Systems: Effective communication is essential to ensure that early warnings reach all stakeholders. This involves reliable dissemination channels such as TV, radio, mobile networks, sirens, and social media.

Response Capability: Communities and authorities need to have pre-established plans and resources to respond to warnings. This includes evacuation plans, disaster shelters, and emergency response teams to minimize damage and protect lives.

4.1.3 Role of Early Warnings in Disaster Risk Reduction

Early warning systems are critical in reducing the impacts of natural hazards by enabling proactive disaster risk management. They serve several essential functions:

Minimizing Loss of Life: Timely warnings give people enough time to evacuate or take shelter, significantly reducing fatalities during disasters like cyclones, tsunamis, and floods.

Reducing Economic Losses: Early warnings allow industries, businesses, and governments to secure infrastructure, relocate resources, and halt operations in high-risk areas, helping to mitigate the economic impact.

Enhancing Preparedness: By providing clear information on upcoming hazards, early warnings promote community preparedness and ensure that response teams are activated ahead of time.

Protecting Livelihoods: Early warnings help farmers protect their crops and livestock, communities to secure food and water supplies, and health systems to prepare for potential outbreaks of disease following disasters.

Supporting Resilience Building: Over time, the presence of reliable early warning systems encourages a culture of preparedness, enabling communities to build resilience against recurring natural hazards.

4.1.4 IMD’s seamless forecasting system from seasonal to nowcast

The India Meteorological Department (IMD) has developed a comprehensive and seamless forecasting system that spans from seasonal predictions to nowcasts, ensuring timely and accurate weather information for various sectors.

Long Range Weather Prediction (LRF) focus on forecasting seasonal weather patterns, such as the monsoon, months in advance. These models integrate data from oceanic, atmospheric, and land surface processes to predict large-scale climate phenomena, including overall rainfall, temperature, and seasonal anomalies. This long-range forecasting is crucial for effective planning in agriculture, water resource management, and disaster preparedness, allowing stakeholders to mitigate potential impacts from climate extremes.

IMD employs Extended Range Weather Prediction Models (ERF), which provide forecasts for periods ranging from 10 to 30 days. Using advanced numerical techniques, these models simulate atmospheric conditions to predict trends such as heatwaves, cold spells, and rainfall patterns. This information is particularly beneficial for the agricultural sector, aiding farmers in making informed decisions regarding crop management and irrigation.

For medium-range forecasting, IMD utilizes Numerical Weather Prediction (NWP) models to cover periods of up to 10 days. Similarly, for short-range forecasts—which provide insights for up to 3 days—IMD also relies on NWP models. These forecasts are enhanced by integrating multiple data sources, including surface observations, satellite data, upper air observations, and radar inputs, such as Doppler radar systems. These tools significantly improve forecast accuracy, allowing for more localized predictions.

In terms of nowcasting, which provides detailed forecasts for the immediate future (next 3 hours), IMD employs various tools, including high-resolution numerical models, satellite imagery, and radar data, which help in tracking and predicting short-lived weather phenomena like thunderstorms, heavy rainfall, and fog. The integration of these technologies allows IMD to issue timely alerts and warnings, helping communities effectively prepare for and respond to adverse weather events. Through this seamless forecasting framework, IMD enhances its capability to deliver timely alerts and warnings, significantly improving community safety and preparedness.

4.1.4.1 Impact-Based Forecasting Systems

IMD's Impact-Based Forecasting (IBF) system focuses on predicting not just the weather but its potential effects on people, infrastructure, and ecosystems. This approach integrates weather data with vulnerability and risk assessments, providing more actionable information for disaster management and public safety. By predicting the likely impacts of events such as floods, cyclones, or heatwaves, IBF helps authorities and communities prepare and mitigate the consequences more effectively. The system delivers location-specific forecasts, highlighting the potential dangers to critical infrastructure, agriculture, and human health. IMD's IBF is a crucial tool for reducing the socio-economic impacts of extreme weather events and improving decision-making in disaster-prone areas. IMD issues warnings using a color-coded system to indicate the severity of the impending weather event. Green indicates no warning, Yellow indicates watch (be updated), Orange signifies alert (be prepared), and Red indicates a severe warning (take action).

4.1.4.2 Colour code for Weather warnings:

The following colour codes are used in weather warnings for bringing out the severity of the weather phenomena expected. This mainly serves as a signal for the disaster management authority about the impact of the weather expected so as to keep them ready for necessary action related to disaster risk reduction.

🟥 WARNING (TAKE ACTION)
🟧 ALERT (BE PREPARED)
🟨 WATCH (BE UPDATED)
🟩 NO WARNING (NO ACTION)

In order to decide upon the colour to be assigned to a given weather warning situation under the 7-day forecast scheme, the matrix given in Figure 4.1 is followed, giving thrust on the probability of occurrence of the event as well as its impact assessment.

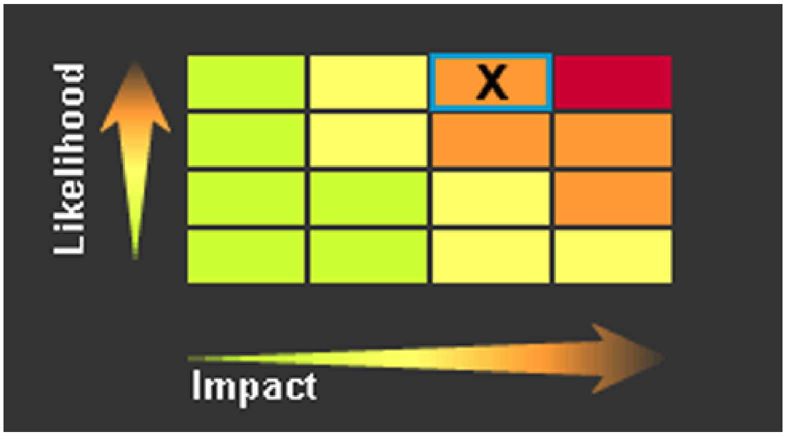


Figure 4.1: The matrix Decision of Colour Code for Warning

The probability of occurrence of severe weather for Day1 to Day7 may be decided based upon the inference derived from the synoptic analysis of Observations, analysis of model forecasts (including probabilistic outputs) and diagnostic products available with respect to different weather phenomena.

For impact assessment, the conceptual model of the weather associated with the disaster events from past and the impact caused by them along with the topography, land-use pattern, socio-economic factors and livelihood of the region needs to be taken into consideration.

The colour code for impact-based warning for a district or subdivision depends upon many factors including (i) meteorological factors (ii) hydrological factors (iii) geophysical factors etc. which may interact with each other to determine the impact and risk. Hence the forecaster will decide the impact considering all these factors and colour code for the warning will be decided accordingly.

4.1.5 Early warning systems for cyclones:

As tropical cyclone cannot be tamed to reduce their adverse effects, one has to learn to live with them. Effective Cyclone Disaster Prevention and Mitigation Plan require:

- Hazard analysis
- Vulnerability analysis.
- Early Warning and Mitigation
- Community preparedness and planning at all levels to meet the exigencies.

It is important to observe and understand the development of tropical disturbances for forecasting and warning the various user agencies and general public. India Meteorological Department (IMD) monitors and predicts CDs over Northern Indian Ocean (NIO) and provides early warning services for management of the cyclone. Various components of early warning system for a cyclone include (i) monitoring and prediction, (ii) warning organization, (iii) warning generation, presentation & dissemination, (iv) coordination with disaster management agencies, (vii) public education & reaching out and (viii) post-event review.

Cyclone forecasting predicts the formation, movement, and impact of tropical cyclones using advanced meteorological models, satellite imagery, radar data, and weather observations. These tools help identify where and when cyclones may form, track their path and intensity, and project landfall locations. This information allows authorities to issue early warnings to mitigate impacts on vulnerable areas. An operational forecast by the IMD for the track of Cyclone ‘DANA,’ issued at 0600 UTC on 23rd October 2024, is shown in Figure 4.2.

Continuous monitoring tracks storm characteristics like wind speed, pressure changes, and storm surge potential. Real-time data from satellites, radars, and ocean buoys enable updated forecasts and timely alerts. Early warning systems help governments and communities prepare through evacuations and infrastructure protection, minimizing loss of life and property damage.

4.1.6 Thunderstorm Monitoring and Forecasting

4.1.6.1 Thunderstorm monitoring

Thunderstorm monitoring in India is primarily conducted by the India Meteorological Department (IMD) using advanced technologies. Key tools include:

(i) Doppler Weather Radars (WDR): IMD operates a network of radars that track the formation, movement, and intensity of thunderstorms in real-time, providing critical data on precipitation and wind patterns.

