MODULE 2:
CLIMATOLOGY

BANGLADESH METEOROLOGICAL DEPARTMENT
LOCAL TRAINING

Project: Strengthening Meteorological Information Service and Early Warning System (Component A)

Prepared by:
Grant Thornton Consulting Bangladesh Ltd.

AIMS AND OBJECTIVES:

- Participants can identify the difference between climate and weather.
- They can demonstrate critical and analytical skills to interpret and predict weather systems using weather products (model results, maps, satellite imagery, etc.).
- Participants can demonstrate knowledge of the climate weather of Bangladesh.
- They can describe the different types of climate on earth and history of climatology.
- Participants can demonstrate skills for communicating their technical knowledge.

DELIVERY AND DESCRIPTION:

Methodology:

This module is designed in such a way that the participants get explicit idea regarding the Climatology and its terms and concepts. Besides, we also wish that the participants will be enhance their official works. To achieve this objective, we have made the sessions based on the most important topics of Climatology that are used in everyday life.

Key learning outcomes:

By the end of the course, delegates will have a knowledge and understanding of:

- Interpret, describe and explain the relationships between large-scale ocean-atmosphere processes and regional and global climates, using simple statistical techniques.
- Use an understanding of atmospheric processes to elucidate the practice of weather prediction.
- Analyse and interpret climate data to evaluate past, present and future climate variability and change.
- Demonstrate an awareness of the difficulties involved in the detection of any unusual global warming 'signal' above the 'background noise' of natural variability in the Earth's climate and of attributing (in whole or in part) any such signal to human activity
- Interpret, describe and explain the interactions between the atmosphere, ocean, cryosphere and land in the Earth's climate system.

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SESSION 1: PHYSICAL CLIMATOLOGY

1.1 Climatology

Climatology, or climate science is the study of the Earth's long-term average of weather patterns. The climate systems cause from the ocean oscillations to trade winds, pressure systems that drives temperature, airborne particles that influence local conditions and even the phases of the moon and Earth's wobble. The word "climatology" comes from the Greek word Klima which means "zone" or "area" and "logia" means "study".

Therefore, climatology is the "study of long-term weather pattern of a specific zone or area of the earth. Earth's climate system is the complex, interactive system consisting of the atmosphere, hydrosphere, cry sphere, lithosphere and biosphere. So, the study of Climatology is a complicated science. Climate science investigates the structure and dynamics of earth's climate system. It seeks to understand how global, regional and local climates are maintained as well as the processes by which they change over time. In doing so, it employs observations and theory from a variety of domains, including meteorology, oceanography, physics, chemistry and more. These resources also inform the development of computer models of the climate system, which are a core of climate research today.

1.2 Climate and Weather

Climatology is not meteorology; both concern weather patterns and their causes and effects but differ in many ways although they will be interested in each other's data. Climate science examines long-term patterns of weather trends, whereas meteorologists examine short-term weather patterns and their impact. Climatologists study the trend of temperature change, water and ice levels, cloud cover, flood and drought patterns, and their impacts on region and global level for long period of time. Meteorology is what the weather is doing now whereas climatology is what we expect to see. Therefore, Meteorology is short-term effects and results, climatology is long-term consequences. Even climatologist and meteorologists have been using same equipment's but in different ways. For example, Satellites are used in meteorology to track weather systems and to monitor atmospheric fronts to predict what the weather will do next. Climatologists use different data sets from satellites - temperatures at various levels through the atmosphere and at ground level, for example, or mapping energy flows and noticing changes that could affect local climate.

1.3 History of Climatology

The Ancient Past to the Modern Age

Many of the ancient precursors to modern science lived in Ancient Greece, Ancient Rome, and the Islamic Middle East. Two names that come up repeatedly are Aristotle and Theophrastus; the latter was a pupil of the former and made note of some strange climatic phenomena. He was a known early ecologist, noting how changes to a local climate could change some aspects of how it functioned such as how draining swamps brought the temperature down and how a tree existed in a landscape, its profile, was largely determined by the climate in which it lived - plants thrive when living in a "favorable place".

Dawn of The Industrial Revolution

The history of climate science/climatology mainly is the history of ecology and also the history of paleoclimatology. These areas are intrinsically linking in many ways. Particularly, the idea that a climate could change quite dramatically as for example , desert revealed as once being a tropical swamp, the Arctic circle being more like lush tundra than fields of ice, the retreat of sea levels and ice demonstrated quite clearly how the landscape can change dramatically. Ice Age Theory developed through limited evidence as research headed into the 19th century and towards the Industrial Revolution.

Yet it remained, until the 20th century, a sub discipline of meteorology, It was during the height of the Industrial Revolution that chemists identified the greenhouse gases. Many of these were being pumped out by the thousands of tons each year, with the warming effects of CO_2 emissions identified early on. At the time, it was still linked to studying ancient changes to the planet including Jean-Pierre Perraudin who posited that mountain valleys and the boulders within them were created by ancient glaciers. Initially mocked for such a suggestion, his theory soon gained traction.

The Later 19th Century

Still, climate science remained a small section of meteorology but in 1896 came the first breakthrough into understanding anthropogenic climate change. It all began a few years earlier when American scientist Samuel Pierpoint Langley tried to work out the surface temperature of the moon. He noted lower infrared absorption when the moon was low. Those measurements and others were then used to work out the level of cooling resulting from a lower CO_2 level, that that would lead to lower water vapor, more cooling, and more snow and ice coverage. The idea of global cooling based on lower CO_2 levels didn't require much of a leap to presume the opposite could also be true.

In 1896, the first paper was published attempting to explain and discover sources of increased atmospheric CO_2. Volcanoes were an obvious choice, but researchers knew the chemical composition of the coal being burned all over the developed world during the industrial revolution and knew that a byproduct of that burning was CO_2. This was the breakthrough that the young science of climatology had been waiting for. However, because emissions were relatively low, it was not seen as a negative thing to take thousands of years- and would not until the turn of the century. Early scientists saw it as a good thing but that was without the understanding of the impacts on ecology, biodiversity, the food cycle, sea levels, and long-term weather patterns.

Early 20th Century

The evidence for paleoclimate stacked up as the major area of focus for climate science. Studies in clay deposits across the globe showed climate cycles; the evidence for a non-static climate was building. Researchers in the 1920s and 1930s came up with the theory that the oceans could be a carbon sink. Later decades would prove this right, but few understood the implications at the time. Around 1920, it was discovered that the "Solar Constant" was not true; the idea that climate could change through natural means was finally beginning to take shape. In line with evidence from the last century based on the fossil record (Paleobotany, Paleoclimate data and the anomalies of discovering marine remains in desert) demonstrated finally that planetary systems were not constant, that they were always subject to change - our planet, as a living system, had undergone both gradual and catastrophic change and would likely do so again. That would take researchers after the war years to examine, using new techniques and technologies, to finally record and analyze data produced during the modern industrial era.

The 1960s and 1970s

In the 1960s, researchers began looking at the climate and ecology through the lens of humanity's actions. The publication of Rachel Carson's *Silent Spring* led to the banning of some toxic chemicals, the birth of ecology and research into how and to what extent humanity's actions in industries and every-day life impacted the climate. Many competing theories sprang up. Amongst them was the idea that we were creating a new Ice Age - Global Cooling was posited and then dismissed and despite claims from modern critics of climate science, it never gained traction and remained a fringe theory for its brief life. This is also the decade of the Greenhouse Effect and the discovery of multiple ice ages - including small and brief instances lasting anything from a few hundred to a couple of thousand years. It is not difficult to see why some early researchers believed in Global Cooling as a very real threat, something that the media ran away with but never lasted in academic literature. There was a slight cooling between 1945 and 1975 that may have fueled this briefly.

The 1980s to the Turn of the Millennium

By now, climatology was firmly in the ranks of anthropogenic causes of modern fluctuations in the climate. It was, and is, still concerned with the natural changes and many researchers today still examine this aspect of climatology but typically the evidence from this source is produced to demonstrate human activity and use it as a mitigating factor. The 1980s was a turning point in many ways. It saw critical reductions in aerial pollution, the phasing out (in many countries) of leaded fuel in our vehicles (and its eventual ban in 1996), similarly with CFCs which were damaging the ozone layer, climate change data consensus. It was also clear that the mitigating factor of carbon emissions reducing the amount of global warming (sometimes known as global dimming) were never going to be enough to mitigate the heating effect of the greenhouse's gases. Consensus only escalated and today, 97% of research data suggests an almost certain correlation between human activity and the present warming.

The IPCC (Intergovernmental Panel on Climate Change) was founded in 1988 under the direction of the United Nations and World Meteorological Association at the request of its most senior members. Their role is to assess climate change data as it comes to light and to make proposals to the UN and its member bodies on what to do to face down the challenges of a warming world. It was in the final decade of the millennium that climate science finally broke out of its niche within the Earth Sciences and began forming bonds elsewhere - anthropology, archaeology, geology, and even economics and business, as the changes required to mitigate our warming world would create a fundamental global economic shift.

The 21st Century

This millennium is just a couple of decades old, but climatology has come a long way in that time. Since the turn of the Millennium, few scientific issues have become so popular as a matter of public discourse as climate change. The arrival of big data analytics has helped to further the collection, collation and analysis of data sets, making it far easier and faster than ever before to produce accurate results based on land temperature, sea temperature, and at various points in the atmosphere. It is also helping scientists all over the world make decisions and present accurate data to decision makers in government. Big data analytics also allows scientists to process disparate data sets without intense labor. One of the results of this is the understanding of the subtle nuances that exist between natural forcings (such as solar activity and volcanoes) and human-induced climate change such as greenhouse gas emissions.

1.4 The Future Challenges for Climatology

Many challenges associated with climate change are challenges for ecologists, conservationists, and for politicians and other decision-makers to solve, not necessarily for climate researchers. But climatology does have an exciting future of new discoveries and new technologies; it also has some new challenges to rise to as we head deeper into the 21st century.

Subdivisions of Climatology

Climatology in its modern form is less than a century old, but already a number of subdivisions have grown up within the discipline to cope with the data and to create niches for experts to specialize.

Applied Climatology

As with applied chemistry, applied physics and so on, applied climatology is about studying what is actually happening now rather than climate theory of what will happen, or the use of theoretical models to predict events in the short or long-term future . This means that applied climatology has much in common with some of the other atmospheric sciences such as meteorology. Climate events that are happening now have immediate and measurable impacts on weather systems - locally and far away.

Bioclimatology

Overlapping with ecology in many ways, bioclimatology is the study of climate change (both natural and anthropogenic) on various life forms and ecological systems. Mostly, bioclimatology researchers are concerned with the human impact on ecology and biodiversity, but they study any landscape change resulting from climate change. Some researchers will also overlap with medical research.

Boundary-Layer Climatology

The Boundary Layer is the lowest level of the atmosphere, the area most affected by local and planetary climate change. This is the atmospheric layer that experiences the most turbulence and holds the important weather systems, interacting with the "thermals", distributing air and moisture across the planet. Therefore, boundary layer climatologists study the networks and interactions of the lower atmosphere, and their impact on weather and climate systems, but also how the network of winds are affected by such climate phenomena as rising air and sea temperatures, urban heat islands, and natural events such as volcanic activity. It also has critical uses for immediate weather patterns in meteorology. Neither boundary-layer climatology nor meteorology exist in isolation and are intrinsically linked.

Dynamic Climatology

Dynamic climatologists are concerned with examining the accumulated sum total of information acquired from all related sciences, typically quantitative in nature, based on observed phenomena. Dynamic climatology examines and handles everything from paleo data to volcanic eruption to looking at short range or short-term weather patterns to long-term climate effects from natural or anthropogenic causes. This area of climatology uses a holistic approach.

Historical Climatology

Historical climatology is concerned with climate change, alteration and patterns that have existed on the human measurement scale. It blends climatology with environmental history and sometimes, can complement research in the human Earth sciences such as anthropology, archaeology and human geography. It seeks to recreate or profile past environments, examining past natural disasters and their effects. It can also examine the human impact on the environment and the after-effects of such human activities as land clearance for agriculture.

Hydro climatology

How do the natural and anthropogenic changes to the climate affect our waterways? Increased drought and flooding, ocean acidification, coral bleaching, the effects of ocean temperature and pH of our oceans affect how much plankton is produced in any cycle. In turn, this affects the ocean lifecycle. Hydro climatology is a vitally important area of climatology because around 2/3 of our planet is covered in ocean. It's a vast, complex and vital ecosystem. Sea level rises, ice cap melt, ocean particles, the oceans as a carbon sink, precipitation and drought all contribute to something called the "Water Budget" and it is this that hydro climatologists spend most of their time analyzing.

Paleoclimatology

Historical climatology covers the historical record - starting with the invention of instruments able to take measurements while paleoclimatology is concerned with the entire history of the planet's climate record. Typical data sets include taking radiocarbon dates and chemical signatures as ecological indicators from such areas as tree rings - also known as dendrochronology - Antarctic and Arctic ice cores, information from fossilized coral and vegetation, and lake and river sediments. It is through this area that we know the Earth has always changed; it is how we know that Earth has undergone at least five ice ages, the Medieval Warm Period and Little Ice Age, and, when comparing ecological data and fossils, how we know the effects that high or low atmospheric carbon will have on the climate. It has also been integral to demonstrating how quickly a climate can change - with a catastrophe or massive climatic event, sometimes within a matter of decades.

Physical Climatology

Most of climatology is concerned with looking at data and making projections or presenting the data as facts, statistics, graphs and hard figures - it is quantitative in nature. Physical climatology is more qualitative. It examines and explains how climate can shape topography and geographical systems. For example, it seeks to explain how glaciation is one factor capable of forming valleys and mountains, how extreme flooding events will change a landscape.

Synoptic Climatology

This branch of climatology is concerned with circulation patterns within the atmosphere, paying particular attention to how these circulations create differences in climate between either topographically comparable or geographically close locations. It creates categories of synoptic climate patterns and then attempts to discern what a climate is going to look like in the immediate future based on season weather patterns and anomalous phenomena. Typically, they may be concerned with the weather patterns that create hurricanes and tornadoes.

1.5 Natural Variables That Influence Our Climate

Much of the discussion of climatology in public discourse concerns anthropogenic climate change - the contribution of human activity to such events as carbon particles, greenhouse gases, and their effects such as the Greenhouse Effect and coral bleaching. But climatology is not just about the human impact, it is about looking at, and predicting the effects of the natural processes on our planet and the Solar System. It is to long-term trends and large-scale processes to which we direct our efforts in understanding why the climate looks or acts the way it does, and what variations and anomalies can potentially change it. Some of the natural trends are:

El Niño and La Niña Oscillation

Perhaps the two best-known oscillations are El Niño and La Niña. El-Nino refers to the extensive warming of central and eastern tropical Pacific that leads to a major shifting in weather patterns across the Pacific Ocean. During El Nino trade winds (easterlies) decrease in strength. El Niño typically arrives between June and December in a given year and takes place with the depletion and failure of replacement of the Pacific Trade Winds following the Pacific monsoon season. The warm air then creates this oscillation and the waters become warmer.

La Nina is the extensive cooling of the central and eastern tropical Pacific Ocean, often accompanied by warmer than normal sea surface temperatures in western Pacific and to the north of Australia. La Niña occurs when the situation is reversed of El Nino and it usually follows El Niño within a year. During La Nina trade winds are stronger than normal, moving warm water westward across the Pacific. The east of the ocean is colder than normal while the west is warmer than average, but the effects don't just affect the Pacific, they are global.

The southern oscillation is the atmospheric component of El Nino. This component is an oscillation in surface air pressure between the tropical eastern and western Pacific Ocean waters. Southern oscillation is measured by Southern Oscillation Index (SOI). SOI is calculated by the pressure differences between Tahiti and Darwin. El Nino and La Nina episodes occur roughly once every seven years, and the latter always follows the former after a few months. They are usually predictable, but the increasing effects of climate change can sometimes push them back to a little later. El Nino and Southern Oscillation are known as ENSO.

Madden-Julian Oscillation

Not as well-known as ENSO, the Madden-Julian Oscillation (MJO), it functions differently. While ENSO is static, occurring in one place due to the causes that create those conditions, MJO moves across a geographical area - eastwards along the tropics, bringing higher levels of cloud, increased precipitation and therefore the risk of rainfall. It returns to its starting position anything between one and two months after it began. It can be tracked and was only identified in the 1970s. There may be multiple events in a single place since it moves. It also experiences variable speed, creating conditions ahead, during, and behind it. With each event, there is an increased rainfall event and a suppressed rainfall event.

North Atlantic Oscillation:

The North Atlantic Oscillation (or the NAO) occurs in the northern area of the Atlantic Ocean, the second largest ocean on our planet. It describes fluctuations between the sea level atmospheric pressure from the areas known as the Azores High and the Icelandic Low although these are not set in stone. When the waters fluctuate between these two points, the westerly winds direction and strength change. In turn, this also affects the strength, frequency and direction of Atlantic storms. It has been known since the 19th century, and unlike some of the others discussed in this section, it is mostly atmospheric, affected and part of the Arctic Oscillations.

It is a natural oscillation and can massively impact the continents on either side of it - North America and Europe. When one side has certain conditions, the other side has opposite conditions. It will also affect the North Atlantic Jet Stream which keeps Western Europe and North America temperate compared to adjacent areas.

Positive NAOis when warm westerly winds dominate the North Atlantic, bringing warm air from the southern US coastal states northeast towards northwestern Europe. The British Isles, for example, tend to experience warm but wet weather. However, this direction means colder weather in the northern coastal states and Canada on the Atlantic side and southwestern Europe.

Negative NAOalso carries weather fronts from North America to Western Europe but in this case, the southern US states experience cold and snowy weather conditions while their northern counterparts experience warmer weather. In Europe, Scandinavia tends to be cold but dry while the Mediterranean Basin is warmer and wetter.

Other Natural Climate Drivers

Solar Activity

At the center of our solar system is a star that we call “The Sun”. The sun receives a constant stream of energy produced by nuclear processes that generate an immense amount of heat, light, and radiation. This radiation hits the atmosphere and is absorbed by the ozone layer which reduces the most harmful radiation. The resulting heat and ultraviolet rays that do make it to the surface enable all life on the planet from the plants that use the chemical processes to reproduce through photosynthesis which, in turn, feeds animals. But the sun's energy is not constant. The temperature and therefore the heat levels fluctuate and that can have a knock-on effect for the Earth.

Volcanoes

Large-scale volcanic activity may last only a few days, but the massive outpouring of gases and ash can influence climate patterns for years. Sulfuric gases convert to sulfate aerosols, sub-micron droplets containing about 75 percent sulfuric acid. Following eruptions, these aerosol particles can linger as long as three to four years in the stratosphere.

Major eruptions alter the Earth's radiative balance because volcanic aerosol clouds absorb terrestrial radiation and scatter a significant amount of the incoming solar radiation, an effect known as "radiative forcing" that can last from two to three years following a volcanic eruption.

Earthquake

The geological foundations on which structures are built can have a significant impact on earthquake shaking. When an earthquake happens, the seismic waves produced have a wide range of frequencies. The energy of the higher frequency waves tends to be absorbed by solid rock, while the lower frequency waves (with periods slower than one second) pass through the solid rock without being absorbed but are eventually absorbed and amplified by soft sediments. It is therefore very common to see much worse earthquake damage in areas underlain by soft sediments than in areas of solid rock. A good example of this is in the Oakland area near San Francisco, where parts of a two-layer highway built on soft sediments collapsed during the 1989 Loma Prieta earthquake.

SESSION 2: CLIMATE OF BANGLADESH

2.1 Geography of Bangladesh

Bangladesh is densely populated, low-lying, mainly riverine country located in South Asia with a coastline of about 720km on the northern littoral of the Bay of Bengal. The delta plain of the Ganges (Padma), Brahmaputra (Jamuna) , Meghna Rivers and their tributaries occupy 79 percent of the country. Four uplifted blocks (including the Madhupur and Barind Tracts in the center and northwest) occupy 9 percent, and steep hill ranges up to approximately 1,000 meters (3,300 ft) high occupy 12 percent in the southeast (the Chittagong hill Tracts) and in the Northeast. Standing the Tropic of Cancer, Bangladesh has a tropical monsoon climate characterized by heavy seasonal rainfall, high temperature, and high humidity. Natural disasters such as floods and cyclone accompanied by storm surges periodically affect the country. Most of the country is intensively farmed, with rice the main crop, grown in three seasons.