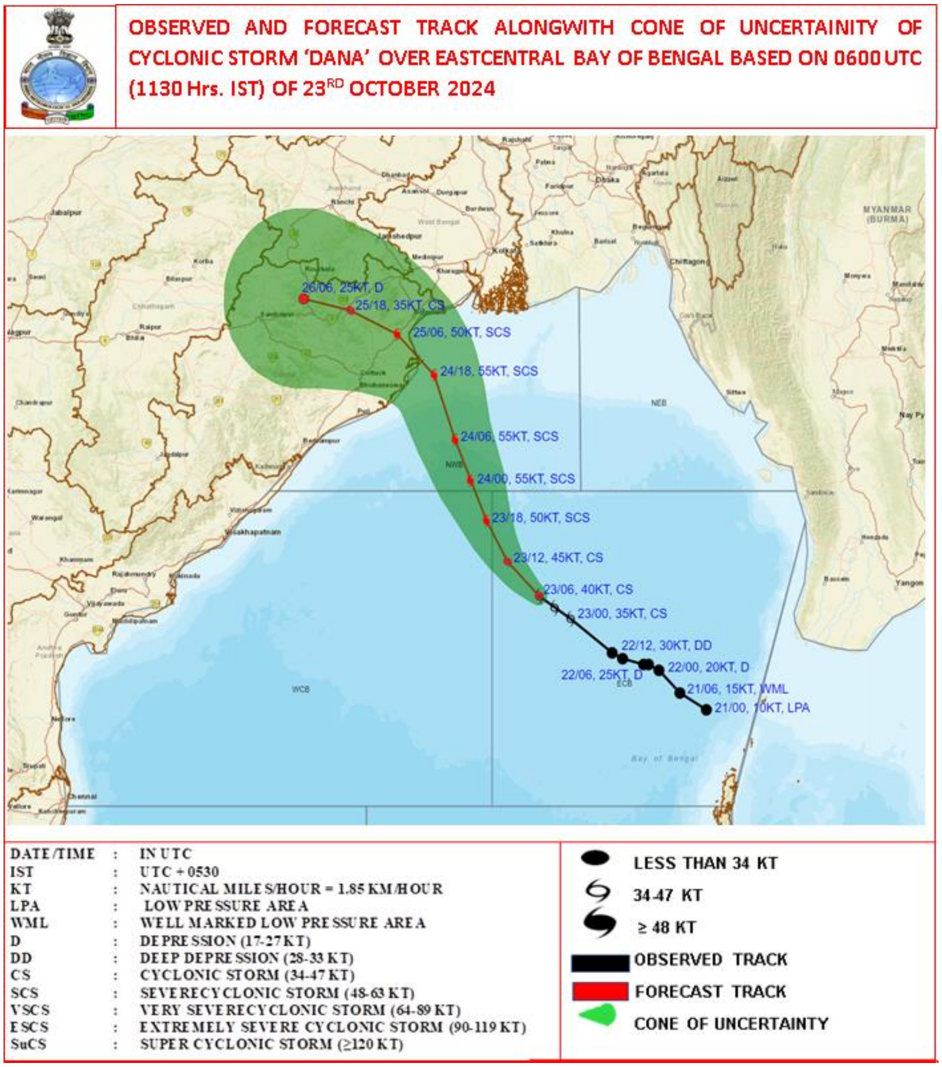


Figure 4.2: Operational forecast by the IMD for the track of Cyclone 'DANA,' issued at 0600 UTC on 23rd October 2024

(ii) Satellite Systems: Indian satellites like INSAT-3D and INSAT-3DR offer high-resolution imagery and atmospheric data. Foreign satellites equipped with lightning detectors also aid in real-time monitoring of lightning activity.

(iii) Lightning Detection Systems (ILDN): This network detects and locates lightning strikes across India, while the Damini app provides real-time alerts to reduce casualties.

(iv) Synoptic Information: Analysis of surface observations and upper air soundings enhances the understanding of local atmospheric conditions and storm dynamics, helping to identify potential thunderstorm development.

4.1.6.2 Thunderstorm Forecasting:

IMD provides crucial thunderstorm and lightning warning services aimed at enhancing public safety during severe weather events. IMD issues seven-day thunderstorm forecasts and warnings tailored for meteorological subdivisions and districts, facilitating local preparedness and response. In addition to these forecasts, IMD offers nowcasts for specific districts and weather stations, delivering real-time updates that allow communities to act quickly against imminent threats. A key feature of IMD's warning system is its color-coded impact-based forecasting, which categorizes risk levels: green for no significant impact, yellow for caution, orange for moderate impact, and red for severe impact (Figure 4.1). IMD also emphasizes public awareness through guidelines that advise people such as to stay indoors, unplug electrical devices, and avoid contact with plumbing or water during thunderstorms. Like other global meteorological agencies, IMD employs a combination of Numerical Weather Prediction (NWP) models, real-time observations (DWR, satellites, etc), and specialized forecasting systems to predict thunderstorms.

4.1.7 Heat Wave and Cold wave Prediction

Heat waves and cold waves pose serious health and environmental risks, making accurate prediction crucial for preparedness.

(i) Weather Forecasting: Meteorologists analyze temperature trends 7-10 days in advance to identify potential extreme heat or cold events. Atmospheric patterns and historical data help predict when and where these events may occur, aiding public health and emergency responses.

(ii) Heat Index (HI): HI combines temperature and humidity to assess how hot conditions feel, informing the public and authorities about heat severity. This data guides health warnings to protect vulnerable groups, such as the elderly.

(iii) Wind Chill Index (WCI): WCI combines temperature and wind speed to measure perceived cold, helping assess risks from extreme cold. It guides public warnings to safeguard at-risk populations.

(iv) Early Warning Systems (EWS): Heat/Cold Wave EWS alert authorities and communities of impending events, enabling proactive measures like public awareness campaigns and resource allocation to reduce health impacts.

4.1.8 Early Warning Systems for Floods and Droughts

Flood Early Warning Systems are designed to predict potential flooding and provide advance notice to those at risk. These systems use a combination of hydrological data (such as river levels and rainfall patterns), weather forecasting models, and satellite imagery to detect potential flood conditions. They are vital for preventing loss of life and reducing the economic and environmental impact of floods.

4.1.8.1 Components of Flood Early Warning Systems and drought early warning system:

Flood Early Warning Systems predict potential flooding by utilizing hydrological data, weather forecasting models, and satellite imagery. Key components include data collection through rain gauges and river monitoring, numerical weather prediction models, real-time monitoring of water levels, and dissemination of alerts via multiple channels. In India, the India Meteorological Department (IMD) collaborates with the Central Water Commission to issue flood forecasts and manage the Flash Flood Guidance System for timely alerts.

Drought Early Warning Systems monitor water scarcity by relying on meteorological data, soil moisture levels, and agricultural conditions. Components involve meteorological monitoring, soil moisture assessments using satellites, water resource tracking, and agricultural impact evaluations. IMD provides Agro-Meteorological Advisory Services and utilizes the Standardized Precipitation Index to predict drought conditions, offering region-specific advisories to aid farmers and manage water resources effectively.

4.1.9 Fog Monitoring and Forecasting

For improving aviation operations, transportation safety and public health fog conditions needs continuous monitoring. Several tools and techniques are used to observe, detect, and predict fog formation and dissipation. The following two are the key methods for collection of fog information.

4.1.9.1 Fog Monitoring

a. Location Based Fog Information: This type of information is collected with the help of visibility sensors and weather stations. The depth of the fog layer is estimated by radiometers. Station based synoptic observations is available at every 3-hour gap from around 250 stations across India. At airports, specialized instruments such as **Drishti systems** are used to estimate visibility during foggy conditions. These systems provide real-time data on runway visual range (RVR), which is essential for pilots and air traffic controllers to make informed decisions regarding take-offs and landings. Drishti instruments use laser technology to measure the density and extent of fog, offering accurate assessments of visibility

b. Aerial Based Fog Information**:** The aerial fog information is often collected with the help of satellites (both geostationary and polar-orbiting). Satellites can observe fog formation over oceans, remote areas, and places without ground-based sensors. Specialized fog detection algorithms are applied to satellite data to enhance the identification of fog layers. Indian satellite INSAT 3D provides information which is further used to produce RGB day – night fog map at 15 – 30 minute gap.

Fact: Northern India, particularly the Indo-Gangetic Plains, experiences some of the most persistent and dense fog events during the winter months.

4.1.9.2 Fog Forecasting:

Advanced forecasting techniques, including numerical weather prediction models, satellite data, and ground-based observations, are employed to predict fog formation, intensity, and duration. In India, the Indian Meteorological Department (IMD) plays a key role in providing timely fog forecasts. The 330-meter Delhi fog forecasting model developed by the National Centre for Medium Range Weather Forecasting (NCMRWF) helps predict fog and visibility issues specifically over Delhi. The model also factors in aerosol concentrations and the urban heat island effect, which impact visibility, ensuring more reliable forecasts for safer air and road transport. In addition, the Winter Fog Experiment (WiFEX) led by IITM is aimed at improving fog forecasting, especially for the densely fog-prone northern parts of India. WiFEX focuses on understanding the physical, chemical, and microphysical processes of fog formation, persistence, and dissipation. By utilizing advanced ground-based instrumentation and studying factors like aerosols, surface conditions, and radiation balance, the goal is to develop more reliable and dynamic fog forecasting models to minimize its impacts.

4.1.10 IMD’s multi-Hazard warning system

IMD operates a comprehensive multi-hazard warning system aimed at enhancing disaster preparedness and response capabilities across the nation. This system encompasses a range of hazards, including cyclones, heavy rainfall, thunderstorms, heat wave, cold wave, fog, and other severe weather conditions. IMD's approach involves the integration of advanced forecasting techniques and state-of-the-art technology to deliver timely and accurate warnings.

One of the key features of this multi-hazard warning system is the color-coded impact-based forecasting service (for 7 days), which classifies different warnings and its potential impacts on various sectors. An image of IMD’s multi-hazard warning map is given in Figure 4.3. The color codes and icons help in quickly communicating the severity of impending weather events, guiding communities and stakeholders in their preparedness efforts. In addition to the color-coded map, the IMD provides information on the impacts of extreme weather events and the actions taken in response to this condition. Additionally, IMD issues seven-day forecasts and real-time warnings for specific districts, ensuring that localized information is available for effective decision-making.