Climate of Bangladesh

Bangladesh has a subtropical monsoon climate characterized by heavy seasonal rainfall, high temperature, and high humidity. Natural disasters such as floods and cyclone accompanied by storm surges periodically affect the country. Most of the country is intensively farmed, with rice the main crop, grown in three seasons. The climate of Bangladesh is subtropical in the center-north and tropical in the south, with a pleasantly warm and sunny winter from November to February, a short hot spring between March and May, and a long rainy season from June to October due to the summer monsoon. The country is flat and occupied by the huge Ganges-Brahmaputra Delta, and it's therefore exposed to floods as well as to storm surges when cyclones hit the Bay of Bengal.

Tropical monsoon climate of Bangladesh

Heavy rainfall is characteristic of Bangladesh causing it to flood every year. Except for the relatively dry western region of Rajshahi, where the annual rainfall is about 1,600 mm (63.0 in), most parts of the country receive at least 2,300 mm (90.6 in) of rainfall per year. Because of its location just south of the foothills of the Himalayas, where monsoon winds turn west and northwest, the region of Sylhet in northeastern Bangladesh receives the greatest average precipitation. From 1977 to 1986, annual rainfall in that region ranged between 3,280 and 4,780 mm (129.1 and 188.2 in) per year. Average daily humidity ranged from March lows of between 55 and 81% to July highs of between 94 and 100%, based on readings taken at selected stations nationwide in 1986.

About 80% of Bangladesh's rain falls during the monsoon season. The monsoons result from the contrasts between low and high air pressure areas that result from differential heating of land and water. During the hot months of April and May hot air rises over the Indian subcontinent, creating low-pressure areas into which rush cooler, moisture-bearing winds from the Indian Ocean. This is the southwest monsoon, commencing in June and usually lasting through September. Dividing against the Indian landmass, the monsoon flows in two branches, one of which strikes western India. The other travels up the Bay of Bengal and over eastern India and Bangladesh, crossing the plain to the north and northeast before being turned to the west and northwest by the foothills of the Himalayas.

Natural calamities, such as floods, tropical cyclones, tornadoes, and tidal bores—destructive waves or floods caused by flood tides rushing up estuaries—ravage the country, particularly the coastal belt, almost every year. Between 1947 and 1988, 13 severe cyclones hit Bangladesh, causing enormous loss of life and property. After 1988 18 cyclonic storms of different intensities crossed the coast of Bangladesh, causing huge amount of damages. Among these cyclones severe cyclonic storm with a core of hurricane wind of 1991, 1994, 1997 & 1998, Sidr (2009), Aila (2009), Mahasen (2013), Komen (2015), Roanu (2016), Mora (2017) and Fani & Bulbul (2019) were significant.

Environmental concerns

Natural hazards: Much of the country is submerged by floodwater in the monsoon season (and traditional settlements and agriculture are adapted to this); damaging floods occur when rivers rise higher than normal; tropical cyclones (hurricanes) and storm surges; droughts; riverbank erosion along the country's major rivers and in the Meghna estuary; earthquakes; possibly tsunamis.

2.2 Seasonal variation

2.2.1 Temperatures

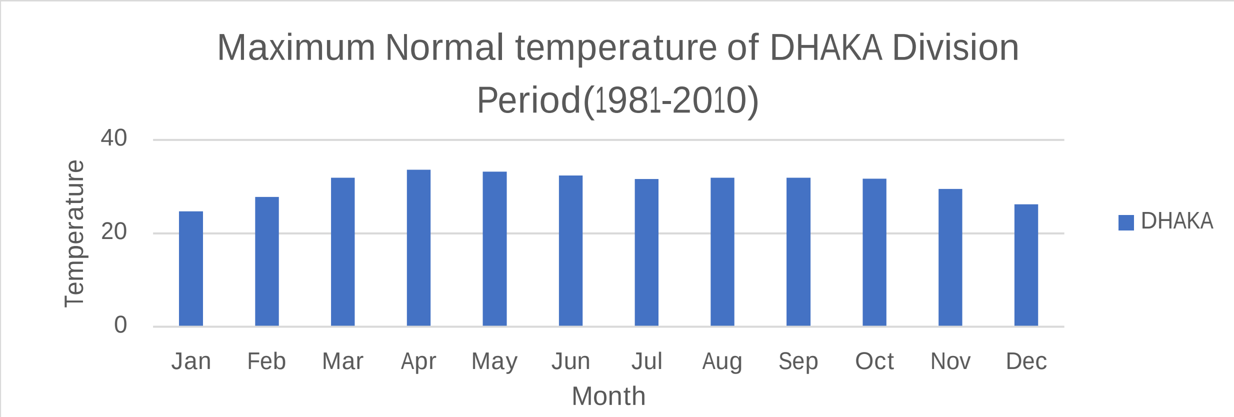
The dry season runs from November to February. The monsoon has left the country during the month of October, but the rains can sometimes last until November, especially in the south-east, or when a cyclone arrives. In general, from November temperature starts to fall gradually.

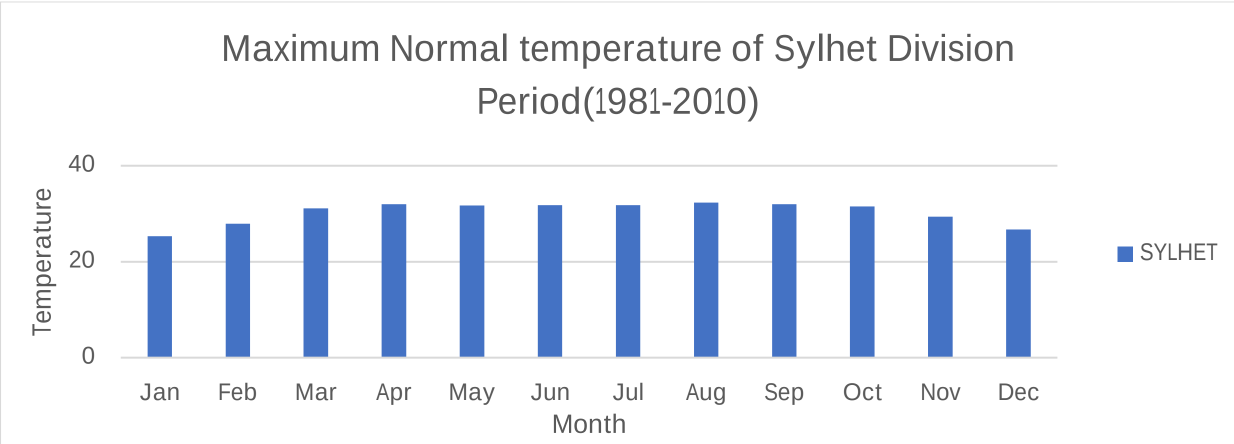
The actual winter begins in December and is characterized by sunny days, followed by cool nights. Lowest minimum temperature of winter usually finds during the month of January and February in the northwest and northeastern part of the country.

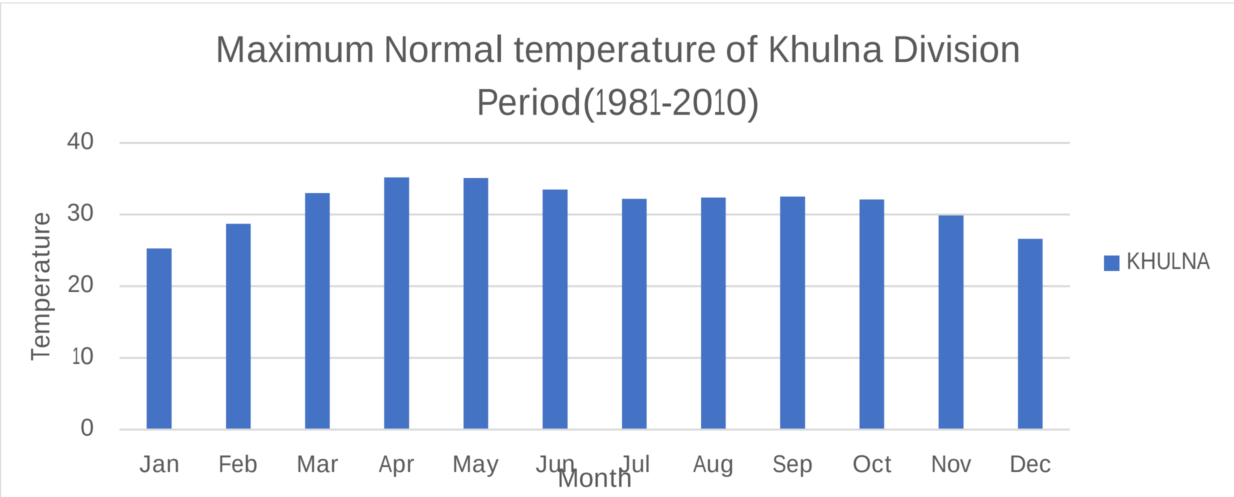
Divisional Monthly Normal Maximum Temperature (°C) of Bangladesh

Division	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
DHAKA	24.7	27.8	31.9	33.6	33.2	32.4	31.6	31.9	31.9	31.7	29.5	26.2
SYLHET	25.3	27.9	31.1	32	31.7	31.8	31.8	32.3	32	31.5	29.4	26.7
RAJSHAHI	24.3	27.7	32.4	34.9	34.3	33.4	32.2	32.5	32.3	31.7	29.6	26.1
RANGPUR	23.1	26.4	30.7	32.3	32.3	32.3	31.9	32.3	31.7	30.9	28.7	25.2
KHULNA	25.3	28.7	33	35.2	35.1	33.5	32.2	32.4	32.5	32.1	29.9	26.6
BARISAL	25.7	28.6	32	33.2	33.1	31.7	30.9	31.1	31.4	31.6	29.7	26.8
CHILLAGONG	25.9	28.4	31.2	32.4	32.5	31.4	30.6	31.1	31.5	31.6	29.9	27
Country Average	24.9	27.9	31.8	33.4	33.2	32.4	31.6	31.9	31.9	31.6	29.5	26.4

Graphical presentation of divisional normal maximum temperature



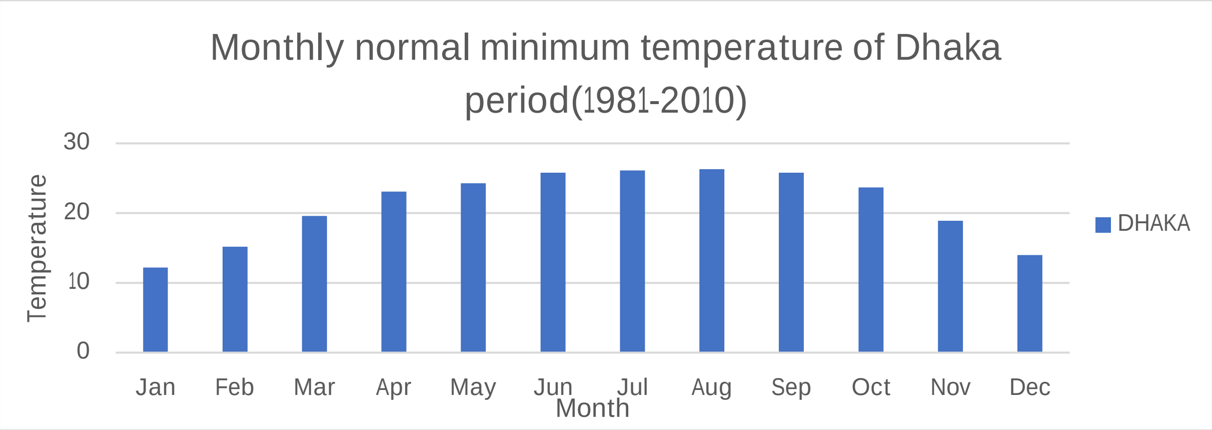


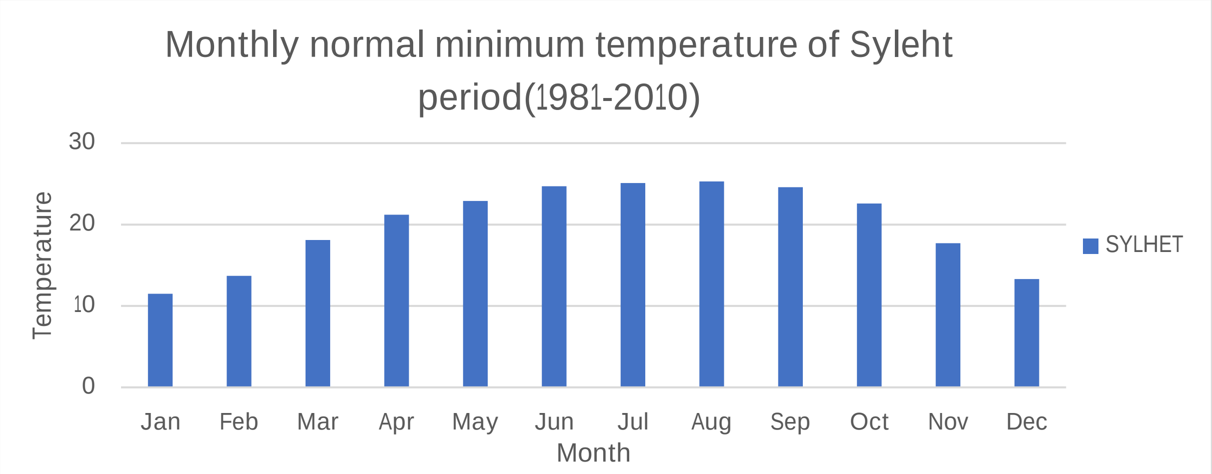


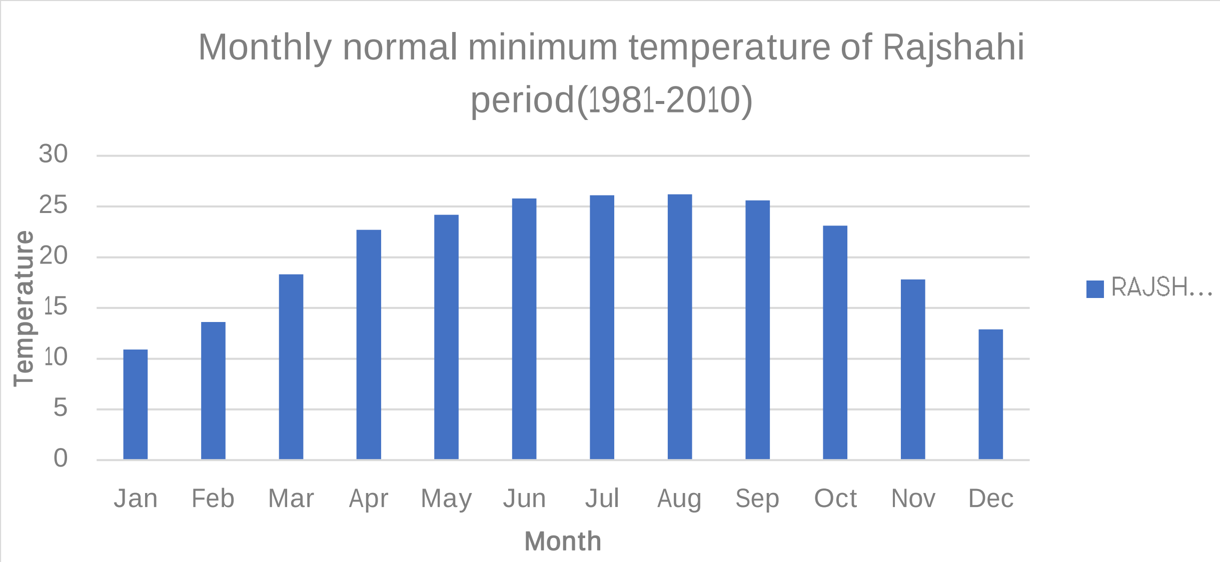
Divisional Monthly Normal Minimum Temperature (°C) of Bangladesh

Division	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
DHAKA	12.2	15.2	19.6	23.1	24.3	25.8	26.1	26.3	25.8	23.7	18.9	14
SYLHET	11.5	13.7	18.1	21.2	22.9	24.7	25.1	25.3	24.6	22.6	17.7	13.3
RAJSHAHI	10.9	13.6	18.3	22.7	24.2	25.8	26.1	26.2	25.6	23.1	17.8	12.9
RANGPUR	10.7	13.3	17.3	21.1	23.3	25.2	25.9	26.2	25.3	22.5	17.2	12.7
KHULNA	12	15.6	20.3	24.1	25.4	26.2	26.2	26.2	25.7	23.7	18.8	13.7
BARISAL	13	16.3	21	24.2	25.3	26	25.8	25.9	25.7	24	19.6	14.6
CHILLAGONG	13.8	16.4	20.6	23.7	24.8	25.5	25.4	25.4	25.3	24.1	20	15.5
Country average	12	14.9	19.3	22.9	24.3	25.6	25.8	25.9	25.4	23.4	18.6	13.8