By leveraging data from satellites, radar, and numerical weather prediction models, the IMD provides detailed and actionable alerts, aiming to minimize the risks associated with extreme weather events and to protect lives and property. This proactive stance is crucial for effective disaster management in a country prone to diverse meteorological challenges

4.1.11 Community Involvement in Flood and Drought Preparedness and Action

Community involvement is crucial for reducing the risks and impacts of both floods and droughts. Whether faced with the rapid onset of floods or the slow onset of droughts, local communities must be engaged, informed, and prepared. Active participation enables individuals to take timely actions to safeguard lives, property, and livelihoods.

(i) Awareness and Education: Local governments, the National Disaster Management Authority (NDMA), NGOs, Medias, and IMD work together to educate communities about flood and drought risks. Awareness campaigns cover evacuation plans, water conservation, and emergency protocols.

(ii) Early Warning Systems and Local Monitoring: Communities engage in setting up and monitoring early warning systems. For floods, this includes tracking water levels, while for droughts, monitoring rainfall and water availability is key. IMD’s forecasts are shared through mobile apps, radio, and community networks.

(iii) Disaster Management Committees: Local and National disaster management authorities coordinate response actions and ensure warnings reach all residents. These committees collaborate with state and district authorities and are essential in guiding community efforts.

(iv) Water and Resource Management: During droughts, communities adopt water-saving practices like rainwater harvesting and drip irrigation.

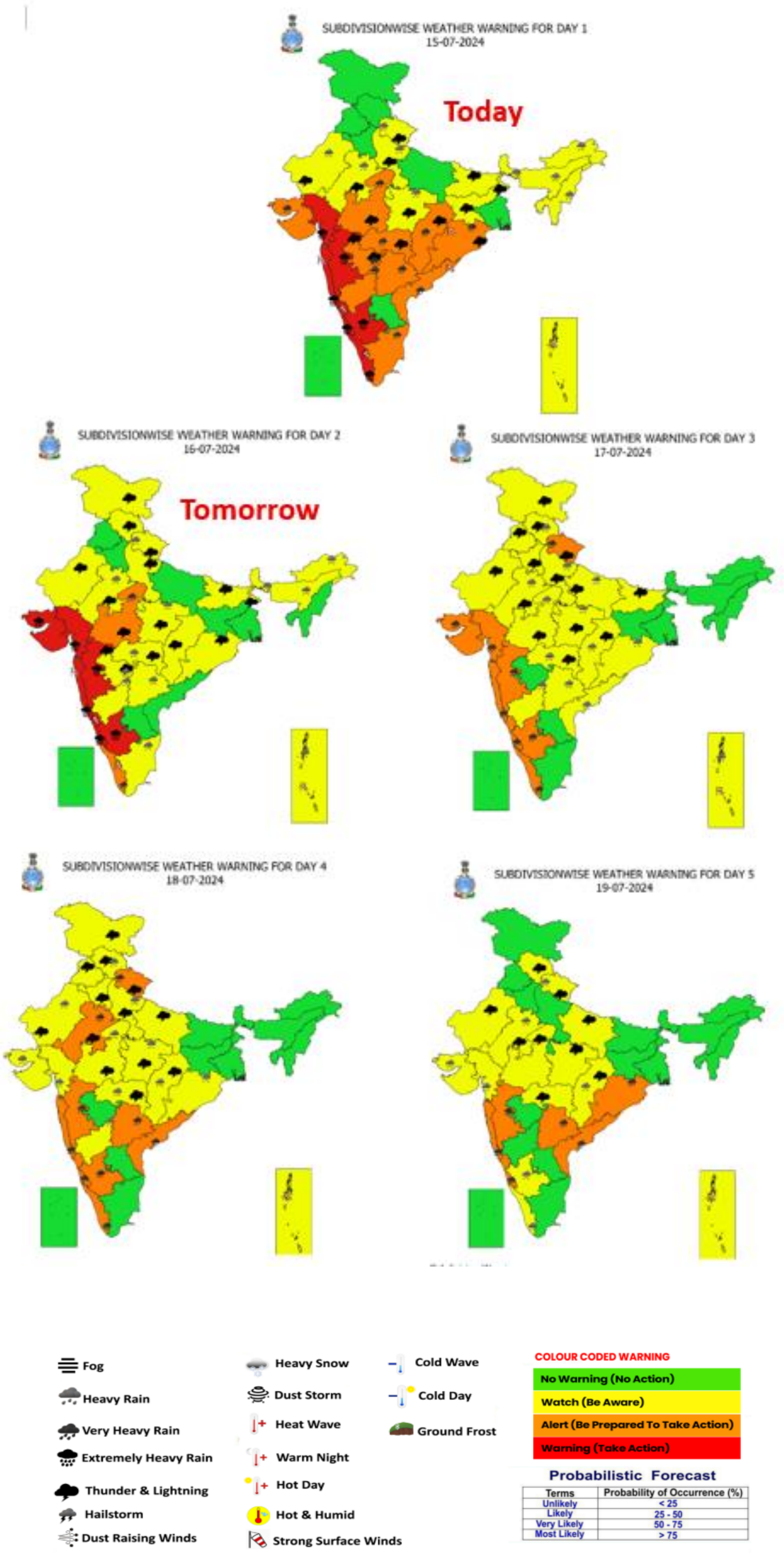


Figure 4.3: IMD’s multi-hazard warning map.

4.1.11.1 IMD and NDMA’s Role:

IMD provides early warnings and weather updates, supporting communities with real-time information for both floods and droughts. NDMA, along with state and local governments, ensures that communities are equipped to respond with disaster preparedness plans, including evacuation procedures and resource management.

Involving communities in disaster preparedness, alongside IMD and NDMA, strengthens India’s resilience against floods and droughts. This collaborative approach helps minimize the impact of natural hazards and protects vulnerable populations.

4.1.12 The role of computers in weather prediction and forecasting

Computers, particularly high-performance computers (HPCs), play a crucial role in predicting extreme weather events and natural hazards by processing vast amounts of data and running sophisticated models. Advanced algorithms, artificial intelligence, and machine learning techniques enable computers to analyze weather patterns, seismic activity, and atmospheric conditions to forecast events like earthquakes, tsunamis, heavy rainfall, floods, and cyclones. HPCs allow for rapid, precise simulations, improving early warning systems and helping communities prepare for disasters. In India, HPCs like Pratyush and Mihir, used by Ministry of Earth Science (MoES) and its officers, have greatly enhanced the accuracy of cyclone and monsoon predictions, saving lives and reducing economic losses.

4.2 Disaster Preparedness and management

Disaster preparedness and management involve actions taken before a hazard occurs to minimize risks to life and property. A disaster is defined as a serious disruption of a community's or society's functioning due to hazardous events, resulting in human, material, economic, and environmental losses. The impacts of a disaster can be immediate but often extend over time, challenging a community's ability to cope and requiring external assistance. Key concepts in this field include risk, vulnerability, and capacity. Risk refers to the likelihood of loss when a hazard strikes, influenced by the nature of hazards and the vulnerabilities of the affected resources. Vulnerability indicates how susceptible a community is to hazards, based on physical, social, and economic conditions. It encompasses exposure, resistance, and resilience—where exposure refers to at-risk populations and property, resistance involves measures to prevent loss, and resilience is the ability to recover post-disaster. Capacity is defined as the resources and strengths available within communities to prepare for and recover from disasters. Adaptation involves long-term actions to lessen sensitivity to hazards, while emergencies require immediate attention. Resilience highlights a system's ability to absorb losses and adapt for future protection. Recent trends show that while the number of people affected by disasters is rising, they are becoming less deadly but more costly, with poorer countries bearing a disproportionate burden. Disaster management emphasizes proactive planning and organizing to reduce the negative impacts of disasters, acknowledging that while they cannot always be prevented, their effects can be minimized.

4.2.1 India's Comprehensive Approach to Disaster Preparedness and Management

India's disaster preparedness model is a comprehensive approach that integrates early warning systems, effective communication, and a robust disaster management framework to mitigate the impact of natural hazards. Frequent exposure to natural hazards has led to valuable lessons learned, prompting a focus on community involvement in disaster preparedness. The Indian Meteorological Department (IMD) and the National Disaster Management Authority (NDMA) play pivotal roles in forecasting and issuing timely warnings for events like cyclones, floods, heavy rainfall, landslides, heat wave, cold waves, drought, earthquakes, and tsunamis. Technological innovations, such as Doppler weather radars, satellite-based systems, and mobile applications like Mausam, Meghdoot and DAMINI (link available at https://mausam.imd.gov.in/), provide real-time updates and hazard-specific alerts to the public and authorities.

India has developed an efficient communication network to ensure that these warnings reach the most vulnerable communities, utilizing mass media, mobile alerts, and traditional methods like sirens and community radios. The Common Alert Protocol (CAP) ensures consistent messaging across platforms. The role of communities is vital in disaster preparedness, as local knowledge and participation enhance resilience. The National Disaster Response Force (NDRF), in coordination with local agencies, provides rapid response and relief during emergencies, while the State Disaster Management Authorities (SDMAs) and District Disaster Management Authorities (DDMAs) tailor efforts to regional needs.

Furthermore, the model emphasizes the importance of disaster-resistant infrastructure, public awareness, and education to foster a culture of preparedness. Efficient and coordinated government responses, coupled with rapid recovery and rehabilitation strategies, minimize losses and expedite return to normalcy. Cultural resilience also plays a crucial role, as communities draw on traditional practices and social cohesion to withstand and recover from disasters. Together, these elements create a robust framework for disaster management that enhances safety and resilience across the country.

4.3 IMD’s Website: A Vital Resource for Weather Forecasting and Disaster Management

The India Meteorological Department (IMD) website, www.mausam.imd.gov.in, is a comprehensive platform that acts as a powerful tool in weather forecasting and disaster management. It offers real-time weather observations, including meteorological sub-division, district, and station-wise forecasts and warnings, covering up to a 7-day medium range and nowcast (for next 2-3 hour), crucial for timely interventions during adverse weather conditions. The website also provides special forecasts for diverse sectors such as marine regions, aviation, agriculture, and transport, as well as warnings for health, tourism, and pilgrimages

IMD’s integration of advanced technology is key to its role in disaster preparedness. It provides real-time satellite and radar images, lightning observations, and cyclone forecasts, making it easier to track and predict hazardous events. The platform also disseminates critical information on the monsoon, flash floods, and climate services, ensuring effective risk management and awareness. For sectors like agriculture and power, it offers tailored advisories, ensuring the safety and continuity of essential services

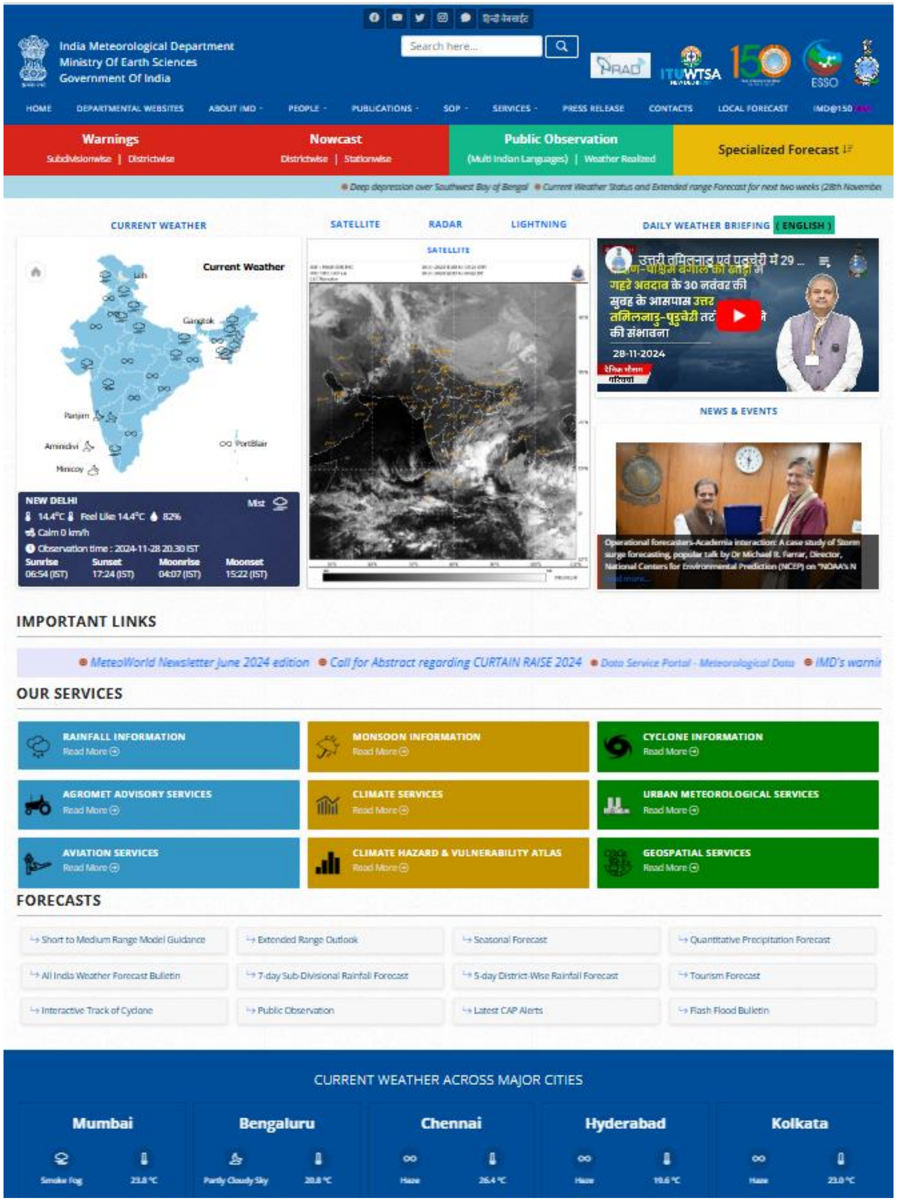


Figure 4.4: A screenshot of IMD’s website**.**

Additionally, the IMD website enables public participation through its weather reporting system, making it an interactive hub for accurate weather data. By making detailed National Weather Prediction Model (NWP) outputs available, it aids in the short-to-seasonal forecasting process, improving decision-making at all levels. Through these features, the IMD website supports rapid responses and mitigates the impact of natural disasters.

In addition to the IMD’s Mausam websites, the IMD's regional websites serve as critical resources for disseminating localized weather forecasts and warnings, enhancing public awareness and preparedness for extreme weather events. These regional platforms play a pivotal role in disaster management by providing timely information, enabling communities to respond effectively to weather-related emergencies. A screenshot of IMD’s website is provided in the Figure 4.4.

4.4 Involving Communities in Hazard Preparedness

4.4.1 Importance of community involvement in natural hazard awareness and action

Community involvement plays a vital role in enhancing natural hazard awareness and promoting effective action. Local communities often possess invaluable knowledge about their environments, including the specific risks they face and historical experiences with past disasters. By actively engaging community members in disaster preparedness programs, authorities can leverage this knowledge to develop tailored strategies that resonate with local needs and conditions. Workshops, training sessions, and simulations empower residents to recognize early warning signs, understand emergency procedures, and adopt safety measures, ultimately fostering a culture of preparedness. When communities are well-informed and actively participate in these initiatives, they become more resilient and better equipped to respond to natural hazards.

Moreover, community involvement facilitates stronger social networks, which are crucial during disasters. In times of crisis, neighbours often rely on one another for support, information, and resources. By encouraging collaboration and communication among community members, local organizations can create a sense of solidarity that enhances collective response efforts. Initiatives such as neighbourhood watch programs, local disaster response teams, and community drills not only build skills and awareness but also strengthen relationships among residents. This social cohesion proves invaluable during emergencies, as it enables quicker mobilization of resources, effective sharing of information, and more efficient recovery efforts. Ultimately, active community involvement in natural hazard awareness and action is essential for building resilient societies capable of effectively mitigating the impacts of disasters.

4.4.2 Educational initiatives for disaster preparedness

Educational initiatives for disaster preparedness in India are crucial for building a resilient society capable of effectively responding to natural hazards. Various programs target different age groups, aiming to instill knowledge and skills related to disaster risk reduction. Schools and colleges play a significant role in this endeavour, incorporating disaster management into their curricula through workshops, training sessions, and drills. The National Disaster Management Authority (NDMA) has developed educational materials and resources tailored for students and educators to enhance understanding of natural hazards and emergency procedures.

Beyond formal education, community-based training programs engage local residents in disaster preparedness activities, fostering awareness and resilience. These initiatives often include workshops, awareness campaigns, and simulation exercises that empower individuals to recognize hazards, understand warning systems, and respond effectively in emergencies. Government and non-governmental organizations collaborate to disseminate information through various media, including social networks, to reach wider audiences. By prioritizing educational initiatives, India aims to cultivate a culture of preparedness, ensuring that citizens are equipped with the knowledge and skills necessary to protect themselves and their communities during disasters.

Chapter 5:

Climate change: Causes, Impacts, Mitigation and Adaptation

Climate change is an undeniable and widespread global issue impacting every facet of life. Since the onset of industrialization, temperatures have been steadily rising, with the past decade being among the hottest in recorded history. This trend of increasing temperatures is largely driven by greenhouse gas emissions from industrial activities. The consequences are evident in the form of more frequent and severe extreme weather events, intense heatwaves, and prolonged droughts. These changes are causing significant damage and adversely affecting the livelihoods of billions worldwide. Addressing this crisis requires two key approaches: adapting to the inevitable changes in climate and slowing the rate of global warming. Successfully managing these challenges will not only influence our current generation but also determine the well-being of future generations.

5.1 Climate Change

Climate change refers to the long-term alterations in Earth's average weather patterns, largely driven by human activities. It presents a profound threat to the environment, economies, and societies across the globe. Over the past decade, the climate crisis has worsened, characterized by unprecedented temperature increases that have led to more frequent and severe extreme weather events. Unseasonal heat waves, flash floods, cloudbursts, intense thunderstorms, and cyclones are becoming alarmingly common, highlighting the urgent need for global climate action.