Graphical presentation of Divisional monthly normal minimum temperature






Monthly normal minimum temperature of Rajshahi period(1981-2010)
30
25
20
15
10
5
0
Temperature
Jan
Feb
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Month
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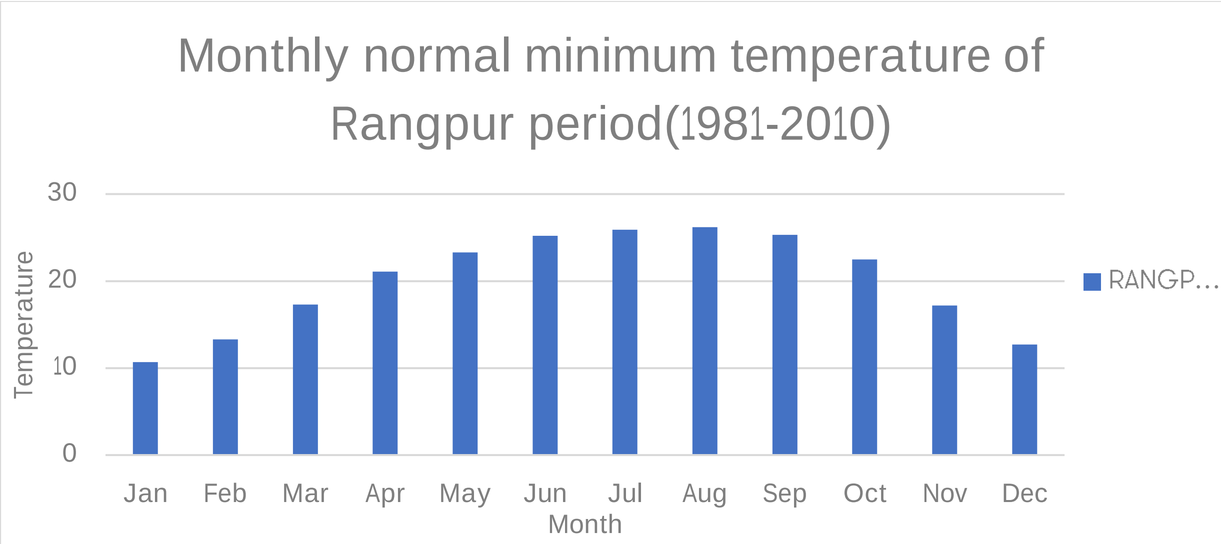
Monthly normal minimum temperature of Rangpur period(1981-2010)
30
20
10
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Temperature
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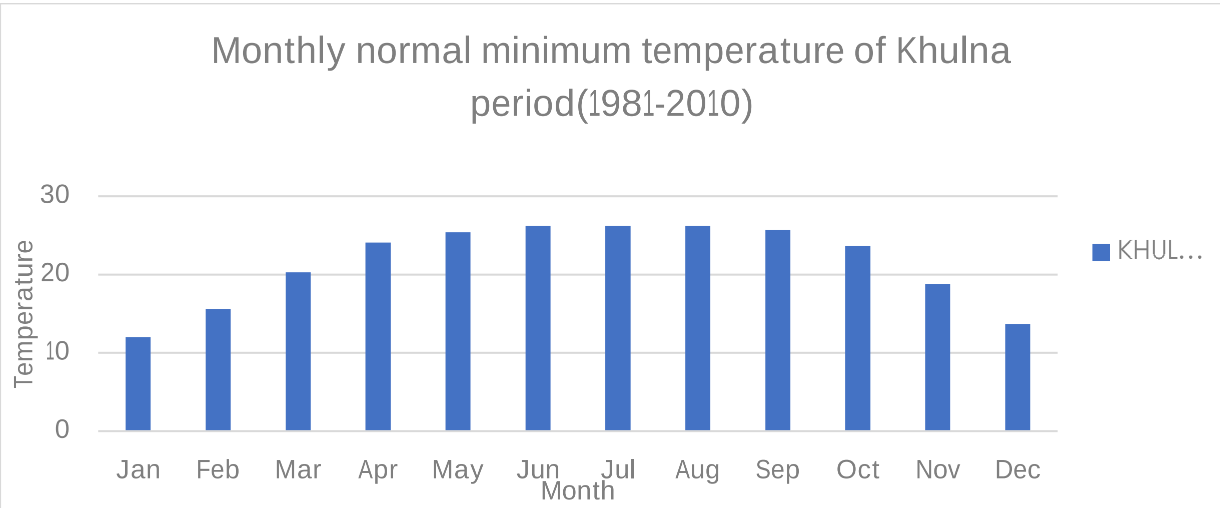
Monthly normal minimum temperature of Khulna period(1981-2010)
30
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Temperature
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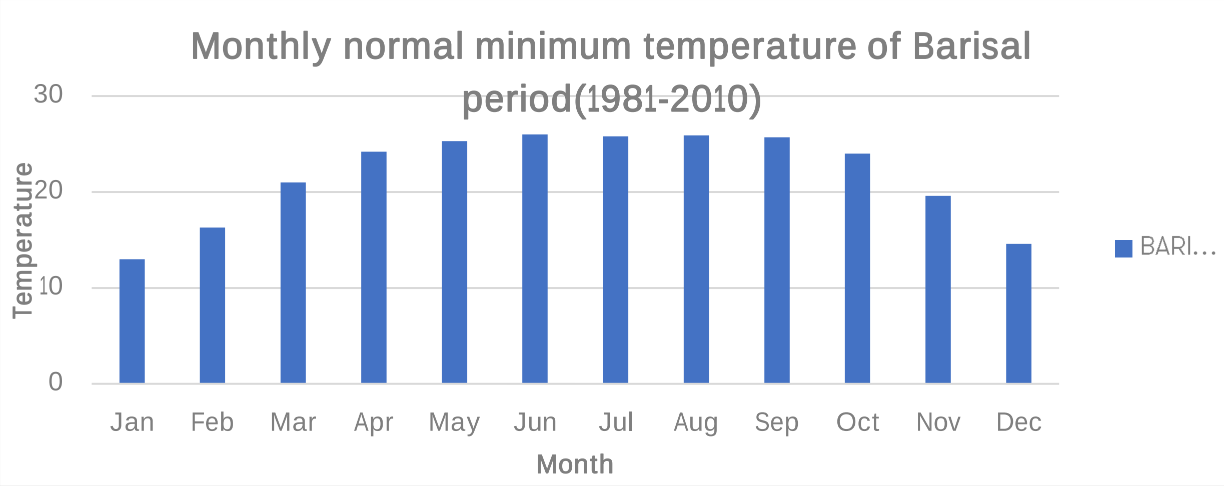
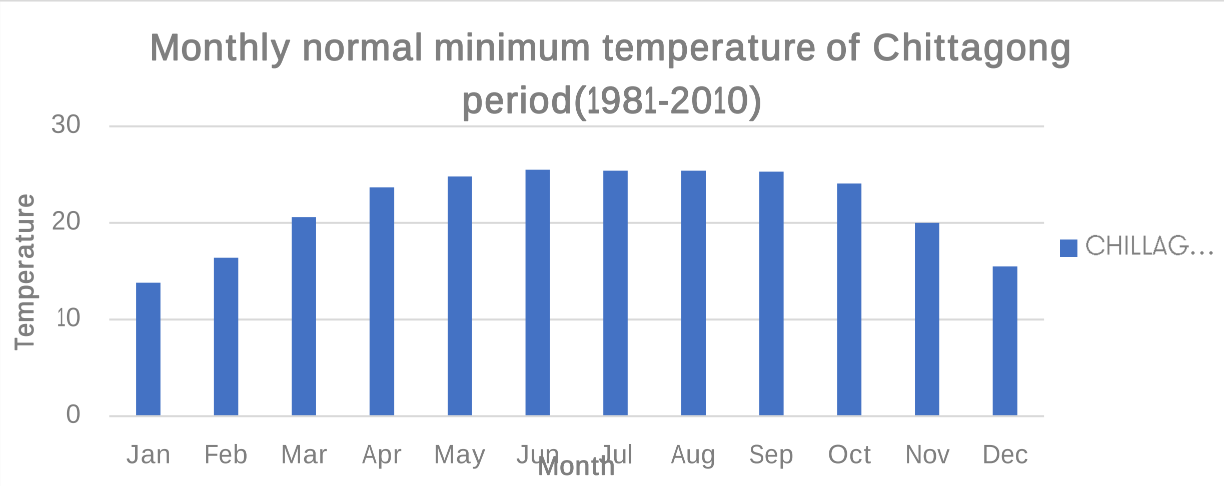




2.2.2 Rainfall

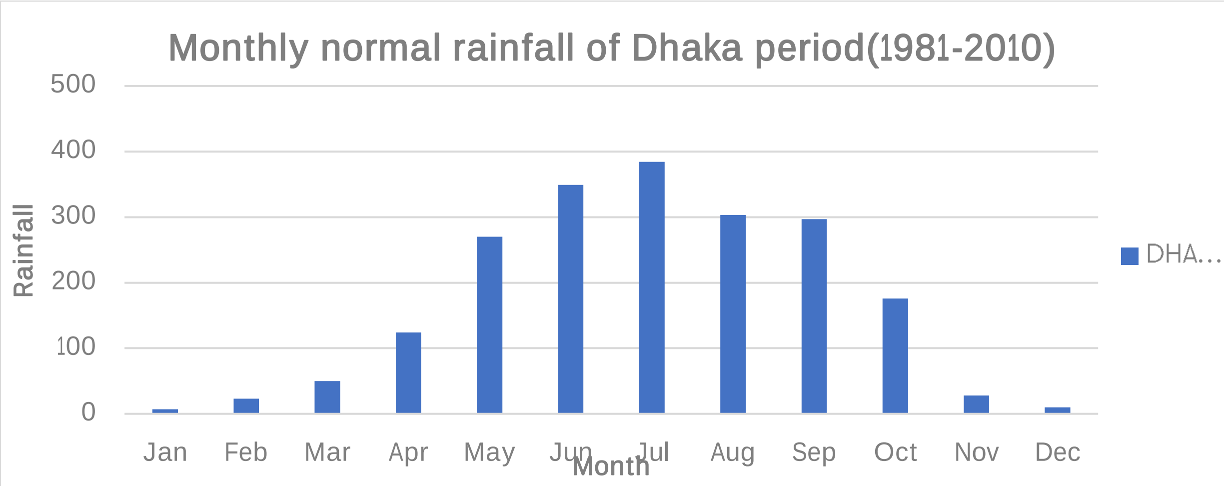
The Southwest monsoon arrives between late May and early June, starting from the south-east. It brings more compact cloudiness, high humidity even during the day, frequent rains, but also a decrease in temperature, which drops to 30/32 °C (86/90 °F) during the day, but remains high at night, about 25 °C (77 °F). The rains are more abundant along the south coast, particularly the south-eastern part and also in the north-eastern part of the country. In July, rainfall amounts toz 800 mm (31.5 in) in Sylhet, to 750 mm (29.5 in) in Chittagong, to 900 mm (35.5 in) in Cox's Bazar, and to as high as 1,000 mm (40 in) in Teknaf.

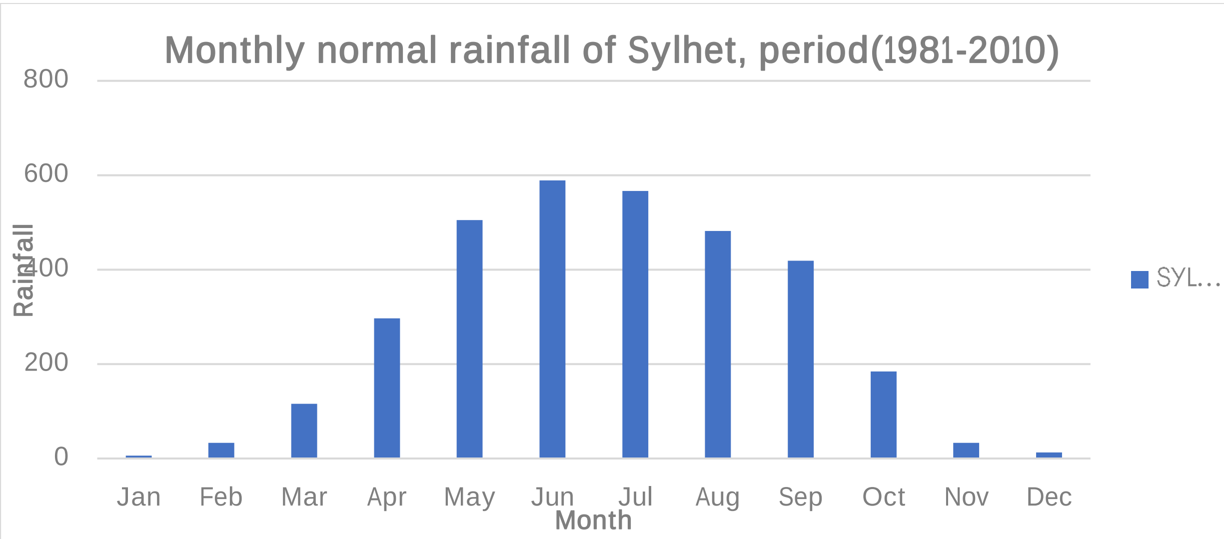
The monsoon is less intense in the west, where the annual rainfall is around 1,500/1,600 mm (60/63 in), with a maximum in July of about 300/350 mm (12/13.5 in), as happens for example in Pabna, Jessore and Rajshahi. In Dhaka, precipitation amounts to 2,100 mm (83 in) per year, of which 370 mm (14.5 in) fall in July. Here is the average precipitation in Dhaka.

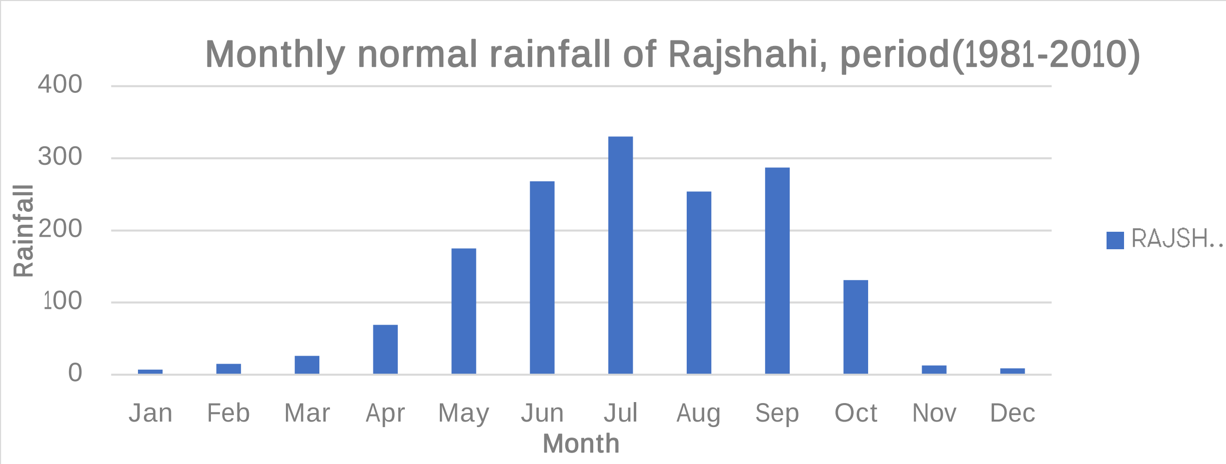
Divisional Monthly Normal Rainfall in(mm) of Bangladesh

Division	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
DHAKA	7	23	50	124	270	349	384	303	297	176	28	10
SYLHET	6	33	116	297	505	589	567	482	419	184	33	13
RAJSHAHI	7	15	26	69	175	268	330	254	287	131	13	9
RANGPUR	10	9	21	93	251	431	455	345	375	175	8	7
KHULNA	12	27	42	66	171	302	345	281	302	152	32	7
BARISAL	9	25	48	104	235	469	527	412	342	221	51	6
CHILLAGONG	6	20	53	122	326	606	728	543	350	224	56	11
Country	8	22	51	125	276	431	477	374	339	180	32	9

Graphical presentation of Divisional monthly normal minimum temperature






Monthly normal rainfall of Rajshahi, period(1981-2010)
400
300
200
100
0
Rainfall
RAJSH..
Jan
Feb
Mar
Apr
May
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Jul
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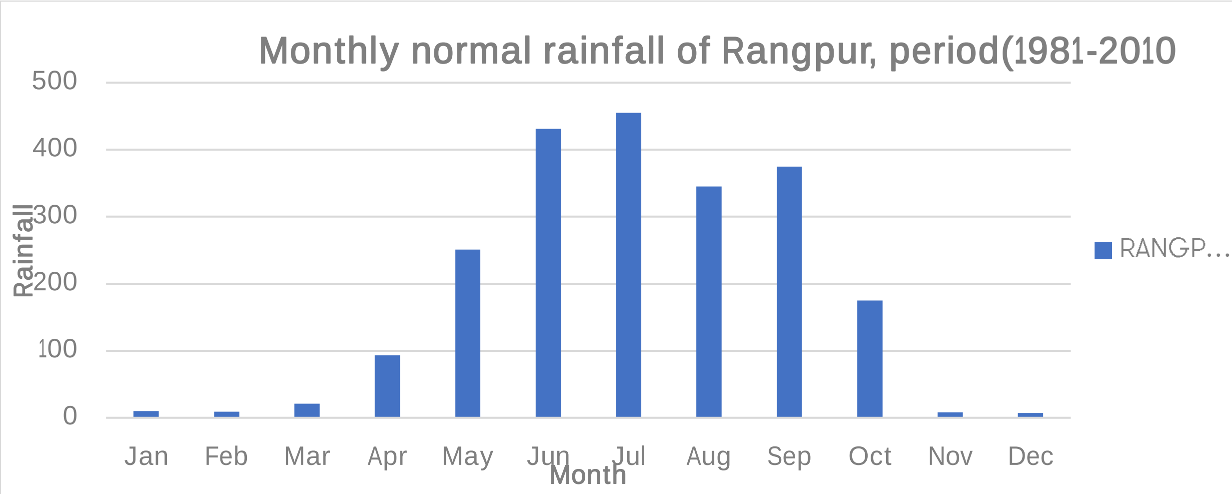
Oct
Nov
Dec
Month


Monthly normal rainfall of Rangpur, period(1981-2010
500
400
300
200
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0
Rainfall
RANGP...
Jan
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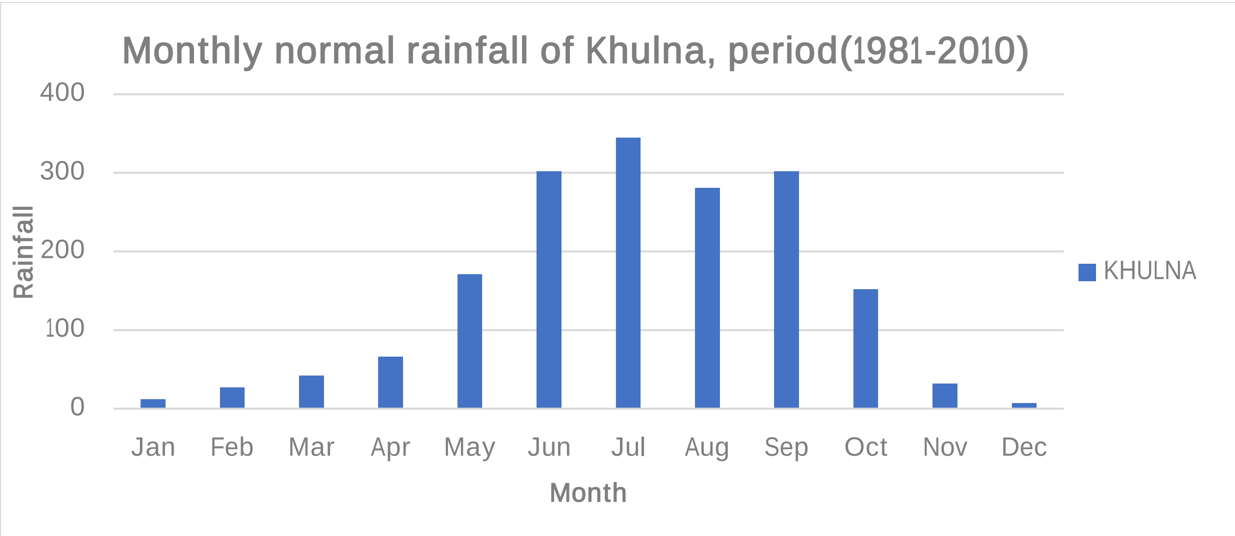
Monthly normal rainfall of Khulna, period(1981-2010)
400
300
200
100
0
Rainfall
KHULNA
Jan
Feb
Mar
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May
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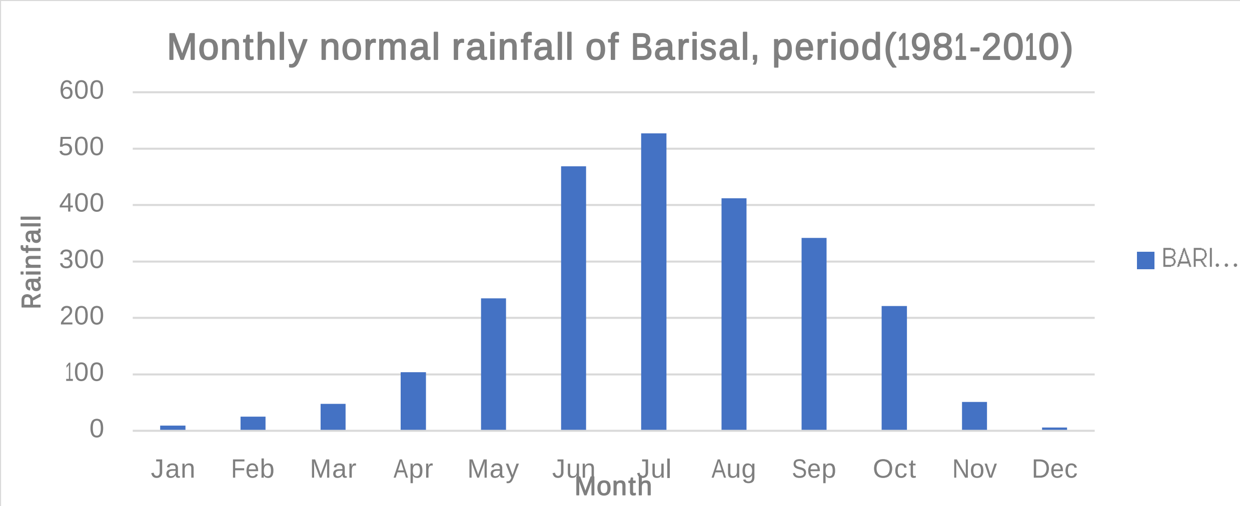
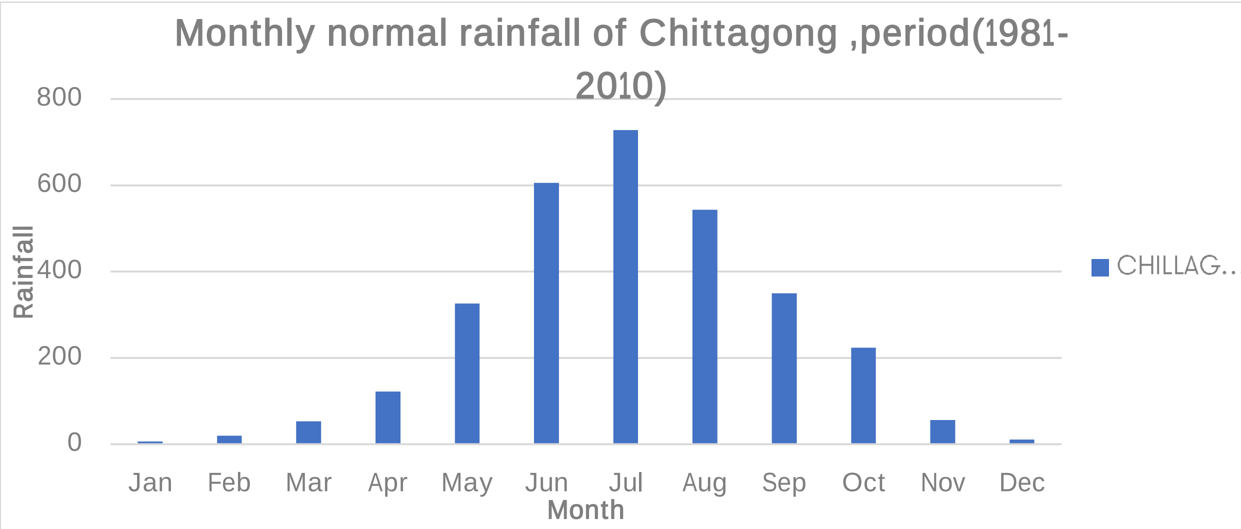




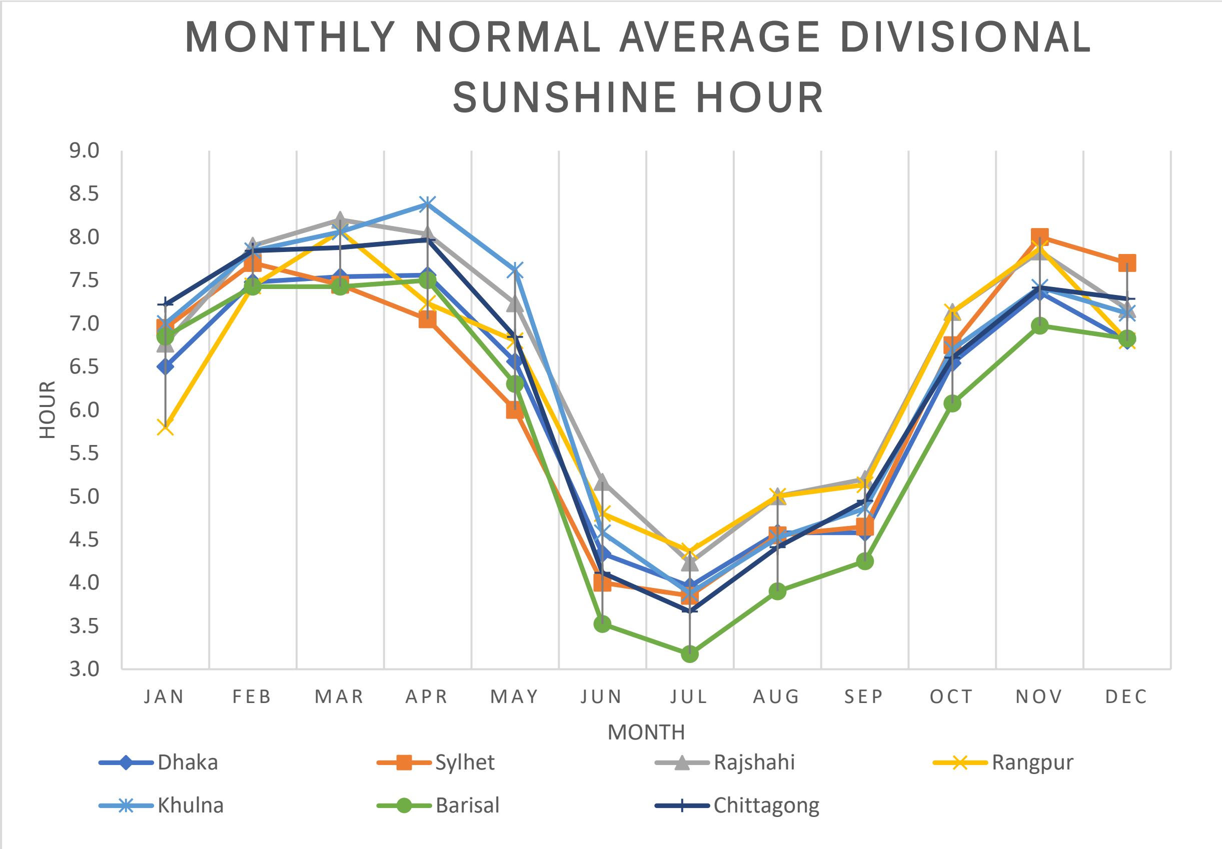
2.2.3 Sunshine Hour

The sun in Bangladesh regularly shines in the dry season, while in the monsoon season, from June to September, it is rarely seen. Here are the average daily sunshine hours in Dhaka.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
9	8	7	6	5	3	2	3	3	6	8	9

Monthly normal Divisional sunshine hour of Bangladesh

Division	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Dhaka	6.5	7.5	7.5	7.6	6.6	4.3	4.0	4.6	4.6	6.5	7.4	6.8
Sylhet	7.0	7.7	7.5	7.1	6.0	4.0	3.9	4.6	4.7	6.8	8.0	7.7
Rajshahi	6.8	7.9	8.2	8.0	7.2	5.2	4.2	5.0	5.2	7.1	7.8	7.2
Rangpur	5.8	7.4	8.1	7.2	6.8	4.8	4.4	5.0	5.1	7.1	7.9	6.8
Khulna	7.0	7.8	8.1	8.4	7.6	4.6	3.9	4.5	4.9	6.7	7.4	7.1
Barisal	6.9	7.4	7.4	7.5	6.3	3.5	3.2	3.9	4.3	6.1	7.0	6.8
Chittagong	7.2	7.8	7.9	8.0	6.8	4.1	3.7	4.4	4.9	6.6	7.4	7.3



2.3 Seasons of Bangladesh

Bangladesh is one of the largest deltaic countries in the world. It is a flat low-lying plain land made up of alluvial soil having small hilly area in the northeast and southeast regions. The great Himalayan Range is to the north and the vast Bay of Bengal is on the south. It is located between 20.57°N to 26.63°N and 88.02°E to 92.68E. It is bounded on the west, north and east by India. In the southeast there is a common border with Myanmar. There are 230 rivers in Bangladesh out of which 57 originate from outside the country and most of the rivers flow to the Bay of Bengal from north to south though Bangladesh. The main rivers are the Ganges (Padma), the Brahmaputra, and the Meghna. The coastline of Bangladesh is about 720 km long along the continental shelf which has a shallow bathymetry. The entire area of Bangladesh is about 1, 44,735 sq. km. The population of Bangladesh is about 160 millions but about 80% of them live in the rural areas. The country is exposed to meteorological, hydrological and seismic hazards. The Great Bakerganj Cyclone of 1876, the Worst Killer Cyclone of November 1970, the Urichar Cyclone of May 1985, the Killer Cyclone of April 1991, Cyclone Sidr of 2007, Cyclone Aila of 2009, floods of 1954, 1987 and 1988, the Historic Flood of 1998, flood of 2007, Demra Tornado of 1969, Manikganj Tornado of 1974, Madaripur Tornado of 1977, Saturia Tornado of 1989, Louhajong Tornado of 1995, and Tangail Tornado 1996 are few of the extreme meteorological and hydrological events. Bangladesh is located in the sub-tropical monsoon climate regime.

Traditionally Bangladeshis subdivide the year into six seasons:

- Grismo (summer)
- Barsha (rainy)
- Sharat (autumn)
- Hemanto (cool)
- Sheet (winter)
- Bashonto (spring)

2.3.1 Meteorological Seasons

A. Winter or Northeast Monsoon (December – February)

This season is characterized by very light northerly winds, mild temperature. Dry weather and clear to occasionally cloudy sky with fog over the country is the common characteristics of this season. The mean temperature is in the range of 18-22o C. During this period when the ridge of sub-continental high pressure extends up to northwestern part of Bangladesh, temperature begins to fall over Bangladesh. Sometimes minimum temperature goes below than 10°C and cold wave situation occurs over western and northern part of the country. Bangladesh Meteorological Department use different categories of cold wave for explaining this situation such as- mild cold wave (when minimum temperature lies between 8-10°C), moderate cold wave (when minimum temperature lies 6-8°C) and severe cold wave (when minimum temperature goes below than 6°C) respectively. Only 2% of the annual total rainfall occurs in this season. But the rainfall occurs in the country only when westerly low (Western Disturbance) which originates over the Mediterranean Sea and moves eastward over Middle East, Pakistan, Afghanistan, northern India and sometimes reach to Bihar, West Bengal, Bangladesh and then to Assam of India.

B. Summer or Pre-Monsoon (March - May)

The mean temperature of Bangladesh during the summer months varies between 23-30° C. April and May are the hottest months. The highest maximum temperature ranging from 36-40° C is attained in the northwestern and southwestern districts. When the maximum temperature goes above 36°C heat wave situation occurs over Bangladesh. The heat wave is classified as-mild heat wave (maximum temperature lies between 36-38°C), moderate heat wave (maximum temperature lies between 38-40°C), severe heat wave (maximum temperature greater than 40°C). Due to intense heating of the land surface heat low develops over Bihar, West Bengal of India and adjoining northwestern part of Bangladesh. Occasionally moisture incurs in the afternoon from the Bay of Bengal to that low pressure results the formation of thunder cloud and development of severe thunderstorms. These severe thunderstorms are known as Nor'westers ('Kalbaishakhi' in Bengali) that often accompanied by destructive squalls, thunder and heavy rainfall with hails. During the pre -monsoon season Nor'westers occur frequently at many places over Bangladesh. Due to heavy rainfall associated with severe thunderstorm in the northeastern part of Bangladesh and adjoining states of India flash flood occurs in the northeastern part of Bangladesh. Only19 % of the total annual rainfall occurs in this season. This season is also characterized by cyclogenesis in the Bay of Bengal. Some of the low pressure formed over the Bay of Bengal intensified into depression and sometimes turned into cyclonic storm move initially northwestwards and then recurve to northeast moves towards Bangladesh and Myanmar coasts. Some of these cyclonic storms attains into a very severe cyclonic storm and landfall to Bangladesh coast. They are occasionally associated with very high storm surges and causes of high causalities and damages. It may be mentioned here that the cyclonic storm that hit the east coast of the country on 29 April 1991.

C. Southwest Monsoon (June - September)

In this season, the surface wind changes to southwesterly/southerly direction over the southern and the central districts and to southeasterly over the northern districts of the country. Wind speed remains light to moderate. The onset and withdrawal of monsoon vary from year to year and place to place. The normal date of onset of Southwest Monsoon in the southeastern districts of the country is 2nd June which engulfs the whole country during 1st half of June. Monsoon starts withdrawal from the northwestern part of the country and the normal date of withdrawal from this part is seven days earlier or later of 30th September (Ahmed and Karmakar, 1993). Generally, rain with widespread cloud coverage and high humidity are the characteristics of this season. Due to occasional heavy to very heavy rainfall landslides occur in the hilly regions of southeastern part of the country. More than 71 % of the total annual rainfall occurs in this season. With the advance of the monsoon, the summer extreme temperatures fall appreciably throughout the country. During this season, monsoon depression forms over the Bay of Bengal. They generally move northwestwards and cross Indian coast. Some of them move towards Bangladesh coasts and caused heavy rainfall. Depressions seldom attain into cyclone state in this season. Due to the presence of southwest monsoon season almost every year flood situation occurs in Bangladesh.

D. Autumn or Post-Monsoon (October - November)

This is the transitional season from summer monsoon to the winter. Rainfall decreases considerably during October and November and the dry period starts setting over the country. Only 8% of the annual total rainfall occurs in this season. Temperature falls noticeably. But the lowest minimum does not generally fall below than 10° C throughout the country. Cyclonic disturbances form over the Bay of Bengal during this season. They move initially westward and then northwest. Sometimes they recurve northeastwards and make landfall to Bangladesh coast. Some of these cyclonic disturbances attains into very severe intensity and make landfall to Bangladesh coast along with storm surge.

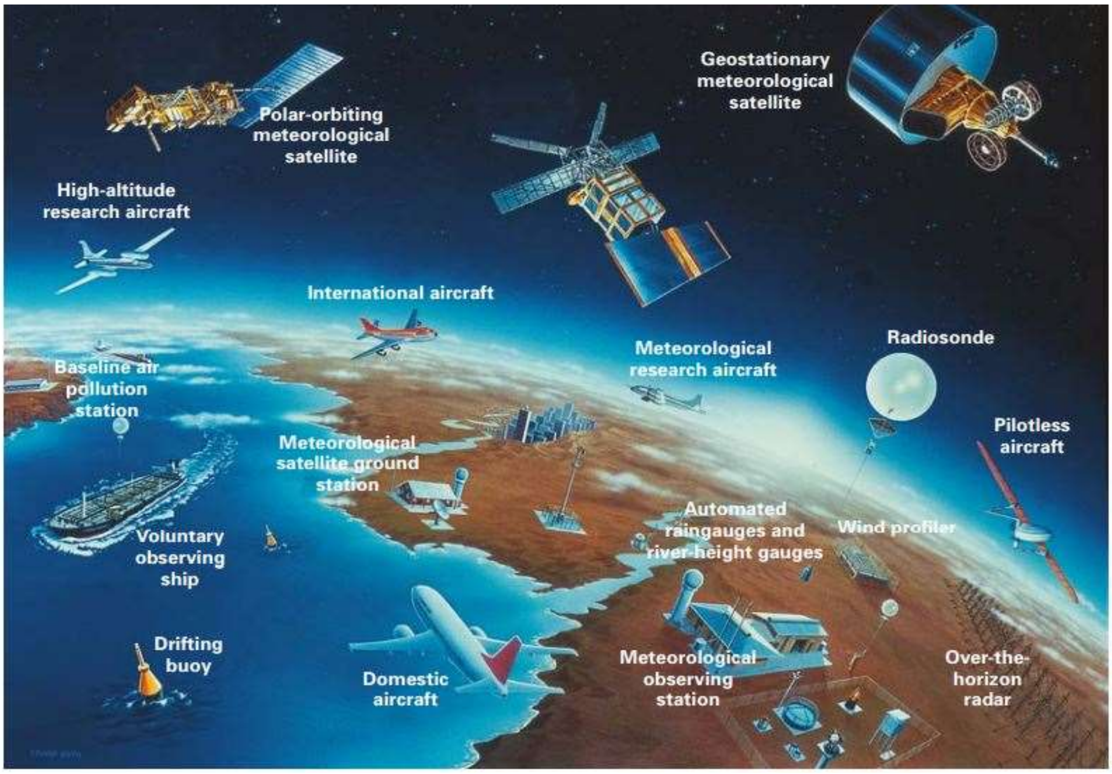
SESSION 3: CLIMATE DATA MANAGEMENT

3.1 Climate data Source

The Climate data component represents a wide range of time-series climate data. It extends well beyond what may be thought of as traditional meteorological observations and includes:

- Global Climate Observing data (GCOS)
- Essential Climate Variables (ECVs)

Multiple observing system



3.2 Different Meteorological Observation System

1 Surface observation

- Pressure, Temperature, Rainfall, Humidity, Radiation, Soil moisture, Evaporation, Wind speed and direction etc

2 Upper air observation

- Pilot balloon observation, RS observation

3 Marine observation

- Ship and buoy observation

4 Remote sensing observation

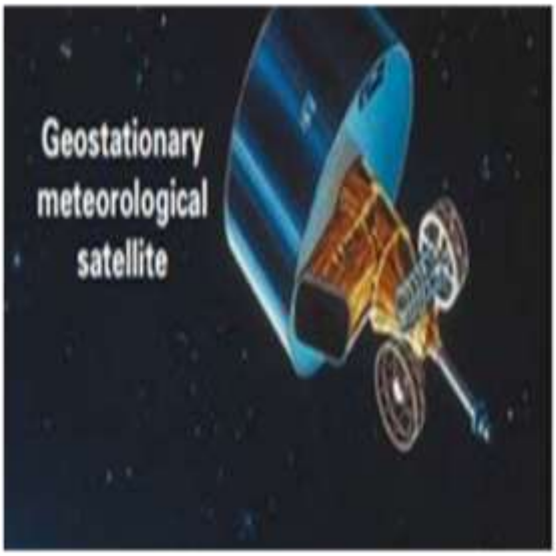
- Satellite and Radar observation

Polar-orbital meteorological satellite

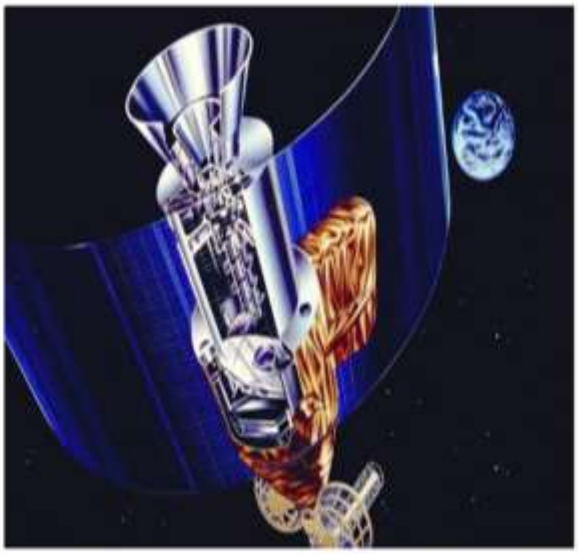
Compared with geostationary weather satellite polar orbital weather satellite provide cloud image with higher resolution this makes them very good at revealing the fine details of cloud structure and facilitates the monitoring of the effects of hazardous weather such as tropical cyclone and rainstorm.

Geostationary Meteorological satellite Himawari (GMS)

The Japanese meteorological satellite series also known as its nick name “himawari”(meaning “sunflower”) is on the geostationary orbit at 140 degrees of east longitude to carry out weather observation from space being part of the World weather watch(www) Project World meteorological Organization . The image of earth and clouds send from satellite series have been used in many areas such as weather forecast in TV and newspapers, therefore it is strongly connected to our daily life. After the himawari-6 The GMS series was replaced by a multifunctional transport satellite series to broaden its scope of operation. It is operated by Japan Meteorological agency for climate observation



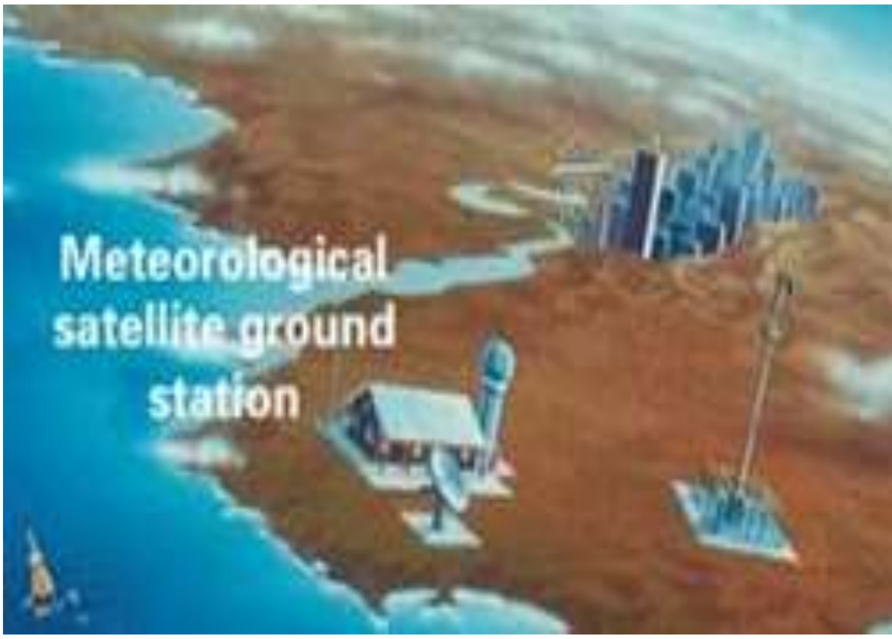
Geostationary Meteorological satellite



Polar-orbital Meteorological satellite

Meteorological Observation Ground Station

The GOES-R-class satellites come with an integrated ground system – a first in the history of GOES. Ground Segment capabilities include data processing, satellite control, mission planning and performance monitoring. GOES Mission Operations are directed from the NOAA Satellite Operations Facility (NSOF) in Suitland, Maryland and the primary Command and Data Acquisition Station is located in Wallops, Virginia with a backup station in Fairmont, West Virginia that can also support Product Generation and Product Distribution normally completed by the Ops Facility. Overall, the ground segment comprises 2,100 servers, 149 Network Racks, 317 workstations, and data storage totaling 3 Petabytes. Product processing is completed by 454 blade servers with 3,632 processor cores capable of 40 trillion floating point operations per second.