5.1.1. Causes of Climate Change

- **Historical Atmospheric Stability**

  For the past 800,000 years, the Earth's atmospheric system has maintained a relatively stable temperature of around 15˚C, with an atmospheric CO2 concentration of approximately 280 ppm. This stability is largely due to the Earth's balanced carbon cycle, which effectively manages greenhouse gas (GHG) emissions and their absorption by natural sinks. This equilibrium has kept the planet's climate relatively consistent over this extensive period.
- **Impact of Industrialization**

  The advent of industrialization marked a significant turning point in Earth's climate system. Large-scale extraction and combustion of fossil fuels such as coal, gas, and oil began to meet the increasing energy demands of humanity and various industries. This process released unprecedented amounts of greenhouse gases, particularly CO2, into the atmosphere. Consequently, atmospheric CO2 levels have surged to 423.96 ppm, as recorded by the Mauna Loa lab of the National Oceanic and Atmospheric Administration (NOAA) on November 17, 2024
- **Accumulation of Excess CO2**

The impact of increased CO2 emissions can be quantified by understanding that the release of 2.13 billion tons of CO2 into the atmosphere results in a 1 ppm increase in CO2 concentration. Given the current atmospheric CO2 level of 421 ppm, there is an excess of 141 ppm when compared to the historical level of 280 ppm (Figure 5.1). This excess corresponds to the accumulation of approximately 300 billion tons of CO2, which has significantly contributed to the acceleration of global warming and climate change.

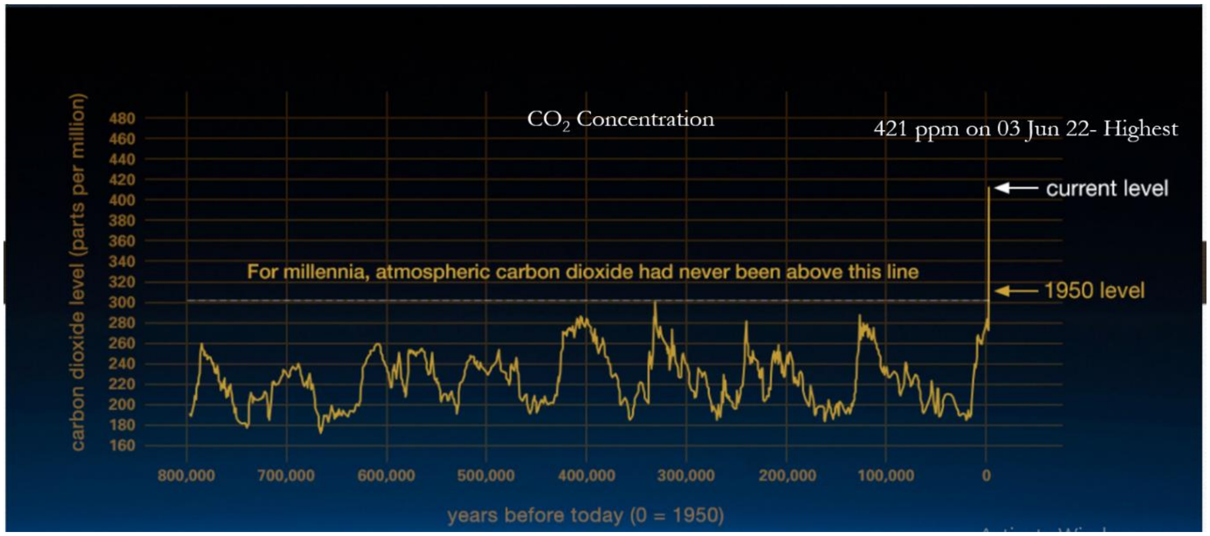


Figure 5.1: Concentration measured at Mauna Loa Lab. Source: Global Climate Change (NASA)

5.1.1.1 Anthropogenic Causes of Climate Change

The dramatic increase in GHG emissions due to human activities is the primary driver of recent climate change. The major anthropogenic causes include:

1) **Greenhouse Gas Emissions**: The burning of fossil fuels for energy, deforestation, industrial processes, and agriculture have led to a significant rise in greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These gases trap heat in the Earth's atmosphere, resulting in the greenhouse effect and contributing to global warming. (May include a figure showing increase
2) **Deforestation and Land Use Changes**: The removal of trees and changes in land use reduce the Earth's capacity to absorb CO2, while also releasing stored carbon back into the atmosphere, exacerbating the increase in CO2 levels.
3) **Industrial and Agricultural Activities**: Industrial processes, including cement production and the use of refrigerants, contribute to GHG emissions. Agriculture adds to this through methane emissions from livestock and rice paddies and nitrous oxide emissions from synthetic fertilizers.

5.1.1.2 Natural Causes of Climate Change

While human activities are the primary drivers of recent climate change, natural factors also play a role, including:

- **Volcanic Activity**: Volcanic eruptions can release significant amounts of aerosols and GHGs into the atmosphere, leading to temporary cooling effects or, in some cases, contributing to warming.
- **Solar Variability**: Changes in solar radiation can affect Earth's climate, though these changes have been relatively minor compared to human-induced factors in recent decades.
- **Natural Climate Cycles**: Natural phenomena such as El Niño and La Niña cause short-term fluctuations in climate patterns. However, these cycles do not account for the long-term trends in global warming observed specially in last few decades although one odd years or days can show significant increase in temperatures.

5.2. Global Warming and Climate Change

Although "global warming" and "climate change" are often used interchangeably, they have distinct meanings. Global warming specifically refers to the long-term increase in Earth's average surface temperature caused by human activities, particularly the emission of greenhouse gases like carbon dioxide (CO_2) from burning fossil fuels, deforestation, and industrial processes. It is a component of climate change, focusing on the rising temperatures of Earth's atmospheric systems.

On the other hand, climate change refers to long-term changes in temperature, humidity, wind patterns, and other atmospheric elements on a global scale, driven by both natural processes and human activities. In essence, global warming is the increase in Earth's temperature, while climate change refers to the broader set of changes affecting the Earth's climate, including but not limited to warming.

5.3. Climate Change: Proof for Climate Change

5.3.1 Scientific evidence of climate change

The Intergovernmental Panel on Climate Change (IPCC) Assessment Report 6 (AR6) identifies several key climate indicators to assess the state of the climate system. These indicators include:

- **Rising Global Temperatures:** Earth's average temperature is increasing.
- **Shrinking Ice Sheets:** Glaciers and polar ice caps are melting.
- **Sea Level Rise:** Ocean levels are increasing due to thermal expansion and melting ice.
- **Ocean Acidification:** Increased CO_2 absorption makes oceans more acidic.
- **Increased Frequency of Extreme Weather Events:** More heatwaves, storms, droughts, and floods.
- **Changes in Ecosystems and Biodiversity:** Species are migrating or becoming extinct due to shifting conditions.

These indicators collectively provide a comprehensive overview of the changes occurring in the Earth's climate system, as detailed in the IPCC AR6.

5.4. Impacts of Climate Change

Climate change has profound and wide-ranging impacts on India, affecting multiple dimensions of the environment, economy, and society. The evidence of these impacts has become increasingly clear in recent years, as the country faces one climate crisis after another. India is particularly vulnerable due to its limited adaptive capacity. Some of the key impacts include:

5.4.1. Extreme Weather Events

- **Heatwaves:** India has been experiencing more frequent and intense heatwaves, leading to serious health issues, reduced productivity, and higher mortality rates. In May 2024 alone, heatwaves claimed hundreds of lives in Northwest India.
- **Floods:** The intensity of rainfall and the unpredictability of monsoon patterns have resulted in severe flooding across various parts of the country year after year. These incidents are on the rise, particularly in hill states, causing widespread damage to infrastructure, agriculture, livelihoods, and leading to loss of life.
- **Cyclones:** Coastal regions are facing an increased frequency and intensity of cyclones, resulting in significant loss of life, property damage, and displacement of communities.
- **Glacial Lake Outburst Floods (GLOFs):** The occurrence of GLOF incidents is on the rise, with the most recent event in Sikkim causing the deaths of hundreds of people and extensive destruction of infrastructure.
- **Landslides:** The frequency of landslides is also increasing. In 2024, the Wayanad landslides alone claimed 500 lives and led to the destruction of several villages.

5.4.2 Social and economic impacts

5.4.2.1. Agricultural Productivity

- **Crop Yields:** Changes in temperature and rainfall patterns are negatively affecting crop yields, particularly for staple crops such as wheat, rice, and maize. This threatens food security and increases the risk of hunger and malnutrition. For example, the early March 2022 heatwave resulted in a 5% reduction in wheat grain production in India due to terminal heat stress.
- **Water Stress:** Altered precipitation patterns and shrinking glaciers in the Himalayas are impacting water availability, affecting irrigation and leading to water scarcity in many regions. In India, increased variability and unpredictability of the monsoon are creating significant uncertainty regarding water availability, particularly in non-irrigated regions, which is severely impacting crop production.

5.4.2.2. Rising Sea Levels:

Rising sea levels have several significant impacts, including coastal erosion, which threatens infrastructure and natural habitats along coastlines. Saltwater intrusion into freshwater sources and agricultural land affects water quality and reduces soil fertility, compromising agriculture and drinking water supplies.

Additionally, communities in low-lying coastal areas face the risk of displacement due to the combined effects of rising sea levels and increased flooding.

5.4.2.3. Health Impacts

Climate change has significant health impacts, including an increase in heat-related illnesses and mortality due to higher temperatures, particularly affecting vulnerable populations. Warmer temperatures and altered rainfall patterns are expanding the range of vector-borne diseases, such as malaria and dengue fever. Additionally, the rising frequency of wildfires, dust storms, and the burning of crop residues contribute to poor air quality, leading to respiratory problems and exacerbating health issues.