Meteorological observation ground station image

Voluntary Observing Ship (VOS)

The VOS Scheme is an international program comprising member countries of the World Meteorological Organization (WMO) that recruit ships to take, record and transmit marine meteorological and oceanographic observations while at sea. All eight Arctic Council member governments participate in the VOS Scheme either directly, by providing ships to the program, or indirectly by providing funding and/or data.

Ships' meteorological observations are recognized as being essential for the provision of safety-related services for ships at sea, marine pollution prevention and climate change studies. Ship-based meteorological and oceanographic reports are often the only data available from data-sparse areas such as the Arctic region.

Voluntary observing ship (VOS) image

High-Altitude Research Aircraft

NASA operates two Lockheed ER-2 Earth resources aircraft as flying laboratories in the Airborne Science Program under the Agency's Science Mission Directorate. The aircraft, based at NASA Armstrong's Building 703 in Palmdale, CA, collect information about Earth resources, celestial observations, atmospheric chemistry and dynamics, and oceanic processes. The aircraft also are used for electronic sensor research and development, satellite calibration, and satellite data validation.

High-altitude research aircraft image

Drifting Buoy/Seafloor Observatory

Weather buoys and Seafloor observatory are instruments which collect weather and ocean data within the world's oceans, The principal characteristic of a seafloor observatory, whether it is a moored-buoy or cabled system, is a two-way communication link between instruments and shore. At present, there are two ways to provide this connection: using either a riser or acoustic link from the seafloor to a surface buoy that communicates via satellite or radio to shore or using a submarine cable linked directly to a shore station.

3.3 Database

A database is a collection of related data which represents some aspect of the real world. A database system is designed to be built and populated with data for a certain task.

3.3.1 Database Management System (DBMS)

Database Management System (DBMS) is a software for storing and retrieving users' data while considering appropriate security measures. It consists of a group of programs which manipulate the database. The DBMS accepts the request for data from an application and instructs the operating system to provide the specific data. In large systems, a DBMS helps users and other third-party software to store and retrieve data.

DBMS allows users to create their own databases as per their requirement. The term "DBMS" includes the user of the database and other application programs. It provides an interface between the data and the software application.

3.3.2 Climate Data Management

Climate data management system (CDMS). A CDMS is an integrated computer-based system that facilitates the

- Effective archival
- Management
- Analysis
- Delivery and
- Utilization of a wide range of integrated climate data

3.3.3 Major components of a climate data management system

Requirements for Data Management of Climate Data Records

- System Design
- Data Quality
- Data Format:
- Data Accessibility

- Data Policy
- Data Security
- Data Stewardship and Long-Term Archive

System Design

A carefully designed, efficient data system is fundamental for ensuring success of the Climate data record (CDR) program. Since CDRs will be stored, analyzed, and reprocessed in an environment of changing technology and user requirements, the system design should focus on simplicity and endurance.

Data Quality

Data quality is a perception or an assessment of data's fitness to serve its purpose in a given context. The quality of data is determined by factors such as accuracy, completeness, reliability, relevance and how up to date it is. As data has become more intricately linked with the operations of organizations, the emphasis on data quality has gained greater attention.

Why data quality is important: Poor-quality data is often pegged as the source of inaccurate reporting and ill-conceived strategies in a variety of companies, and some have attempted to quantify the damage done. Economic damage due to data quality problems can range from added miscellaneous expenses.

Data Format

Different categories of users will require different data formats, and these will change over the decades. If the CDRs are available in multiple, flexible, and well-documented formats or in a form that permits the use of alternate formats.

Data Accessibility

The key to data access is the ability to provide data to the scientists and other users that is as practical and cost-effective as possible. Increasing the data volume will increase the demand of users. Two primary ways of reducing the amount of unwanted data delivered to the users are

1. to increase the accuracy of the search and
2. to provide sub-setting services.

Data Policy

It is essential to build a data policy. Climate data record policy will have to build upon longstanding policies and develop some new aspects as the development process develops, probably determining the applicable policy.

The following are some of the considerations to consider in a data management policy:

- Data is owned by the organization.
- Organizational data must be safe.

- Data to be accessible to individuals with the permission of the authorized person of the organization
- Meta data should be developed and utilized for all structured and unstructured data.
- Data owners should be accountable for data.
- Data should be accessible to users no matter where it exists in.
- Ultimately, a data management policy should guide your organization's philosophy toward managing data as a valued enterprise asset.

Data Security

Data management systems must ensure the security of stored data. The primary means of data security currently involves having authenticated system backups. Redundancy is essential, and backup copies must be regularly placed in widely separated geographical locations.

Data Stewardship and Long-Term Archive

Various scientific and policy-making groups have reviewed and defined the requirements for essential data systems and services needed to ensure a long-term data record in support of climate research.

SESSION 4: REGIONAL CLIMATOLOGY

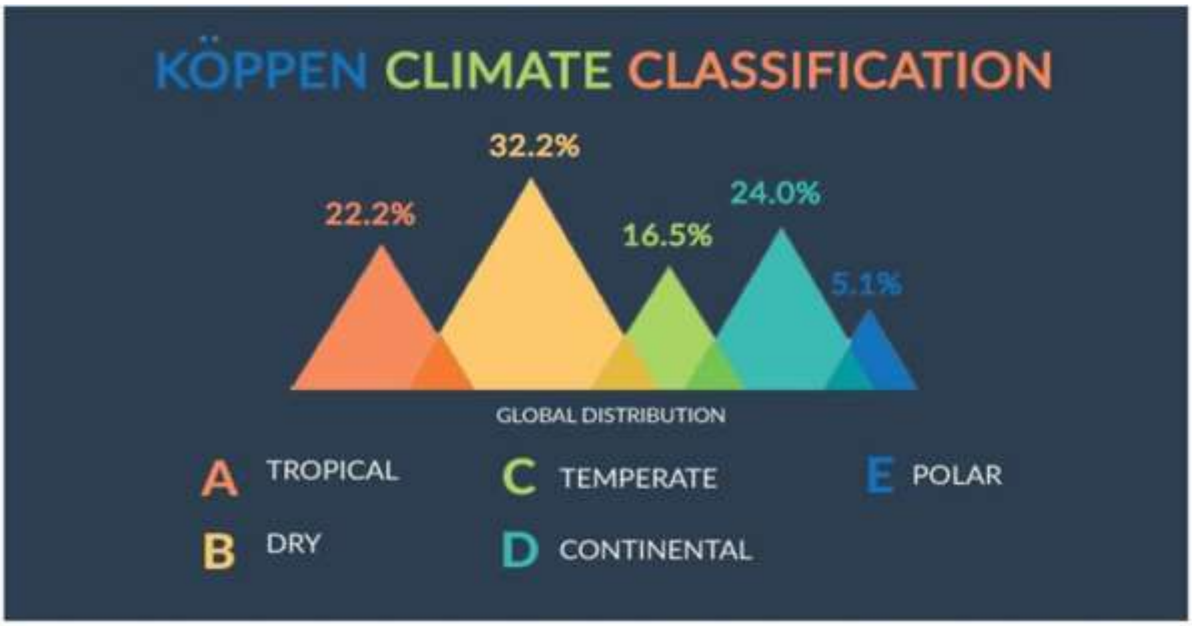
4.1 Regional Climatology

There are different types of climate classification but Koeppen's classification of climate is the most commonly used classification of climate.

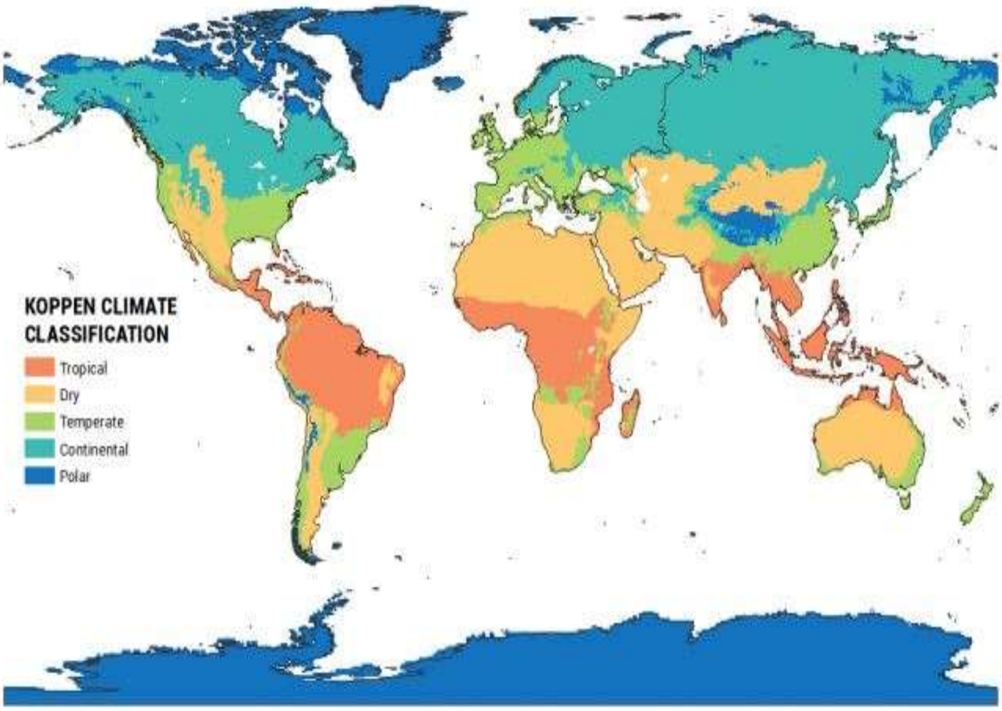
4.2 **Koeppen's classification**

The Koppen climate classification was developed by Wladimir Koppen more than a century ago. He recognized a close relationship between the distribution of vegetation and climate. The categories are based on data of annual and monthly average of temperature and precipitation. He selected specific values of temperature and precipitation and related them to the distribution of vegetation and used these values for classifying the climate. Koppen climate classification system recognized 5 major climate types:

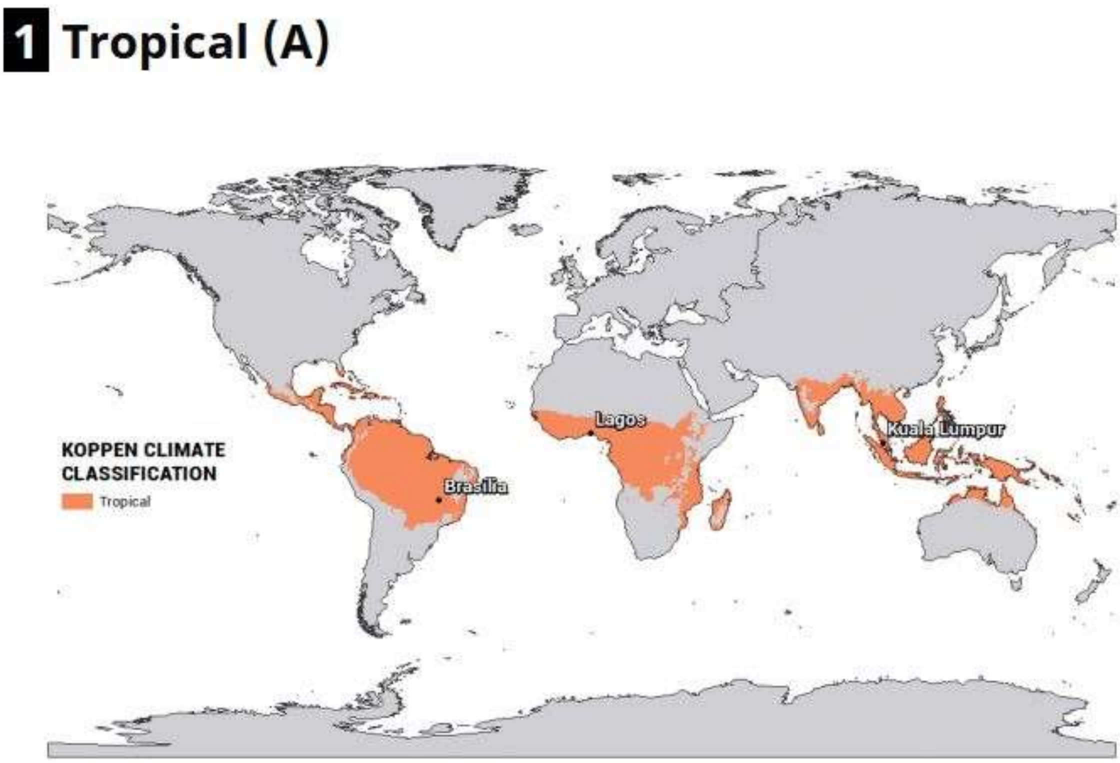
1. Tropical or megathermal climates are characterized as having constant warm temperature.
2. Dry or arid climates have low precipitation rates.
3. Temperate or mesothermal climates maintain mild annual temperatures.
4. Continental or microthermal climates have hot summers and cold winters occurring typically at the interior of a continent.
5. Polar or alpine climates sustain consistent cold temperatures throughout the year.



5Koppen Climate Classification Types



4.2.1 TROPICAL OR MEGATHERMAL CLIMATES (A)



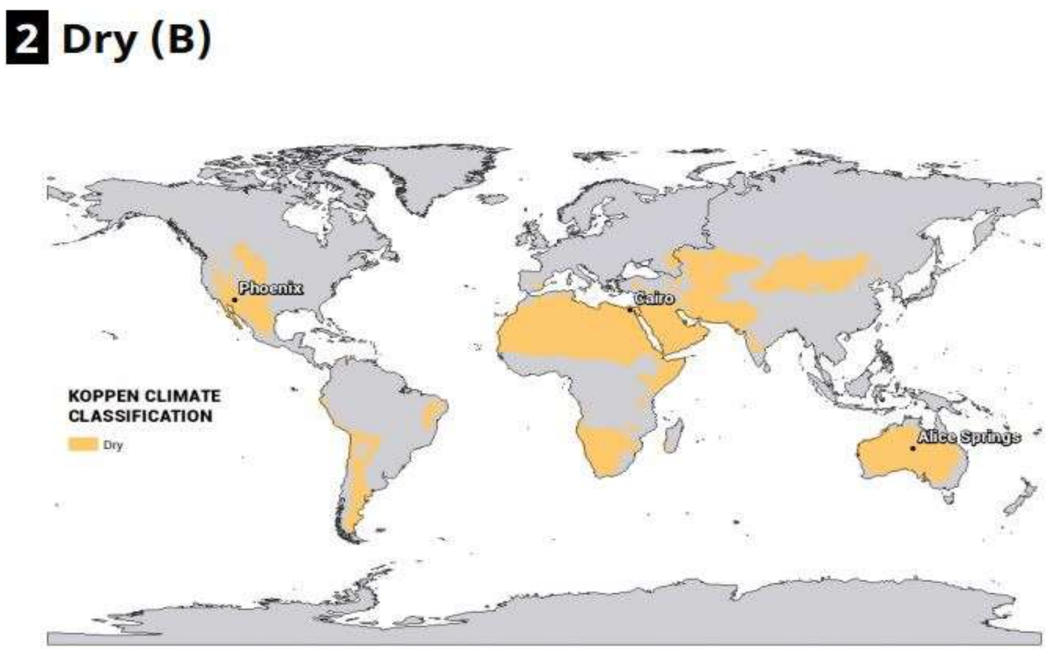
It's warmed all year-round for tropical climates. You can typically find this type of climate near the equator from 15°N to 15°S latitude.

For example, tropical rainforests are hot, moist regions easily distinguishable by their enormous trees, diverse species and thick soils. Tropical climates sustain a healthy portion of high temperature with its lowest mean monthly air temperature is greater than 18 °C.

Tropical Climate Classification:

Climate Type	Criteria
Tropical (A)	Lowest mean monthly temperature is greater than 18°C.
Tropical rainforest (Af)	Precipitation in the driest month is at least 6 cm or greater.
Tropical monsoon (Am)	Precipitation in driest month less than 6 cm but more than 4% total annual precipitation.
Tropical wet and dry savannah (Aw)	Precipitation in driest month less than 10 cm and less than 4% total annual precipitation.

4.2.2 DRY OR ARID CLIMATES (B)



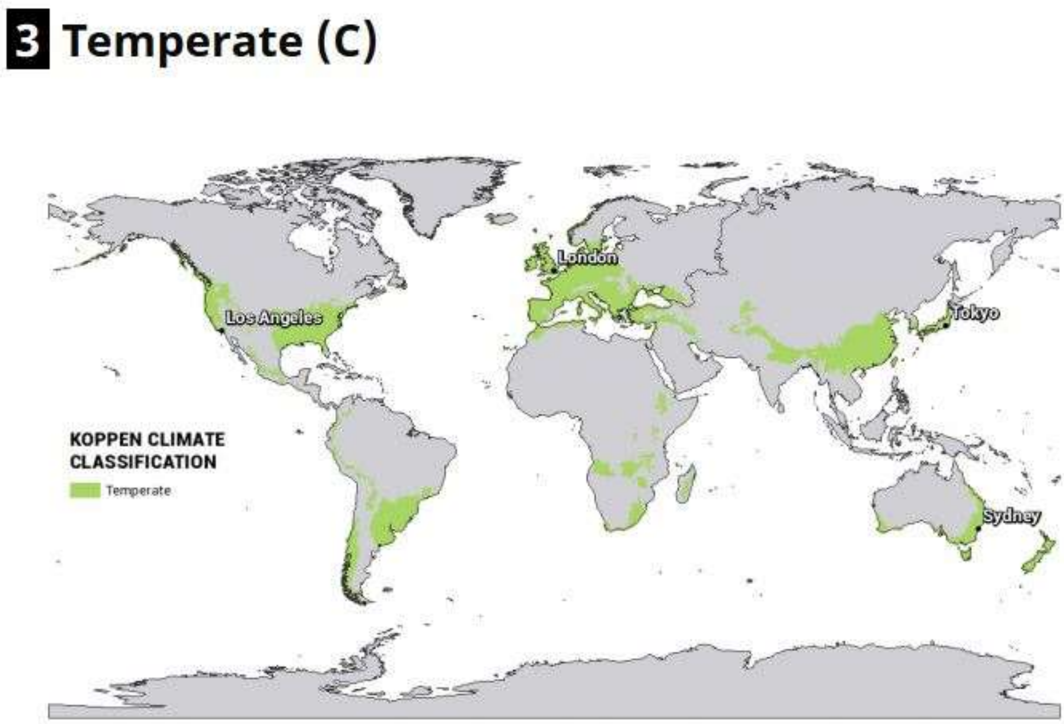
Dry climates are the only category in the Koppen climate classification that isn't entirely based on temperature. They are characterized by having a shortage of water with low annual mean precipitation rate because water evaporates quickly from its temperatures. In order to classify dry climates, you calculate precipitation threshold based on how much total precipitation falls during the high sun period. In the northern hemisphere, the defined period is from April to September. But in the southern hemisphere, it's from October through

March. If the annual precipitation is less than 50% of the precipitation threshold, the classification is BW (arid: desert climate). But if it is more than 50%, the Koppen climate classification is BS (semi-arid: steppe climate). For example, Phoenix, Arizona has an average annual temperature of 21.8°C. Approximately 38.4% of its annual precipitation falls from April to September. Because its precipitation threshold is less than 50%, Phoenix, Arizona is an arid desert climate.

Classification of Dry or Arid Climates:

Climate Type	Criteria
Arid desert (BW)	Annual precipitation is less than 50% of the precipitation threshold.
Semi-arid steppe (BS)	Annual precipitation is more than 50% of the precipitation threshold.

4.2.3 TEMPERATE OR MESOTHERMAL CLIMATES (C):



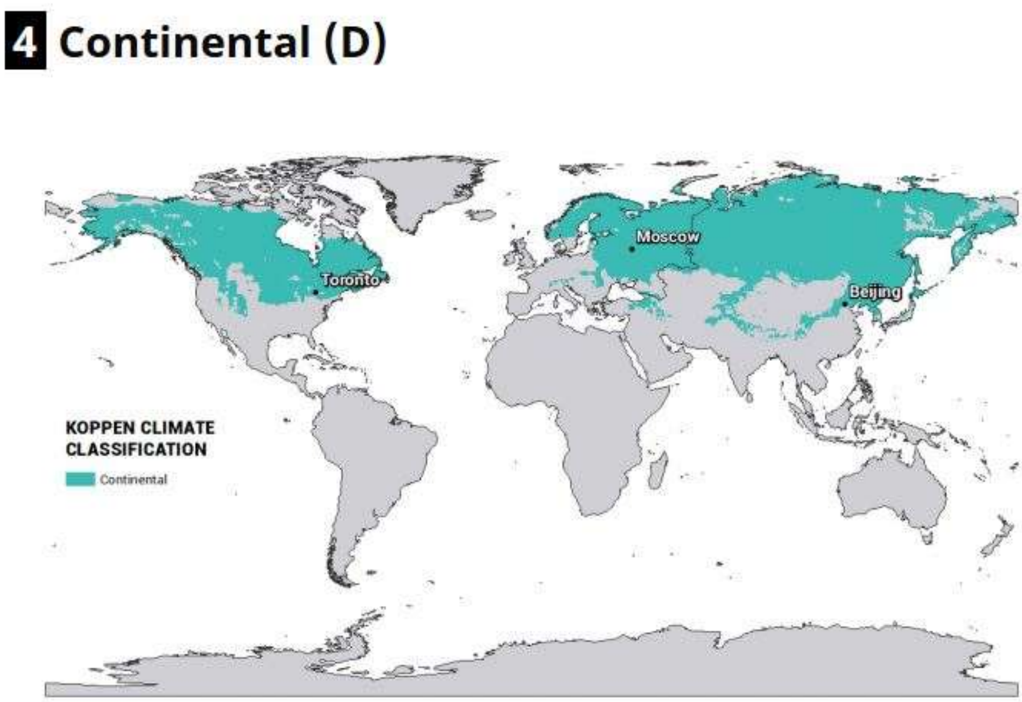
Temperate climate types take the middle road for average temperature. These types of climates are common along the edge of continents.

For example, coastal locations have moderate changes in temperature with mild winters and summers. Seasonal changes aren't as extreme as dry climates. If the average temperature of the warmest month is higher than 10°C and the coldest month is between 18° and 0°C, then it's considered a temperature climate.

Classification of Temperate or Mesothermal Climates:

Climate Type	Criteria
Mild temperate dry summer (Cs)	Precipitation in driest month of summer is less than 1/3 the amount in wettest winter month.
Mild temperate dry winter (Cw)	Precipitation in driest month of winter is less than 1/10 of amount in wettest summer month.
Mild temperate humid (Cf)	Does not satisfy Cs or Cw climate types.

4.2.4 CONTINENTAL OR MICROTHERMAL CLIMATES (D)



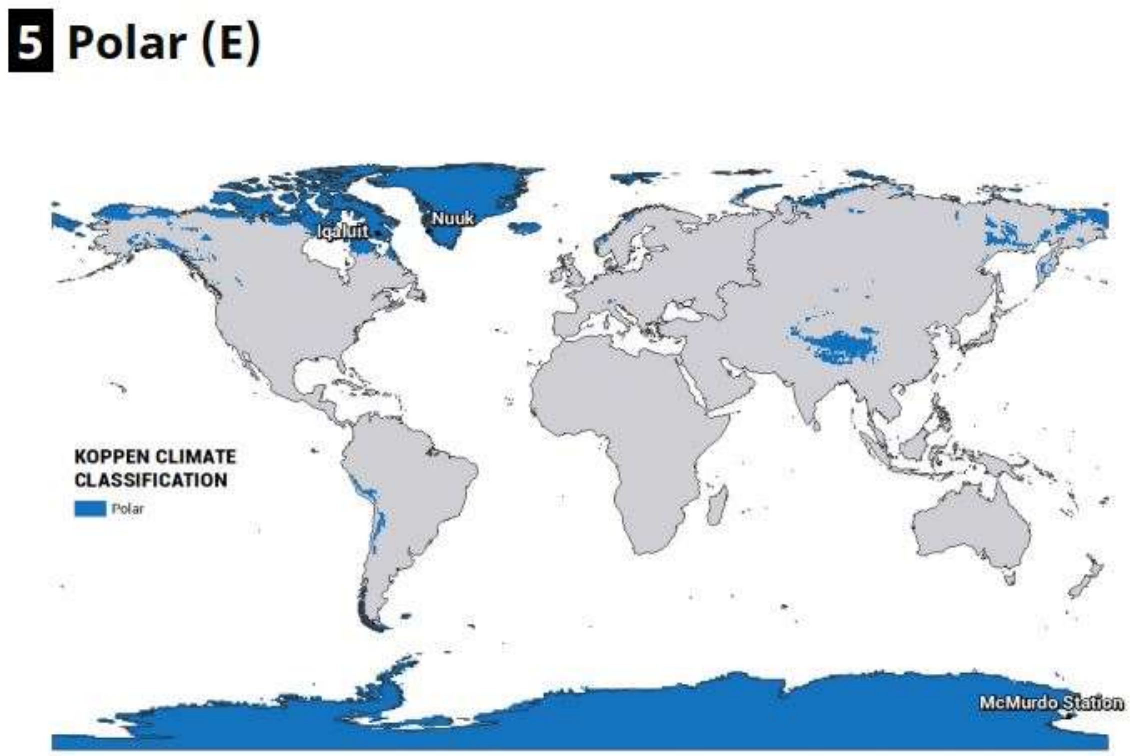
Continental climates are usually situated in the interior of continents. They have at least one month with an average temperature below 0°C. Likewise, at least one-month averages above 10 °C.

When you combine continental and dry climate types, they take up a large portion (approximately 56%) of the surface. It also experiences drastic shifts during seasonal changes. Typically, continental climates range from 40° to 75° latitudes in the northern and southern hemispheres. However, this type of climate type is rare in the southern hemisphere

Classification of Continental Climate

Climate Type	Criteria
Continental dry summer (Ds)	Precipitation in driest month of summer is less than 1/3 the amount in wettest winter month.
Continental dry winter (Dw)	Precipitation in driest month of winter is less than 1/10 of amount in wettest summer month.
Continental humid (Df)	Does not satisfy Ds or Dw climate types.

4.2.5 POLAR OR ALPINE CLIMATES (E)



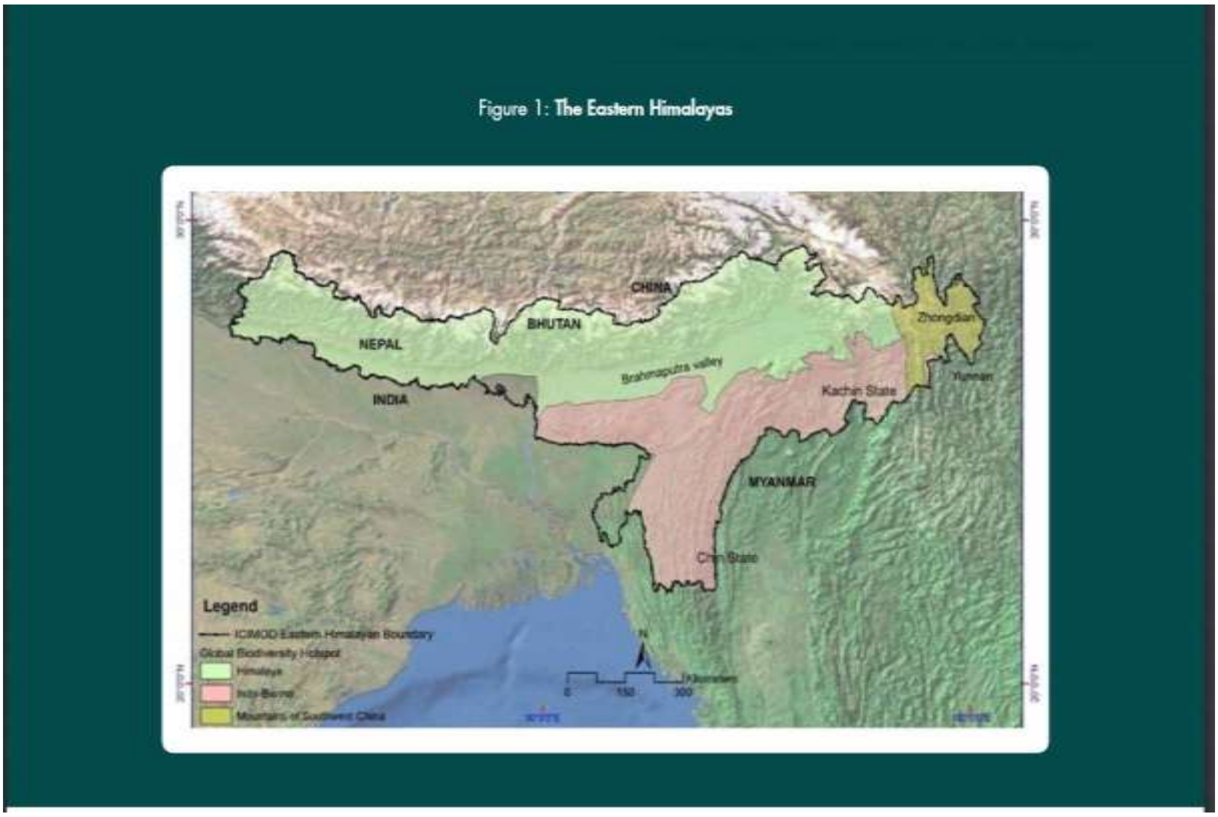
Lastly, polar climates endure frigid temperatures year-round. The average temperature of the warmest month in polar climatic zones is below 10°C.

Typically, these types of climates occur in the polar regions, generally greater than 70° latitude in the northern and southern hemisphere.

Very little vegetation grows in polar types climates because it’s above the tree line. Most icecap type of climates belong to Inner Greenland and Antarctica.

Classification of Polar Climate:

Climate Type	Criteria
Tundra (ET)	Average temperature of warmest month is between 10° and 0°C.
Ice Cap (EF)	Average temperature of warmest month is at 0°C or below.



4.3 Himalayas influence in the climate of Bangladesh

The Himalayas play a very important role in influencing the climate of India Bangladesh subcontinent. This subcontinent is a monsoon land only because of the presence of Himalayas. It traps the monsoon winds from Arabian sea and Bay of Bengal and forces them to shed their moisture content within the sub-continent in the form of snow and rain. It also blocks the cold winter storms from north entering the subcontinent, thus protecting Bangladesh from severe cold and snow fall. The Himalayas splits the westerly jet streams into two branches such that the southward branch entering India-Bangladesh continent plays a significant role in bringing the northeast monsoon.

The Himalayas influence the winds flowing through this subcontinent from all directions. The Himalayas stops South western monsoon winds from moving further north and thereby resulting in retreating monsoons. Also, the cold winds from the north pole, would also get controlled due to the presence of Himalayas. Otherwise, we would be experiencing Tundra climate or temperate climate like Russia and China.

The Arabian Sea and the Bay of Bengal are apologies for North Indian ocean. There develop 6 "HIGHS" during winter of Northern Hemisphere (then it is summer for SH). They are called sub-tropical highs. When summer sets in for NH, all "HIGH" s moves a little north. The HIGH over ASIA is replaced by a big LOW (reducing the number of HIGHs to 5) called "Siberian" low covering Siberia, Tibet and an area of NW India, separated by the Great Himalayas. But for the Himalayas and Tibet, India will be a huge desert as big as the Sahara of Africa.

Tropic of cancer passes through India which means the region north of tropic of cancer in India should experience temperate climate and the region south of it should experience tropical climate. But in reality, whole Indian sub-continent experiences tropical type of climate. It's because of its physiographic position.

4.4 Influence of Bay of Bengal in the climate of India/Bangladesh

There is no region of the world that faces more threats from climate change than South Asia. Of particular concern is the littoral surrounding the Bay of Bengal, including the Eastern Indian states of West Bengal and Orisha, Bangladesh, and coastal Burma. This region is uniquely vulnerable to a changing climate because of a combination of rising sea levels, changing weather patterns, and uncertain transboundary river flows.

Role of Bay of Bengal in Monsoon Sub-Seasonal Rainfall

Monsoon trough over South Asia during summer monsoon is an important synoptic feature of the South Asian monsoon system. From equator the ITCZ moves northward towards South Asian landmass and after onset of monsoon becomes the monsoon trough. It is a semi-permanent feature during moderate to active monsoon conditions. It extends from north-west India West Bengal through Bangladesh to Assam. Sometimes this monsoon axis hangs over North Bay too. The strength of the monsoon trough is an indication of the intensity of the overall whole large-scale monsoon circulation and associated rainfall. The intensity of monsoon trough is modulated by cross-equatorial flow and the low-level westerly jet over the Arabian Sea and the Bay of Bengal.

The head Bay of Bengal region interacts with the monsoon trough and there exists a feedback mechanism between the upper ocean of the head Bay of Bengal and the monsoon trough. This feedback in turn affects the overall strength of the monsoon circulation.

Head Bay of Bengal is also a region of highest freshwater supply from monsoon rainfall and the river systems there. This is also a region of maximum convection producing tall clouds. A shallow freshwater layer is formed in the head Bay region which produces a highly stratified upper ocean which opposing upper ocean mixing and in turn produces a warm layer of water with high SST. This warm bay, via moisture fluxes, further enhances the deep convection in the region. The fluctuations of the intensity of the monsoon trough thus interacts with the upper ocean of the head Bay of Bengal and jointly provide an important component of contribution to the sub-seasonal variability of monsoon and rainfall including the dry/wet spells within the monsoon season.

4.5 Extreme Events of this region

Thunderstorm

Thunderstorms are meso-scale local severe weather systems. Thunderstorms develop during pre-monsoon and post-monsoon time in Bangladesh. From March to April the temperature in Bangladesh rises sharply compared to the preceding months (i.e. winter months). April and May are the hottest months. Thunderstorms develop due to the atmospheric convection, usually created by surface heating. Convection leads the upward atmospheric motion. In the middle of April, the whole country, especially the northwestern part, records a sharp rise in day temperature. Presence of warm and moist air in the lower layer of the atmosphere is an essential precondition for the development of a nor 'wester. Unstable atmosphere and intense convective activity are other important factors for their origin and growth. The mean temperature of Bangladesh during the summer months varies between 23-30 degC. The highest maximum temperature ranging from 36-40degC is attained in the northwestern and southwestern districts. Due to intense heating of the land surface heat low develops over Bihar, West Bengal of India and adjoining northwestern part of Bangladesh. Occasionally moisture incurs in the afternoon from the Bay of Bengal to that low pressure results the formation of thunder cloud and development of severe thunderstorms. These severe thunderstorms are known as nor 'westers ('Kalbaishakhi' in Bengali) that often accompanied by destructive squalls, thunder and heavy rainfall with hails. During the pre -monsoon season nor 'westers occur frequently at many places over Bangladesh. Due to heavy rainfall associated with severe thunderstorm in the northeastern part of Bangladesh and adjoining northeastern states of India flash flood occurs in the northeastern part of Bangladesh. The main reasons behind the nor 'wester is the warm and moist air coming from the southeast which rises up to 2 kilometers, mixes with the relatively cold and dry air coming from the northwesterly and westerly directions. The mixing of these two dissimilar air masses causes storms. The warm and moist air rises due to the Chotanagpur Plateau, Himalayan ranges, and Assam Plateau. The life cycle of a nor 'wester is associated with (1) cumulus; (2) mature; and (3) dissipating stages which are determined by the magnitude and direction of the ascending or descending air currents. After 30 to 45 minutes the mature nor 'wester begins to decrease in intensity and enters the dissipating stage. Because of very steep temperature lapse rate, high water content of clouds and the cumulous updrafts, hail is common to a nor 'wester. The size of a hail is determined by the rate of uplift within a cloud and its high-water content. Thunder and lightning is common with a nor 'wester. Nor 'westers are more frequent in the late afternoon because of the influence of surface heating in producing convection currents in the atmosphere. In the western region of Bangladesh, nor 'westers come in the late afternoon and before evening but in the eastern side it comes generally after evening, moving from a northwesterly to a easterly and southeasterly direction. The average wind speed of a nor 'wester is 40-60 km per hour. But in exceptional circumstances the wind speed may exceed 100 km. The duration of the storm is generally less than an hour but sometimes it may exceed an hour.

Tornado

A tornado is a narrow, violently rotating column of air that extends from the base of a thunderstorm to the ground. It forms a condensation funnel made up of water droplets, dust and debris.

A tornado is a local storm of short duration (usually 5-10 minutes) formed of winds rotating at very high speeds, usually in a counterclockwise direction (in the Northern Hemisphere). This storm is visible as a vortex. A whirlpool structure of winds rotating about a hollow cavity in which centrifugal forces produce a partial vacuum. As condensation occurs around the vortex, a pale cloud appears and develops tornado funnel. Funnels usually appear as an extension of the dark, heavy cumulonimbus clouds of thunderstorms and stretch downward toward the ground. Some tornadoes never reach the surface; others touch and rise again. Air surrounding the funnel is also part of the tornado vortex. As the storm moves along the ground, its outer ring of rotating winds becomes dark with dust and debris which may eventually darken the entire funnel.

Tornadoes develop from mainly two types of thunderstorms: super- cell and non-super cell. Tornadoes that come from a super cell thunderstorm are the most common, and most dangerous. Strong updraft develops in the severe thunderstorm clouds and once the updraft is rotating and being fed by warm, moist air flowing in at ground level a tornado can form, and this rotation of wind occurs due to wind shear.

Most tornadoes have wind speeds less than about 180 km/h (110 m/h) and they travel a several kilometers before dissipating. The very strong tornadoes can attain wind speeds of more than about 400 km/h (300 miles) per hour.

Tropical Cyclone

In general, tropical cyclone formation areas of the world are divided into seven basins in which North Indian Ocean is one of them. It has two wings, the Arabian Sea and the Bay of Bengal. According to global cyclone statistics, only 7% of tropical cyclones occur in the North Indian Ocean, but five to six times as many occur in the Bay of Bengal as in the Arabian Sea.

Tropical cyclone, also named as typhoon or hurricane (depending on location), is an intense rotating system characterized by strong winds that spiral cyclonically (anticlockwise) around the low-pressure centre. Tropical cyclone is formed only when the surface wind speeds is at least 62 km/hr (34 knot), before that it is called a depression (an organized system of clouds and thunderstorms). Some favorable environmental conditions such as wind surge to the depression can trigger the system turning into a tropical cyclone. Tropical cyclone is capable for self-intensification like a heat engine that is fueled by the temperature gradient between the warm tropical ocean surface and the cold upper atmosphere. Development of tropical cyclone in the ocean area additionally requires some particular environment to be satisfied. High sea surface temperature, low vertical wind shear (change of winds with height), high relative humidity at mid-troposphere and low-level relative vorticity are the suitable environment for the formation of tropical cyclone in any basins.

During summer, direct heating of the ocean by the sun increases sea surface temperature, which results in increased evaporation and, thus, increased amounts of water vapor in the atmosphere. Therefore, summer season in each basin is generally favorable time for the genesis of cyclone, however, exception is found in the Bay of Bengal. Here, a distinctly bimodal cyclone seasons are observed: March–May (pre-monsoon) and October-November (post-monsoon). During summer or monsoon season (June–September) many depressions are active in the Bay of Bengal, but intense southwesterly monsoonal wind does not allow initiating them as tropical cyclones.

By names, Gonu (June 2007) and Phet (May 2010) in the Arabian Sea and Sidr (November 2007), Nargis (April 2008), Giri (October 2010) and Phailin (October 2013) in the Bay of Bengal are recent strong, destructive storms that occurred in the North Indian Ocean. Cyclones occurring in the funnel-shaped Bay of Bengal are particularly deadly, because they often cause severe flooding of the densely populated low-lying coasts of Bangladesh, India, and Myanmar.