5.4.2.4. Economic Impacts

Climate change has substantial economic impacts, particularly in India. The agriculture sector, a crucial part of the economy, faces significant vulnerability, leading to economic instability, reduced incomes for millions of farmers, and threats to food security. Extreme weather events, such as floods, flash floods, landslides, glacial lake outburst floods (GLOFs), and cyclones, cause extensive damage to infrastructure, resulting in increased repair and reconstruction costs. For example, in 2021, the United Nations Economic and Social Commission for Asia and the Pacific (ESCAP) estimated a loss of $87 billion for India alone. Additionally, rising temperatures boost energy demand for cooling, placing pressure on energy supplies and increasing costs, while dwindling water resources further threaten energy security.

5.4.2.5. Biodiversity and Ecosystems

Climate change has severe effects on biodiversity and ecosystems, including significant habitat loss and shifts in species distribution that threaten biodiversity across various ecosystems such as forests, wetlands, and coral reefs. Altered climate conditions can lead to the extinction of species that cannot adapt quickly enough, disrupting the balance of ecosystems. Additionally, increased temperatures and prolonged dry spells are causing more frequent and intense forest fires, which not only destroy habitats but also release substantial amounts of carbon dioxide into the atmosphere, further exacerbating climate change

5.4.2.6. Social and Cultural Impacts

Climate change is driving increased migration due to displacement from rural areas to urban centres, creating significant social and economic challenges. For example, rising sea levels in the Sundarbans have submerged homes, forcing vulnerable communities to relocate to higher latitudes. Additionally, the threat of rising sea levels and extreme weather events jeopardizes India's cultural heritage sites, especially those along the coast, endangering valuable historical and cultural landmarks.

Overall, climate change poses a significant challenge to India’s development, requiring urgent and comprehensive adaptation and mitigation strategies to protect its people, economy, and environment.

5.4.3 Characteristics of Climate Change and Its Impacts in India

Climate change is a pressing global challenge characterized by long-term alterations in temperature, precipitation patterns, and extreme weather events. In India, a country with diverse climates and a large population, the impacts of climate change are particularly pronounced, affecting various sectors including agriculture, water resources, health, and biodiversity.

5.4.3.1 Characteristics of Climate Change in India

Rising Temperatures: India has witnessed a significant increase in average temperatures, with projections indicating a rise of 1.5 to 2.5 degrees Celsius by the end of the century. This rise in temperature leads to more frequent and intense heatwaves, especially in northern and central regions of the country.

Erratic Monsoon Patterns: The Indian monsoon, vital for agriculture, has become increasingly unpredictable. Changes in the timing and intensity of monsoon rains lead to both flooding and drought conditions. Delayed onset of monsoon and irregular rainfall patterns severely affect crop yields.

Increased Frequency of Extreme Weather Events: India is experiencing a rise in the frequency and intensity of extreme weather events such as cyclones, heavy rainfall, and floods. Coastal states are particularly vulnerable to cyclones, resulting in loss of life and property.

Glacial Melt: The Himalayan glaciers are melting at an alarming rate due to rising temperatures, leading to altered river flows and threatening water security for millions dependent on these water sources.

Changing Biodiversity: Climate change impacts ecosystems and wildlife, leading to shifts in species distribution and threatening biodiversity. Many species are at risk of extinction due to habitat loss and changing climate conditions.

Impact on Livelihoods: Beyond agriculture, many livelihoods dependent on fisheries, forestry, and tourism are affected. Changes in marine temperatures impact fish stocks, while altered rainfall patterns affect forestry and related industries.

Urban Heat Islands: Rapid urbanization in cities like Delhi, Mumbai, and Bengaluru has created urban heat islands, where temperatures are significantly higher than surrounding rural areas. This exacerbates the effects of climate change and poses health risks.

Soil Degradation: Climate change contributes to soil erosion, salinization, and loss of fertility. These changes affect agricultural productivity and sustainability, leading to long-term challenges for food security.

5.5 International and National Initiatives

5.5.1 International Initiatives

The Intergovernmental Panel on Climate Change (IPCC)

The IPCC was established in 1988 by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO). It assesses scientific information related to climate change, its impacts, and future risks, and provides reports to inform policy decisions. The IPCC does not conduct its own research but reviews and synthesizes existing studies.

The United Nations Framework Convention on Climate Change (UNFCCC)

The UNFCCC is an international environmental treaty adopted in 1992 at the Earth Summit in Rio de Janeiro. Its primary goal is to stabilize greenhouse gas concentrations in the atmosphere to prevent dangerous anthropogenic interference with the climate system. It provides a framework for international cooperation on climate change mitigation and adaptation.

The Paris Agreement

The Paris Agreement is a landmark international treaty adopted at COP21 in Paris. Its main aim is to limit global warming to well below 2°C, preferably 1.5°C, compared to pre-industrial levels. It emphasizes the importance of nationally determined contributions (NDCs) and requires countries to set climate action plans and progressively increase their ambition to reduce emissions.

The Conference of the Parties (COP)

The COP is the decision-making body of the UNFCCC. It consists of representatives from all countries that are signatories to the convention. The COP meets annually to review progress, negotiate agreements, and set new climate action targets. Each session is numbered, with COP26 held in Glasgow in 2021 and COP27 in Egypt in 2022. COP29, is scheduled to be held in Azerbaijan during Nov 24.

5.5.2. National Initiatives

5.5.2.1 Nationally Determined Contributions

Nationally Determined Contributions (NDCs) are commitments made by individual countries under the Paris Agreement to reduce greenhouse gas emissions and adapt to the impacts of climate change. Each country sets its own targets and plans based on its capabilities, priorities, and circumstances, making these contributions "nationally determined."

NDCs are a crucial component of the Paris Agreement, aiming collectively to limit global warming to well below 2°C above pre-industrial levels, with efforts to keep it below 1.5°C. Countries are expected to regularly update and submit their NDCs to the United Nations Framework Convention on Climate Change (UNFCCC) every five years, enhancing them to reflect increasing ambition and progress in reducing greenhouse gas emissions.

India submitted its first set of NDCs to the UNFCCC and updated them in August 2022 with ambitious targets, including:

- Increasing its non-fossil fuel energy capacity to 500 GW by 2030.
- Fulfilling 50% of its energy requirements through renewable energy by 2030.
- Reducing total projected carbon emissions by one billion tons between now and 2030.
- Decreasing the carbon intensity of its economy by 45% per capita of GDP from 2005 levels.
- Implementing a low-carbon strategy to achieve net zero emissions by 2070.

5.5.2.2 India’s National Action Plan on Climate Change

The National Action Plan on Climate Change (NAPCC) of India is a comprehensive framework aimed at addressing climate change through a series of coordinated and strategic actions. Launched in 2008, the NAPCC outlines India's approach to tackling climate change and sets out a range of missions to promote sustainable development. The NAPCC is designed to integrate climate policies into national development planning and to ensure that climate adaptation and mitigation efforts are coordinated across various sectors.

The NAPCC consists of eight key missions, each focusing on a specific area to address climate change challenges:

1. **National Solar Mission**: Aims to promote the development and use of solar energy technologies, with targets for increasing solar power capacity and reducing the cost of solar energy.

2. **National Mission for Enhanced Energy Efficiency (NMEEE)**: Focuses on improving energy efficiency across various sectors, including industrial, transportation, and buildings, through measures such as energy efficiency standards and incentive programs.
3. **National Mission on Sustainable Habitat**: Seeks to promote sustainable urban development and improve the quality of life in cities through better urban planning, waste management, and energy-efficient infrastructure.
4. **National Mission on Sustainable Agriculture**: Addresses the impact of climate change on agriculture by promoting sustainable agricultural practices, improving crop resilience, and enhancing water-use efficiency.
5. **National Water Mission**: Aims to conserve water resources through improved management practices, efficient water use, and better monitoring of water availability and quality.
6. **National Mission on Green India**: Focuses on increasing forest cover and promoting biodiversity conservation, enhancing ecosystem services, and improving the resilience of forests and other green spaces.
7. **National Mission for Sustaining the Himalayan Ecosystem**: Seeks to protect and sustain the Himalayan region's ecological balance by monitoring and mitigating the impacts of climate change on this critical area.
8. **National Mission on Strategic Knowledge for Climate Change**: Aims to enhance research and knowledge related to climate change, including the development of models, data collection, and dissemination of information to support evidence-based decision-making.

Each mission of the NAPCC includes specific goals and action plans to address various aspects of climate change, ensuring a comprehensive and coordinated response to the challenges posed by a changing climate.

5.6 Mitigation to Climate Change

Mitigating climate change involves a multifaceted approach aimed at reducing greenhouse gas emissions and enhancing carbon sinks to limit global warming. Key strategies include transitioning to renewable energy sources such as solar, wind, and hydro power, improving energy efficiency in buildings, transportation, and industries, and adopting sustainable agricultural practices. Reforestation and afforestation efforts help absorb carbon dioxide from the atmosphere, while policies and regulations support reduced emissions and encourage low-carbon technologies. Additionally, international agreements like the Paris Agreement play a crucial role in setting targets and fostering global cooperation to achieve long-term climate goals.