Monsoon

Monsoon, the wind system that dominates the climate of South Asia and the area around the Indian ocean with seasonal reversals of direction caused by the differential heating and cooling of landmass and oceans between summer and winter. The wind blows from the northeast (towards the sea) in winter (the dry-monsoon) and from the southwest (towards the land) in summer (the wet-monsoon). The word 'monsoon' is derived from the Arabic word 'Mawsim' which means seasons. The monsoon cycle is believed to have started about 12 million years ago with the uplift of the Himalayas.

During the summer season, a center of low pressure develops over the western part of India because of the intense heating of the landmass, while high pressure develops over the relatively cooler Indian Ocean. This pressure difference causes the winds to flow from the high-pressure area to the low-pressure area, which is from ocean to land in this case. This flow pattern is known as the summer monsoon circulation. As a result, the summer monsoon winds bring in enormous amount of moisture, causing heavy rainfall in the subcontinent, especially in Bangladesh and the neighboring states of India.

The summer monsoon flow of the Indian Ocean has two branches - the Arabian Sea branch and the Bay of Bengal branch. The Arabian Sea branch dominates the weather scenes in central and peninsular India, while the Bay of Bengal branch dominates the scenes in Bangladesh, northeastern India, Gangetic Plain and the southern slopes of the Himalayas. It enters Bangladesh in late May or early June and continues to flow toward the center of low pressure that lies over the west-central part of India.

Heat wave

Heat wave is a period of excessively hot weather, which may be accompanied by high humidity, especially in oceanic climate countries. While definitions vary, a heat wave is usually measured relative to the usual weather in the area and relative to normal temperatures for the season. According to WMO heat wave condition develops when five or more consecutive days of prolonged heat persists when the daily maximum temperature is higher than the normal average maximum temperature by 5 °C (9 °F) or more. However, some nations have come up with their own criteria to define a heat wave.

Heat waves form when high pressure aloft (from 10,000–25,000 feet (3,000–7,600 meters)) strengthens and remains over a region for several days up to several weeks. This is common in summer (in both Northern and Southern Hemispheres) as the jet stream 'follows the sun'. On the equator side of the jet stream, in the upper layers of the atmosphere, is the high-pressure area.

In Bangladesh heat wave is classified as follows:

- when maximum temperature rises up to 36-38 degree Celsius, then it is considered as mild heat wave
- when maximum temperature rises up to 38-40 degree Celsius, then it is considered as moderate heat wave
- when maximum temperature rises up to 40-42 degree Celsius, then it is considered as severe heat wave
- when maximum temperature exceeds 42 degree Celsius, then it is considered as very severe heat wave.

Landslide

A landslide is defined as the movement of a mass of rock, debris, or earth down a slope. Landslides are a type of "mass wasting," which denotes any down-slope movement of soil and rock under the direct influence of gravity. The term "landslide" encompasses five modes of slope movement: falls, topples, slides, spreads, and flows. These are further subdivided by the type of geologic material (bedrock, debris, or earth). Debris flows (commonly referred to as mudflows or mudslides) and rock falls are examples of common landslide types. Almost every landslide has multiple causes. Slope movement occurs when forces acting down-slope (mainly due to gravity) exceed the strength of the earth materials that compose the slope. Causes include factors that increase the effects of down-slope forces and factors that contribute to low or reduced strength. Landslides can be initiated in slopes already on the verge of movement by rainfall, snowmelt, changes in water level, stream erosion, and changes in ground water, earthquakes, volcanic activity, disturbance by human activities, or any combination of these factors. Earthquake shaking and other factors can also induce landslides underwater. These landslides are called submarine landslides. Submarine landslides sometimes cause tsunamis that damage coastal areas.

Heavy rainfall causes the landslides in hilly areas

In June 2017 Heavy overnight rains triggered a series of landslides in southeast Bangladesh, killing at least 133 people and injuring many more, officials said. The highest total, 98 deaths, were reported in the hilly Rangamati district, where rescuers found bodies buries under mud.

SESSION 5: ACTIVITIES AND DEVELOPMENT GOALS OF CLIMATE DIVISION, BMD

5.1 Activities of Climate Division

a) Meteorological Data

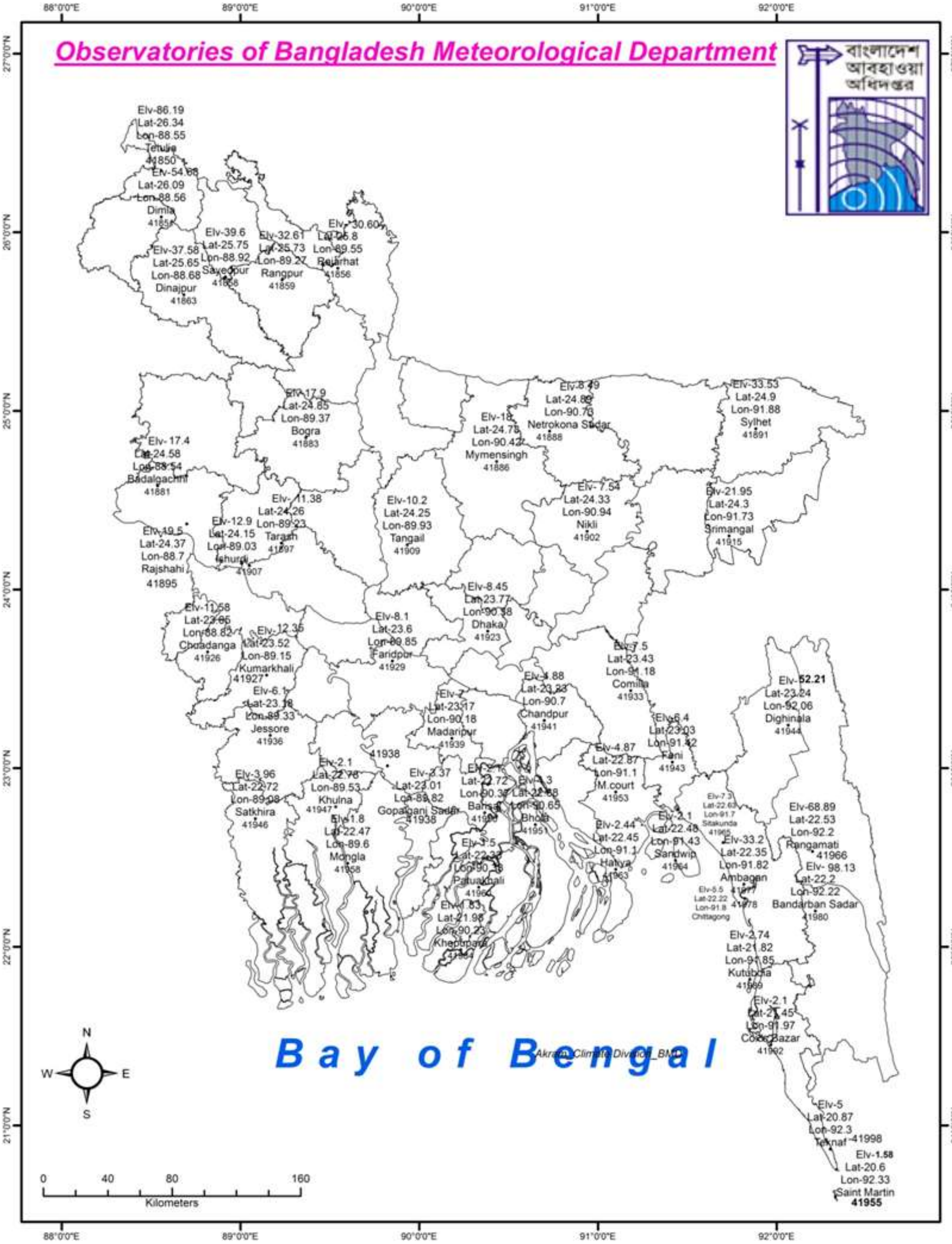
Climate division receives all the recorded meteorological data of 47 departmental meteorological observatories of every previous month in every next month by online and post. The received data is scrutinized manually on regular basis. After the manual scrutiny the computer operators enters the scrutinized data into the computer. The punched data is corrected by running quality control programs and corrected data is preserved in the external hard disc on regular basis. Then corrected data is copied and transferred to Linux Software System and is divided into separated parameter files by using Fortran Programming Language. These separated parameters are also preserved in the external hard disc. The preserved data are supplied to various national and international organizations as per their demands by using Linux Software System and Fortran Programming Language in exchange of Government approved fees by treasury challan and online payment method. The departmental meteorological data base at present contains meteorological data of 1948-2018 as recorded by the departmental meteorological observatories.

b) Seismological Data

Climate division receives all the recorded seismological data of 10 seismological observatories of every previous month in the next month. The received seismological data also preserved in same procedure. The seismological data from 1918 to 2018 are already archived in climate division.

c) Astronomical Data

BMD does not have any astronomical observatory. Hence, the necessary basic astronomical data of every year is downloaded from the official astronomical websites of UK and USA. The list of 1st day of every Arabic month and Islamic Festivals, Moon coordinates and Moon Phases data of every lunar month, daily sunrise-sunset & moonrise-moonset data of every year for 64 districts of Bangladesh, daily sahri-iftar data of every year's Ramadan month for 64 districts of Bangladesh and particulars of every year's solar-lunar eclipses & transits of Mars-Venus over sun are prepared. The prepared astronomical data are supplied to various national and international organizations as per their demands.


Observatories of Bangladesh Meteorological Department
বাংলাদেশ আবহাওয়া অধিদপ্তর
88°0'0"E
89°0'0"E
90°0'0"E
91°0'0"E
92°0'0"E
27°0'0"N
26°0'0"N
25°0'0"N
24°0'0"N
23°0'0"N
22°0'0"N
21°0'0"N
Elv-86.19
Lat-26.34
Lon-88.55
41850
Lat-26.09
Lon-88.56
Dimla
Elv-39.6
Lat-25.75
Lon-88.92
Saidpur
Elv-32.61
Lat-25.73
Lon-89.27
Rangpur
41859
Elv-30.60
Lat-25.8
Lon-89.55
Rajarhat
41856
Elv-37.58
Lat-25.65
Lon-88.68
Dinajpur
41863
Elv-17.9
Lat-24.85
Lon-89.37
Bogra
41883
Elv-17.4
Lat-24.58
Badalgachhi
41881
Elv-8.49
Lat-24.88
Lon-90.73
Netrokona Sadar
41888
Elv-18
Lat-24.75
Lon-90.42
Mymensingh
41886
Elv-33.53
Lat-24.9
Lon-91.88
Sylhet
41891
Elv-7.54
Lat-24.33
Lon-90.94
Nikli
41902
Elv-21.95
Lat-24.3
Lon-91.73
Srimangal
41915
Elv-10.2
Lat-24.25
Lon-89.93
Tangail
41909
Elv-12.9
Lat-24.15
Lon-89.03
Ishurdi
41907
Lat-24.26
Lon-89.23
Tarash
41897
Lat-24.37
Lon-88.7
Rajshahi
41895
Elv-8.45
Lat-23.77
Lon-90.38
Dhaka
41923
Elv-11.58
Lon-88.82
Chuadanga
41926
Elv-12.35
Lat-23.52
Lon-89.15
Kumarkhali
41927
Elv-8.1
Lat-23.6
Lon-89.85
Faridpur
41929
Lat-23.43
Lon-91.18
Comilla
41933
Elv-52.21
Lat-23.24
Lon-92.06
Dighinala
41944
Elv-6.1
Lat-23.18
Lon-89.33
Jessore
41936
Lat-23.17
Lon-90.18
Madaripur
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Lon-90.7
Chandpur
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Elv-6.4
Lat-23.03
Lon-91.42
Feni
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Elv-4.87
Lat-22.87
Lon-91.1
M.court
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Lat-22.78
Lon-89.53
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Satkhira
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Lat-23.01
Lon-89.82
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Barisal
Bhola
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Mongla
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Lat-22.45
Lon-91.1
Hatiya
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Lon-91.43
Sandwip
41964
Sitakunda
Elv-33.2
Lat-22.35
Lon-91.82
Ambagan
Chittagong
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Lon-92.2
Rangamati
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Elv- 98.13
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Lon-92.22
Bandarban Sadar
41980
Patuakhali
Lat-21.98
Lon-90.23
Khepupara
Elv-2.74
Lat-21.82
Kutubdia
41989
Elv-2.1
Lon-91.97
Cox's Bazar
41992
Bay of Bengal
Akram Climate Division BMD
Elv-5
Lat-20.87
Lon-92.3
Teknaf-41998
Elv-1.58
Lat-20.6
Lon-92.33
Saint Martin
41955
N
S
W
E
0
40
80
160
Kilometers

Software's used

Penmen Monteith

- Evapotranspitation

Warplot

- Wind Rose

CPT

- Seasonal Forecast

GIS

- Data Analysis

Synoptic observatory (Dhaka)

Observers are taking observation and resetting the instruments

Observation Time and Recording

1

- BMD takes every three hourly observation

2

- Observation time00,03,06,09,12,15,18, and 21UTC

3

- Observers take the readings and record in a hard copy named CL-17.

4

- After one month they send the bundle of CL-17 to the climate division.

List of surface observation

01	Mean Sea Level Pressure	Surface Data	3-hourly
02	Station Level Pressure	Surface Data	3-hourly
03	Dry Bulb Temperature	Surface Data	3-hourly
04	Wet Bulb Temperature	Surface Data	3-hourly
05	Maximum Temperature	Surface Data	Daily
06	Minimum Temperature	Surface Data	Daily
07	Dew Point Temperature	Surface Data	3-hourly
08	Relative Humidity	Surface Data	3-hourly
09	Horizontal Visibility	Surface Data	3-hourly
10	Present weather	Surface Data	3-hourly
11	Past Weather	Surface Data	3-hourly
12	Form of Cloud	Surface Data	3-hourly
13	Amount of Cloud	Surface Data	3-hourly
14	Direction of Cloud	Surface Data	3-hourly
15	Height of the cloud above ground level	Surface Data	3-hourly
16	Rainfall	Surface Data	Daily up to 2002 & 3-hourly from 2003
17	Wind Speed	Surface Data	3-hourly
18	Wind Direction	Surface Data	3-hourly

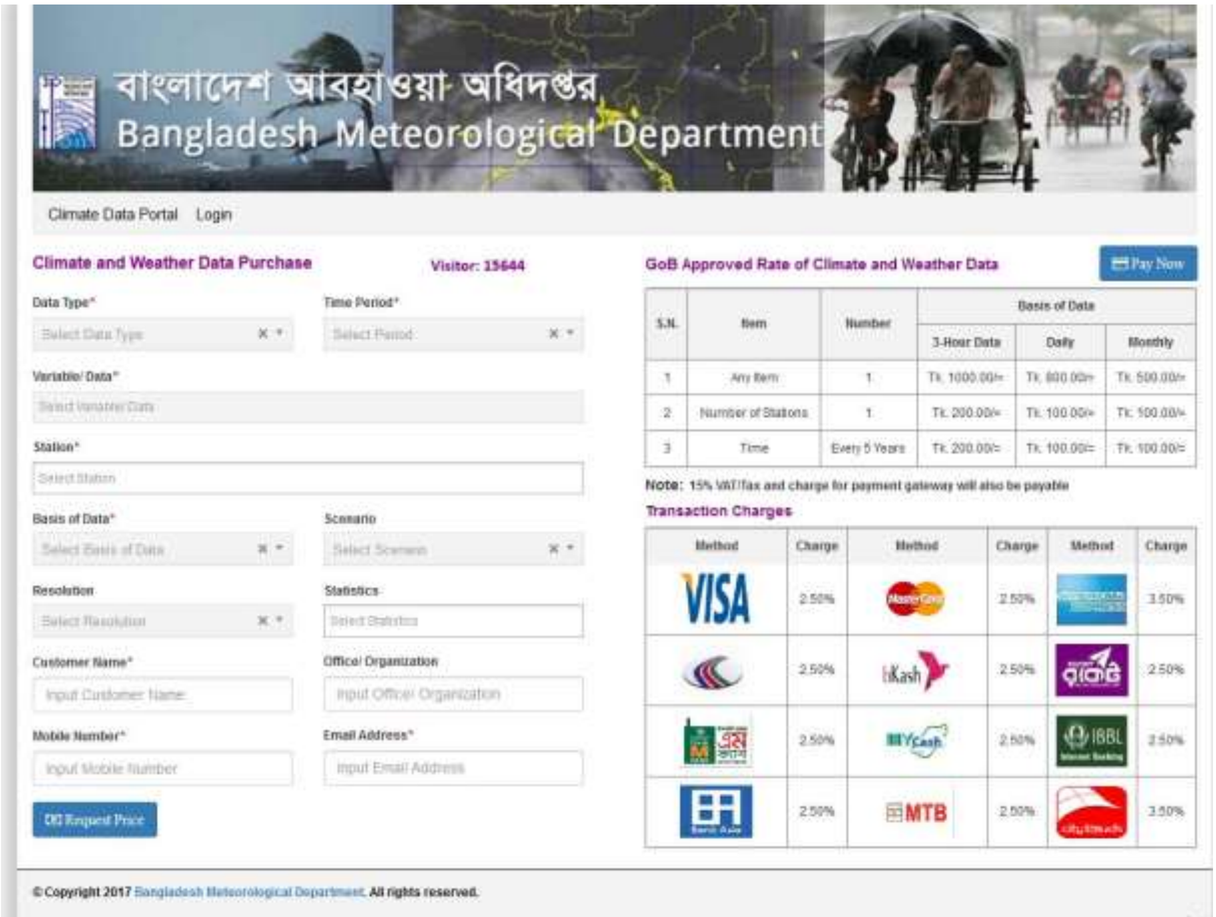
List of upper air observation

20	Wind Speed at Different heights	Upper Air Data	6-hourly
21	Wind Direction at Different heights	Upper Air Data	6-hourly
22	Temperature at Different heights	Upper Air Data	6-hourly
23	Relative Humidity at Different heights	Upper Air Data	6-hourly
24	Geopotential Heights with Air Pressure	Upper Air Data	6-hourly

List of Agromet observation

Sunrise & Sunset of 64 districts	Astronomical Data	Daily
Beginning of Morning Twilight & End of Evening Twilight of 64 districts	Astronomical Data	Daily
Moonrise & Moonset of 64 districts	Astronomical Data	Daily
Sahari & Iftar timings of 64 districts	Astronomical Data	For the month of Ramadan
Moon phases of Bangladesh	Astronomical Data	At the time of occurrence
New Moon Co-ordinates	Astronomical Data	At the time of occurrence
Eclipses , Occultations & Transits	Astronomical Data	At the time of occurrence

Online Data Purchase



5.2 Developing Areas for Climate Division of BMD

Main Frame Server System

Climate division receives bundle of CL-17 of every previous month in every next month by post. Very recently online data receiving system through mail introduced. Number of manpower are engaged in data quality control, archiving and processing. To make the system easier, faster, Secure and up to date climate division require at least one main frame server.

Climate Data Management System

For the better-quality control, archiving and processing of departmental data base, climate division must have an up to date Climate Data Management System (CDMS). This will enable BMD to calculate, rearrange and reset in other formats to make it compatible for the research purposes according to the demand of the clients. This rearranged data will be supplied to the various stake holders.

Digital Archiving System

Right from the beginning observers are recording the observations in a hard copy named CL-17. These hard copies are stored in departmental storeroom. In course of time these hard copies are losing their temper. So, in future missing data rescue procedure may hamper. So, climate division requires a digital data archiving system.

Climate Prediction System

In present system climate division is not issuing any climate outlook or seasonal forecast. But it has become a public demand to have a seasonal forecast. For this purpose, climate division needs some resource person to trained up the existing selected manpower who will be able to provide seasonal forecast and also needs some necessary software.

Astronomical data processing system

BMD does not have any astronomical observatory. Hence, the necessary basic astronomical data of every year is downloaded from the official astronomical websites of UK and USA. This makes BMD dependable upon the external resources which makes the whole process very time consuming. To solve this problem, BMD needs own astronomical observatory, historical data base and data processing system.

Hi Speed internet system

Climate division need to provide data through mail. Every year in August climate division need to download astronomical data from UK and USA astronomical website for the next year. In these purpose climate division intents to install hi speed internet system.