5.6.1 India’s Mitigation Strategies to Combat Climate Change

India's main mitigation strategies to combat climate change focus on reducing greenhouse gas emissions and transitioning to a more sustainable and low-carbon economy. Here are the key strategies:

1. **Expansion of Renewable Energy:**
    - **Solar Power:** India aims to significantly increase its solar power capacity through initiatives like the National Solar Mission, with targets to deploy large-scale solar power projects and promote solar rooftop installations.
    - **Wind Power:** Efforts are being made to enhance wind energy capacity, including the development of wind farms and the promotion of wind turbine technology.
2. **Energy Efficiency Improvements:**
    - **Energy Efficiency Programs:** The National Mission for Enhanced Energy Efficiency (NMEEE) focuses on improving energy efficiency in industrial processes, transportation, and buildings through regulations, standards, and incentive programs.
    - **Standards and Labels:** Implementation of energy efficiency standards and labels for appliances and vehicles to reduce energy consumption.
3. **Sustainable Agriculture:**
    - **Climate-Resilient Crops:** Promoting sustainable agricultural practices, including the development and adoption of climate-resilient crop varieties.
    - **Improved Water Management:** Enhancing water-use efficiency in agriculture through better irrigation techniques and practices.
4. **Forestry and Afforestation:**
    - **Increased Forest Cover:** The National Mission on Green India aims to increase forest cover, promote biodiversity, and enhance ecosystem services.
    - **Reforestation and Afforestation:** Large-scale tree planting and forest conservation efforts to absorb CO2 and restore degraded lands.
5. **Transition to Cleaner Fuels:**
    - **Alternative Fuels:** Promoting the use of cleaner fuels and technologies, such as compressed natural gas (CNG) and biofuels, to reduce emissions from transportation.
    - **Green Hydrogen Mission:** The National Green Hydrogen Mission has been launched to position India as a global hub for the production of clean fuel. This initiative aligns with India’s goal of becoming Aatmanirbhar (self-reliant) through clean energy while serving as a model for the global transition to clean energy. The mission aims to significantly decarbonize the economy, support the achievement of net-zero emissions, reduce dependence on fossil fuel imports, and empower India to take a leading role in green hydrogen technology and market development.
6. **Waste Management:**
    - **Waste Reduction and Recycling:** Implementing policies and practices to reduce waste generation, promote recycling, and manage waste more effectively to minimize methane emissions from landfills.
7. **Policy and Regulatory Framework:**
    - **Climate Policies:** Developing and implementing national and state-level policies and regulations to support climate action, including carbon pricing mechanisms and emission reduction targets.
8. **International Cooperation:**
    - **Climate Agreements:** Participating in international climate agreements such as the Paris Agreement and committing to nationally determined contributions (NDCs) to reduce emissions and enhance climate resilience.

These strategies are part of a comprehensive approach to addressing climate change and are designed to align with India's sustainable development goals and international climate commitments.

Mission LiFE (Lifestyle for Environment)

Mission LiFE, launched by Prime Minister Narendra Modi in 2022, is an initiative that promotes sustainable living by encouraging environmentally conscious behaviors. The goal of Mission LiFE is to inspire individuals and communities to adopt lifestyles that reduce environmental impact, conserve natural resources, and mitigate climate change.

Key aspects of Mission LiFE include:

- **Sustainable Practices**: Encouraging people to reduce waste, conserve water, use energy efficiently, and adopt cleaner technologies.
- **Behavioral Change**: Promoting habits like using public transport, reducing single-use plastics, and conserving natural resources.
- **Community Action**: Engaging citizens, organizations, and communities in grassroots-level climate action.
- **Global Outreach**: India aims to inspire other nations to adopt similar people-centric climate solutions to achieve global sustainability goals.

Mission LiFE emphasizes that individual actions, when taken collectively, can significantly contribute to addressing environmental challenges.

5.7 Adaptation to Climate Change

Climate change adaptation involves making adjustments and preparing for the inevitable impacts of climate change to minimize harm and capitalize on potential benefits. This includes implementing strategies to protect infrastructure from extreme weather events, such as strengthening flood defences and improving building codes. In agriculture, adaptation can involve developing drought-resistant crops and adopting water-efficient irrigation practices. Coastal areas may invest in sea walls and natural barriers to counteract rising sea levels. Additionally, communities may enhance their emergency response systems and update land use planning to address changing conditions. Effective adaptation requires a combination of local, national, and international efforts to build resilience and safeguard both human and natural systems against the challenges posed by climate change.

Climate change is one of the most pressing challenges of our time. Understanding its causes, indicators, and the actions we can take to mitigate and adapt to its effects is crucial for securing a sustainable future. By transitioning to renewable energy, adopting efficient practices, and improving resilience, we can reduce the impact of climate change on our planet. The actions we take today will shape the world for future generations. Top of Form the course content provided here is a general outline. Students are encouraged to visit the UNFCCC website and India’s Ministry of Environment, Forest and Climate Change to explore the connections between various missions and both mitigation and adaptation strategies. This will help them stay updated and deepen their knowledge and understanding of these topics.

Chapter 6

Climate Services to Socio-economic sectors

6.1 Introduction:

Climate services refer to providing climate-related information and products to help individuals, communities, and organizations make informed decisions. These services are based on scientific data, models, and predictions related to climate variability, climate change, and extreme weather events. Compared to weather services, which deal with weather patterns over a few days, climate services focus on longer-term climate patterns and provide a greater lead time for climate risk management actions. Climate services deal with historical climate data, including long-term climate variability and trends, short-term climate forecasts from sub-seasonal to inter-decadal scales, and multi-decadal climate change projections. Climate services also help understand broader climate patterns and their implications for various sectors, such as agriculture, health, water resources, energy, disaster risk management, etc., and support long-term planning and policy development, leading to significant socio-economic benefits.

6.2 Global Framework for Climate Services (GFCS):

The World Meteorological Organization (WMO), of which India is one of the founding members and an active co-sponsor, has promoted an innovative platform called the Global Framework for Climate Services (GFCS), which helps bring together different stakeholders through active coordination and collaborative engagements. The heads of state and governments, ministers and heads of delegations, were present at the World Climate Conference-3 (held in Geneva, 31 August–4 September 2009), established the GFCS. It is a tool to strengthen the production, availability, delivery and application of science-based climate prediction and services. Therefore, GFCS aims to enable society to better manage the risks and opportunities arising from climate variability and change, especially focusing on those most vulnerable to such risks, by developing and incorporating science-based climate information and prediction into planning, policy and practice.

There are five overarching goals of GFCS:

I. Reducing the vulnerability of society to climate-related hazards through better provision of climate information and services
II. Advancing the key global development goals through better provision of climate information and services
III. Mainstreaming the use of climate information and services in decision-making
IV. Strengthening the engagement of providers and users of climate services
V. Maximizing the utility of existing climate service infrastructure

The implementation of GFCS is structured on five foundational pillars (Figure 6.1) comprising (i) observations and monitoring; (ii) research, modelling, and prediction; (iii) climate services information systems; (iv) user interface platforms; and (v) capacity development. The GFCS focuses on developing and delivering services in five initial priority areas, addressing basic societal issues and presenting the most immediate opportunities to benefit human safety and well-being, enabling sustainable development. These priority areas are water, agriculture and food security, energy, health, and disaster risk reduction.

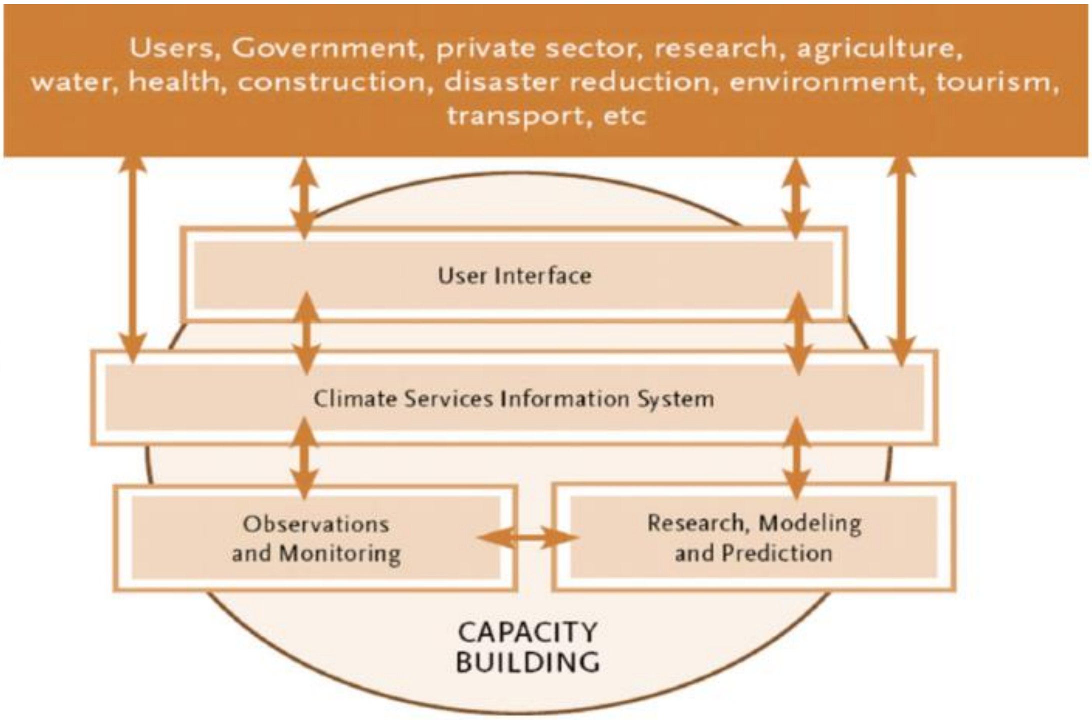


Figure 6.1: Five foundational pillars of GFCS

6.3 National Framework for Climate Services (NFCS):

To help all climate services stakeholders at the national level work together with mutually agreed working arrangements to collectively pursue the common goal of achieving a climate-smart society, a National Framework for Climate Services (NFCS) was established on the concept of the GFCS. This will help strengthen the production, availability, delivery, and application of science-based climate monitoring and prediction services at the national level. The NFCS is a multi-institutional mechanism to coordinate, facilitate and strengthen collaboration among the relevant national institutions and partners to improve the co-production, tailoring, delivery and use of science-based climate information, predictions and services, essentially structured in terms of the five GFCS pillars. In this platform, various organizations can play their roles in a complementary manner and link up with other governmental, non-governmental and international agencies to work together to provide customer-tailored climate services for various sectors. As per the GFCS guidelines, the nodal agency that coordinates the NFCS is the concerned National Meteorological and Hydrological Service (NMHS). The India Meteorological Department (IMD), under the Ministry of Earth Sciences, Government of India, which discharges the responsibilities of NMHS for India within the WMO structure, has therefore taken the initiative to establish and implement NFCS in India.

6.4 Climate Services by IMD

India have a long history in climate monitoring, research, and prediction, empowering its climate services. India had played a leading role in developing and guiding the GFCS right from its beginning. Currently, India Meteorological Department (IMD) is also playing leadership role in the South Asia and international arena through its WMO recognised Regional Climate Centre (RCC) and Regional Specialized Meteorological Centre (RSMC). In this way, IMD plays a key role in organising various activities of climate data, monitoring, forecasting and services with operationally sustained international collaboration and partnership. Since its inception, IMD has been providing climate-related services to the country through its different units in some form or another. Through its Climate Research and Services (CRS) division at Pune, the IMD plays a key role in providing climate services, including climate monitoring, seasonal forecasts, surface meteorological instruments, and capacity building. Below are some of the climate services provided by IMD.

I. Climate Data Services: IMD installs and upkeep of surface meteorological instruments across the country. This office also provides services in all aspects of testing, calibration & standardization of instruments with WMO standards. Meteorological data from the entire country are received and archived at the National Data Centre (NDC). IMD supplies meteorological data to various government and non-government organisations, research institutes, universities, students, and private firms from all sectors, media, etc, through its Data Supply Portal.

II. Climate Monitoring: IMD has been preparing and publishing monthly, seasonal and annual climate summaries for the country. IMD also operates climate stations where long-term weather data is available, providing an essential climate service. IMD also prepares quality-controlled, high-resolution daily gridded rainfall and temperature products for the user community. This climate monitoring also includes the preparation of a climate diagnostic bulletin, monthly and annual climate summary, monsoon report, disaster weather event report, etc.

Climate Prediction: IMD has been issuing the long-range climate forecast since the 1880s. Over the years, the operational LRF system in India underwent many changes in its approach and scope. Currently, the statistical Ensemble Forecasting system and dynamical model forecasts are used to issue seasonal monsoon rainfall forecasts. Since 2021, IMD introduced a Multi-Model Ensemble (MME) forecasting system based on the Coupled Global Climate Model (CGCM) for monthly and seasonal forecasts.

III. Climate Applications: The climate application includes providing climate information for various sources such as agriculture, water resources, health, disaster management, etc. IMD carries out drought monitoring and prediction on different time scales. Also, it provides a weekly climate outlook for vector-borne diseases like Malaria, Dengue, etc. IMD has recently prepared a Climate Hazards and Vulnerability Atlas of India for the thirteen most hazardous meteorological events. The Atlas provides districts maps on Hazard events and vulnerability for all the calendar months and at annual scale. In the agriculture sector, it supports the farmers to cope with the impact of adverse weather on crops to boost agricultural production. The organization also disseminates Agromet Advisories to the farmers at district and block levels twice a week.

IV. Capacity Building: The Meteorological Training Institute (MTI) at CRS, Pune is a Regional Training Center, recognized by the World Meteorological Organization. This provides training in weather & climate services to the personnel of IMD, Defence Services and National Meteorological services from South Asian countries.

6.4.1 IMD Pune Website: A Comprehensive Resource for Climate Research, Forecasting, and Disaster Management

The IMD's Pune website (imdpune.gov.in) is a key resource for climate research and services, playing a crucial role in weather forecasting, climate monitoring, and disaster management in India. The site offers a wide array of services, with a focus on both real-time weather data and long-term climate insights.

One of the core services is climate monitoring, which includes data collection and analysis of rainfall, temperature, and extreme weather events. The website provides tools for drought monitoring, rainfall statistics, and temperature forecasts at various scales, from district to national levels. This helps in the accurate prediction of agricultural conditions, reservoir management, and other hydrological applications.

IMD Pune also excels in climate prediction, providing seasonal forecasts and extended-range predictions. These forecasts are vital for sectors such as agriculture, water management, energy, and health. For instance, the website delivers specialized information on drought conditions and heatwaves, which are critical for planning in agriculture and disaster risk reduction. Additionally, IMD Pune disseminates agrometeorological advisories under its Gramin Krishi Mausam Sewa (GKMS) initiative, reaching millions of farmers across India.

The site also hosts tools and data for sector-specific applications, which extend to health, energy, tourism, and transport. The IMD's climate services framework integrates a wide range of users by providing timely forecasts, early warnings, and climate impact analyses. For disaster management, it tracks cyclones, thunderstorms, and other hazardous events using numerical weather prediction models, including global and regional forecasting systems.

Lastly, the IMD Pune website offers extensive training and capacity-building programs and serves as a hub for climate-related publications, including monthly and annual climate summaries, and research papers. A key aspect of its offerings is its contribution to the National Framework for Climate Services (NFCS), which is designed to integrate climate information into decision-making processes across sectors. This framework aligns with the Global Framework for Climate Services (GFCS), which promotes climate resilience by providing accurate and timely climate information to various sectors like agriculture, health, energy, water management, and disaster risk reduction.

In summary, the IMD Pune website is a comprehensive resource that supports research, forecasting, and climate services for various sectors, aiding in efficient climate-related decision-making and disaster management.

6.5 Applications of Weather and Climate Information in Socio-Economic Sectors

Weather and climate information plays a vital role in various socio-economic sectors, significantly influencing decision-making and enhancing resilience to climate variability. Here are key applications across different sectors:

6.5.1 Agriculture

Weather and climate information is crucial for agricultural planning and management. Farmers utilize forecasts to determine optimal planting and harvesting times, manage irrigation, and mitigate the impacts of adverse weather events, such as droughts or floods. Seasonal forecasts, such as monsoon predictions, inform farmers about expected rainfall patterns, helping them make informed decisions about crop selection and management practices.

6.5.2 Water Resource Management

Accurate weather forecasts are essential for managing water resources. Hydrologists and water managers rely on climate data to predict water availability, plan reservoir operations, and ensure sustainable water supply for agricultural, industrial, and domestic uses. This information helps in minimizing water scarcity and optimizing the use of available water resources.

6.5.3 Disaster Management

Timely weather information is critical for disaster preparedness and response. Meteorological data helps authorities issue early warnings for severe weather events such as cyclones, hurricanes, and heavy rainfall. This enables communities to take precautionary measures, evacuate if necessary, and minimize loss of life and property. Effective disaster management plans rely on accurate and timely weather predictions.

6.5.4 Health Sector

Weather and climate information significantly impacts public health. Understanding climate patterns helps predict the spread of vector-borne diseases, such as malaria and dengue, which are influenced by temperature and rainfall. Health authorities use climate data to implement preventive measures, allocate resources, and plan health interventions, particularly in vulnerable regions.

6.5.5 Energy Sector

Weather information is critical for energy production and consumption management. Renewable energy sectors, particularly solar and wind energy, depend on accurate weather forecasts to optimize energy generation. Utilities use climate data to anticipate energy demand fluctuations due to seasonal changes, ensuring reliable supply and efficient grid management.

6.5.6 Transportation

Weather conditions directly affect transportation safety and efficiency. Airlines, shipping companies, and road transport agencies use weather forecasts to plan routes, schedule operations, and ensure passenger safety. Timely weather information helps in minimizing delays and optimizing logistics in transportation networks.

6.5.7 Insurance and Risk Management

Insurance companies use weather and climate data to assess risk and determine premiums for policies related to agriculture, property, and natural disasters. Understanding historical weather patterns and climate risks helps insurers develop products that cater to clients' needs and improve their risk assessment models.

6.5.8 Urban Planning and Infrastructure Development

Urban planners and engineers utilize climate data to design resilient infrastructure that can withstand extreme weather events. Climate projections inform decisions on land use, flood management systems, and urban heat island mitigation strategies, ensuring sustainable urban development

6.5.9Tourism:

Weather conditions significantly influence tourism activities. Forecasts help businesses and tourists plan trips, ensuring safety and optimizing experiences. Seasonal climate trends can also inform marketing strategies for tourism operators.

6.5.10 Construction: The construction industry relies on weather information for scheduling and planning projects. Adverse weather conditions can delay construction timelines, so forecasts help in planning work schedules to avoid disruptions.

6.5.11 Forestry and Fisheries: Climate data is essential for managing forests and fisheries. In forestry, understanding climate patterns helps in forest management and wildfire prevention. For fisheries, climate information assists in predicting fish migration patterns and optimizing fishing efforts.

6.5.12 Finance and Investment: Financial markets and investment strategies can be influenced by weather patterns and climate risks. Investors may use climate forecasts to assess risks associated with sectors like agriculture, real estate, and insurance.

6.5.13. Food Security: Beyond agriculture, broader food security initiatives rely on climate data to ensure stable food supplies. Understanding climate impacts on supply chains helps in strategic planning to address potential food shortages.