Publication System

Climate division das not have their own publication system. But it possible to publish any journal from climate division that it wound become an income source of BMD.

SESSION 6: CLIMATE MODELLING

6.1 The climate system and its Components

The climate system can be divided into five components (Fig. 6.1) which are introduced below. The overview mentions some important processes as examples:

1. Atmosphere: Gaseous part above the Earth's surface including traces amounts of other gaseous, liquid and solid substances. Weather, radiation balance, formation of clouds and precipitation, atmospheric flow, reservoir of natural and anthropogenic trace gases, transport of heat, water vapor, tracers, dust and aerosols.
2. Hydrosphere: All forms of water above and below the Earth's surface. This includes the whole ocean and the global water cycle after precipitation has reached the Earth's surface. Global distribution and changes of the inflow into the different ocean basins, transport of ocean water masses, transport of heat and tracers in the ocean, exchange of water vapor and other gases between ocean and atmosphere, most important reservoir of carbon with fast turnover.
3. Cryosphere: All forms of ice in the climate system, including inland ice masses, ice shelves, sea ice, glaciers and permafrost. Long-term water reserves, changes of the radiation balance of the Earth surface, influence on the salinity in critical regions of the ocean.
4. Land Surface: Solid Earth. Position of the continents as a determining factor of the climatic zones and the ocean currents, changes in sea level, transformation of short-wave to long-wave radiation, reflectivity of the Earth's surface (sand different from rock, or other forms), reservoir of dust, transfer of momentum and energy.
5. Biosphere: Organic cover of the land masses (vegetation, soil) and marine organisms. Determines the exchange of carbon between the different reservoirs, and hence the concentration of CO2 in the atmosphere, as well as the balances of many other gases, and therefore also the radiation budget. Influences the reflectivity of the surface, hence the radiation balance (e.g., tundra different from grassland), regulates the water vapor transfer soil-atmosphere, and via its roughness, the momentum exchange between the atmosphere and the ground.

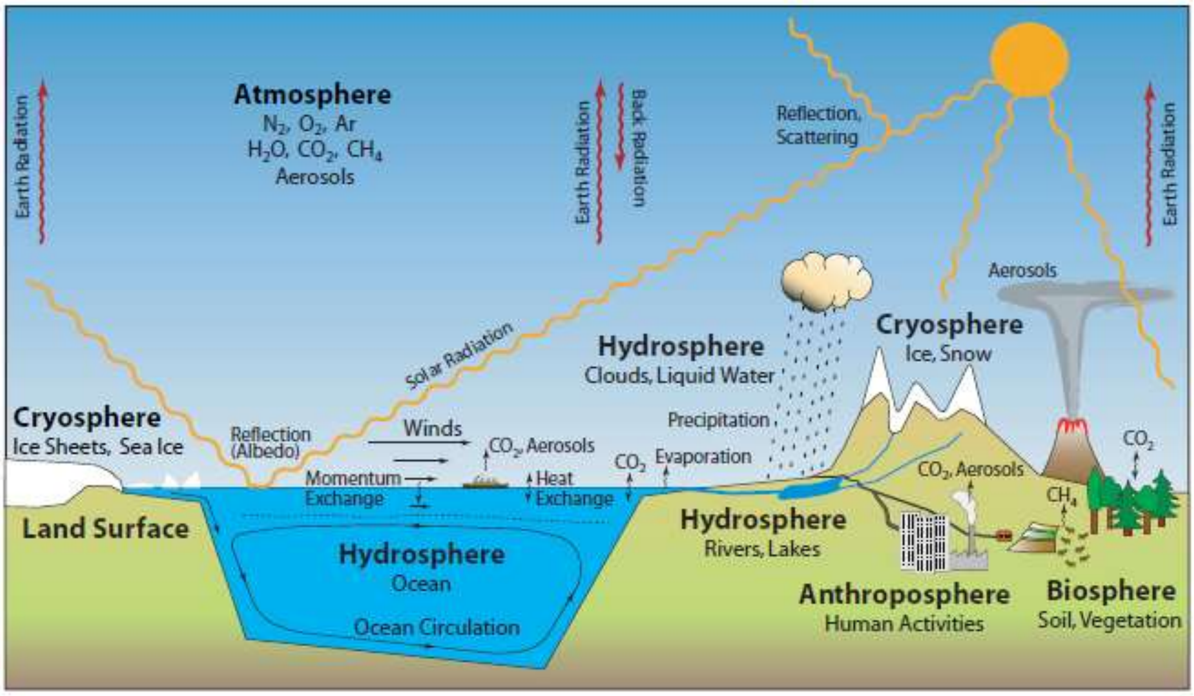


Fig. 6 1: The most important components and associated processes of the climate system on a global scale.

A sixth component, which is particularly relevant for the assessment of future changes, is often treated as a distinct part of the climate system: the anthroposphere, consisting of the processes which are caused or altered by humans. The most important ones are the emission of substances which alter the radiation balance, and land use change (deforestation, desertification, degradation and transformation into constructed areas).

Most of the climate models treat processes and fluxes of the anthroposphere as an external forcing, i.e., the models are run by prescribing atmospheric concentrations and emissions of CO2. Prescribed are also dust and sulphate emissions from volcanoes: for the past based on documented data and paleoclimatic information of volcanic eruptions, for the future they may be based on the statistics of such events.

Table 1: Some examples of processes determining the climate with their characteristic time and spatial scales.

Component of the Climate System	Process	Characteristic Time Scale	Characteristic Spatial Scale
Atmosphere	collision of droplets during cloud formation	$10^{-6} - 10^{-3}$ s	10^{-6} m
	formation of convection cells	$10^{4} - 10^{5}$ s	$10^{2} - 10^{4}$ m
	development of large-scale weather systems	$10^{4} - 10^{5}$ s	$10^{6} - 10^{7}$ m
	persistence of pressure distributions	10^{6} s	$10^{6} - 10^{7}$ m
	Southern Oscillation	10^{7} s	10^{7} m
	troposphere-stratosphere exchange	$10^{7} - 10^{8}$ s	global
Hydrosphere	gas exchange atmosphere-ocean	$10^{-3} - 10^{6}$ s	$10^{-6} - 10^{3}$ m
	deep water formation	$10^{4} - 10^{6}$ s	$10^{4} - 10^{5}$ m
	meso-scale oceanic gyres	$10^{6} - 10^{7}$ s	$10^{4} - 10^{5}$ m
	propagation of Rossby waves	10^{7} s	10^{7} m
	El Niño	$10^{7} - 10^{8}$ s	10^{7} m
	turnover of deep water	$10^{9} - 10^{10}$ s	global
Cryosphere	formation of permafrost	$10^{7} - 10^{9}$ s	$1 - 10^{5}$ m
	formation of sea ice	$10^{7} - 10^{9}$ s	$1 - 10^{6}$ m
	formation of land ice masses	$10^{9} - 10^{11}$ s	$10^{2} - 10^{7}$ m
Land Surface	changes in reflectivity	$10^{7} - 10^{9}$ s	10^{2} m – global
	isostatic equilibration of the crust by covering ice masses	$10^{9} - 10^{11}$ s	10^{6} m – global
Biosphere	exchange of carbon with the atmosphere	$10^{4} - 10^{9}$ s	10^{-3} m – global
	transformation of vegetation zones	$10^{9} - 10^{10}$ s	$10^{2} - 10^{7}$ m

A complete climate model contains physical descriptions of all five components mentioned above and takes into consideration their coupling. Some components may be described in a simplified form or even be prescribed. Not all questions in climate sciences require a model comprising all components. It is part of the scientific work to select an appropriate model combination and complexity, so that robust results are produced for a specific science question.

Each climate system component operates on a range of characteristic temporal and spatial scales. The knowledge of these scales is necessary for a correct formulation of climate models. Table 6.1 summarizes some of relevant scales. Usually, the definition of processes to be represented in the model restricts the temporal and spatial resolution of the model's grid.

Global radiation balance of the climate system

The Sun is the only relevant energy source for the climate system on a temporal scale of less than about 106 years. The different energy fluxes are shown in Fig. 1.2. Coming from the Sun, on average 341 W/m2 reach the top of the atmosphere (this corresponds to about a quarter of the solar flux density, Solar Constant S0 =1367 W/m2), while barely half of this is available for heating of the Earth's surface. Major parts of the short-wave radiation are reflected by clouds or reflected directly on the Earth's surface itself and are absorbed by the atmosphere. Incoming radiation contrasts with surface long-wave outgoing radiation of around 396 W/m2. Through convection and evaporation, the surface loses another 100 W/m2, which would—if other important processes absent—result in a negative energy balance of the surface.

The natural greenhouse effect, caused by greenhouse gases such as H2O, CO2, CH4, N2O and further trace gases, is responsible for the infrared back-radiation of around 333 W/m2. This results in an energy balance with a global mean surface temperature of about 14°C.

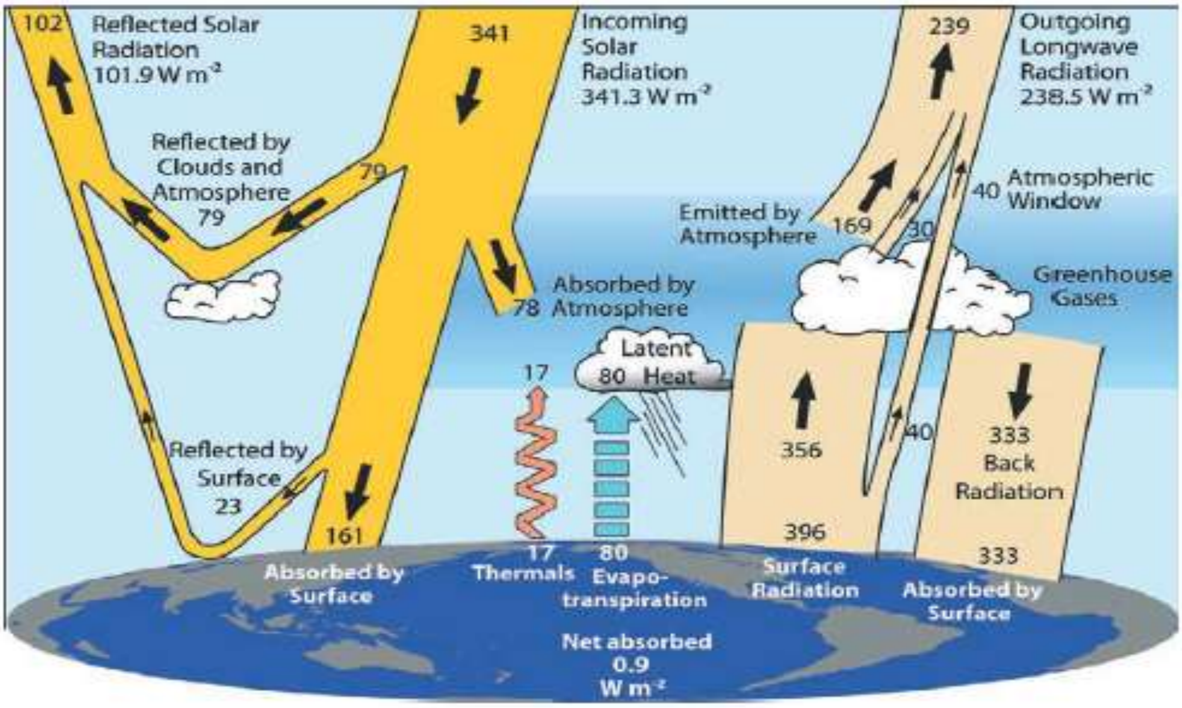


Figure 6.2: Global energy fluxes from different sources which determine the radiation balance of the Earth. Figure from Trenberth *et al.* (2009).

6.2 Climate Modelling

6.2.1 Introduction

Any climate model is an attempt to represent the many processes that produce climate. The objective is to understand these processes and to predict the effects of changes and interactions. This characterization is accomplished by describing the climate system in terms of basic physical, chemical and biological principles. Hence, a numerical model can be considered as being comprised of a series of equations expressing these laws. Climate models can be slow and costly to use, even on the fastest computer, and the results can only be approximations.

A model must be a simplification of the real world. The processes of the climate system are not fully understood, although they are known to be complex. The components of the climate system interact with each other, producing feedbacks, so that any solution of the governing equations must involve a great deal of computation. The solutions that are produced start from some initialized state and investigate the effects of changes in a particular component of the climate system. The boundary conditions, for example the solar radiation, sea-surface temperatures or vegetation distribution in the case of the atmosphere, or the bathymetry and atmospheric wind field in the case of the ocean, are set from observational data or other simulations. These data are rarely complete or of adequate accuracy to specify completely the environmental conditions, so that there is inherent uncertainty in the results.

In this process the simplifications of the laws of governing climatic processes are approached in several ways. In general, two sets of simplifications need to be made. The first involves the processes themselves. It is usually possible to treat in detail some of the processes, specifying their governing equations fairly fully. However, other processes must be treated in an approximate way, either because of our lack of exact information, lack of understanding or because there are still inadequate computer resources to deal with them. The second set of simplifications involves the resolution of the model in both time and space. While it is generally assumed that finer spatial resolutions produce more reliable results, constraints of both data availability and computational time may dictate that a model may have to have, for example, latitudinally averaged values as the basic input. In addition, too fine a resolution may be inappropriate because processes acting on a smaller scale than the model is designed to resolve may be inadvertently incorporated. Similar considerations are involved in the choice of temporal resolution. Most computational procedures require a 'time step' approach to calculations. The processes are allowed to act for a certain length of time and the new conditions are calculated. The process is then repeated using these new values. This continues until the conditions at the required time have been established. Time stepping is a natural consequence of there not being a steady state solution to the model equations.

6.2.2 Purpose and Limitations of Climate Modelling

Until around the early 20th century, climate sciences were primarily concerned with the study of past climatic states. This was done by observation of the environment using mostly geological, geographical and botanical methods. By the end of the 1950ies, important physical measurement methods were developed. The measurement of weak radioactivity of various isotopes was the basis for the dating of organic material and enabled the determination of flux rates in different environmental systems. The measurement of the stable isotopes in precipitation revealed a conspicuous temperature dependence. By analyzing stable isotope ratios in permanently deposited water (i.e., polar ice) a natural "paleo-thermometer" was realised.

The determination of the concentration of trace gases and other tracers in ice cores from Antarctica and Greenland made it possible, for the first time, to produce an accurate reconstruction of the chemical composition of the atmosphere. By exploring different paleoclimatic archives, which may be described as environmental systems that record and conserve physical quantities varying with time, an important step towards a quantitative science was taken. Such archives include ice cores from Greenland and Antarctica, ocean and lake sediments, tree rings, speleothems, and many more. This enabled the transition of climate science from the purely descriptive to a quantitative science providing numbers with units.

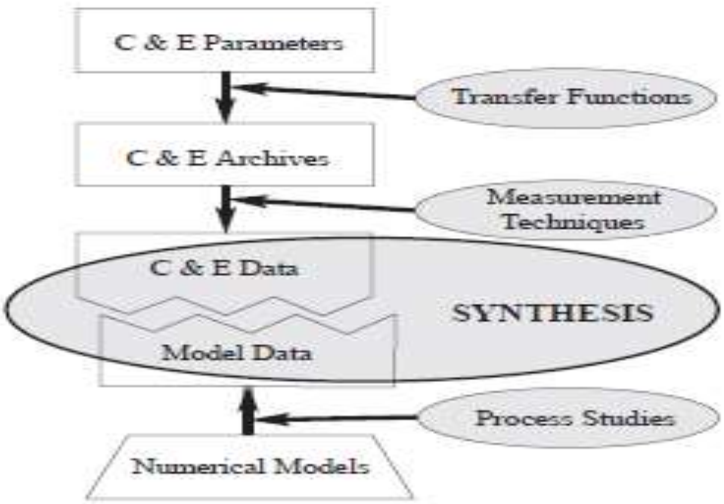


Figure 6.3: The role of climate modeling in climate science. C & E stands for *climate and environmental*

The increasingly detailed paleo-data require that hypotheses are quantitatively captured with regard to the mechanisms responsible for climate change. This is where climate modelling begins. Its goal is the understanding of the physical and chemical information and data retrieved from, among others, paleo-data. Such models permit a quantitative formulation and testing of hypotheses about the causes and mechanisms of past, and the magnitude and impact of future climate change.

Figure 6.3 visualizes the role of modelling in paleoclimate science in a schematic way. Climate change alters certain climate and environmental (C & E) parameters which then can be "read" using appropriate transfer functions. Even in this case, model formulation and application play a central role, but the term climate modelling is not applicable. Climate archives can only be made accessible to research by reliable measurement techniques. An experimental physicist produces climate data (e.g., the reconstruction of the atmospheric CO_2 concentration over the past 800,000 years). The modeler works on the development and application of models that yield model results within the framework process studies. The goal is the synthesis of model results and climate data, which is achieved when the underlying mechanisms and hypotheses are in quantitative agreement. Hence, the model yields *a quantitative interpretation of the evolution of climate*, based on the laws of physics and chemistry. The evolution of the annual mean surface temperature averaged over the northern hemisphere over the course of the last 1,200 years is part of some of the most important climatic information in the debate on current climate change (Fig. 6.4).

A central question, that has to be resolved by models, is whether the reconstructed warming—and what fraction of it—can be explained by the increase in atmospheric CO2 and the resulting changes in the radiation budget. The modelling of the last 1,200 years of climate evolution necessitates an accurate knowledge of the different forcing to the radiation budget and a credible representation of natural variations by climate models. The most important forcing are the variations in solar radiation, the magnitude, location and duration of volcanic eruptions, the changes in land cover by deforestation and other activities and variations in concentration of climate relevant atmospheric tracers. Besides sophisticated statistical methods, only climate models are able to answer these questions in a quantitative way.

Figure 6.4 compares the most recent reconstructions of northern hemispheric temperature with those simulated by an ensemble of climate models run over the past millennium and forced by prescribed solar variations and volcanic eruptions. The model simulations exhibit variations within the range of reconstructed temperatures over the past 1,150 years and reproduce the significant increase in northern hemispheric temperature during the 20th century. Some paleoclimate reconstructions suggest warm temperatures around the year 1000 CE but climate models do not show such anomalies during that period. Multi-annual cooling caused by volcanic eruptions are well simulated.

The estimation of the climate sensitivity, that is the increase in the global mean temperature with a doubling of the atmospheric CO2 concentration above the preindustrial level (from 280 ppm to 560 ppm), provides important information about the coupled climate system. Models, that are employed to address this question, must be capable of simulating the natural climate variability as well as past climate changes in a quantitatively correct manner.

An example is shown in Fig. 6.5. Here, the Bern2.5d model, a simplified climate model that describes the large-scale processes in the ocean and atmosphere, was used (Stocker et al., 1992; Knutti et al., 2002). The globally averaged warming, which is observed between 1860 and 2000 (grey band) can roughly be reproduced with different model simulations (lines). While the long-term trend is modeled in an acceptable way, single variations on a time scale of less than 10 years can only partly be captured. The uptake of heat by the ocean is only simulated in broad terms. The important deviations between 1970 and 1990 in ocean heat uptake may well be captured by particular simulations but, until today, have not been explained by climate models in a satisfactory way. However, this is a rare, but interesting example of a case in which a recent correction of the observational database has brought an improvement of the correspondence between experimental and computed data (Domingues et al., 2008).

As any mathematical model of natural systems, a climate model is a simplification. The degree of accepted simplification determines the complexity of the model and restricts the applicability of the model to certain questions. Hence, the complexity of a chosen model sets the limitations to its application. Determining these limitations requires considerable experience since no objective rules or guidelines exist. Especially for the development of climate models, particular care and a natural skepticism are needed: It is not desirable to implement and parametrise all processes without careful consideration of overall model consistency. The quality of a climate model is not judged by the mere number of processes considered, but rather by the quality of how chosen processes and their couplings are reproduced.

Of course, it is the duty of research and development to continuously increase the resolution and realism of climate models and this is happening at a fast pace. However, this rather quickly and regularly reaches the limits of computing resources particularly if long-term simulations (e.g., over 105 years or more) are performed. For this reason, intelligent simplifications and models of reduced complexity are required. This becomes manifest in the way how a hierarchy of models is used in current climate research.

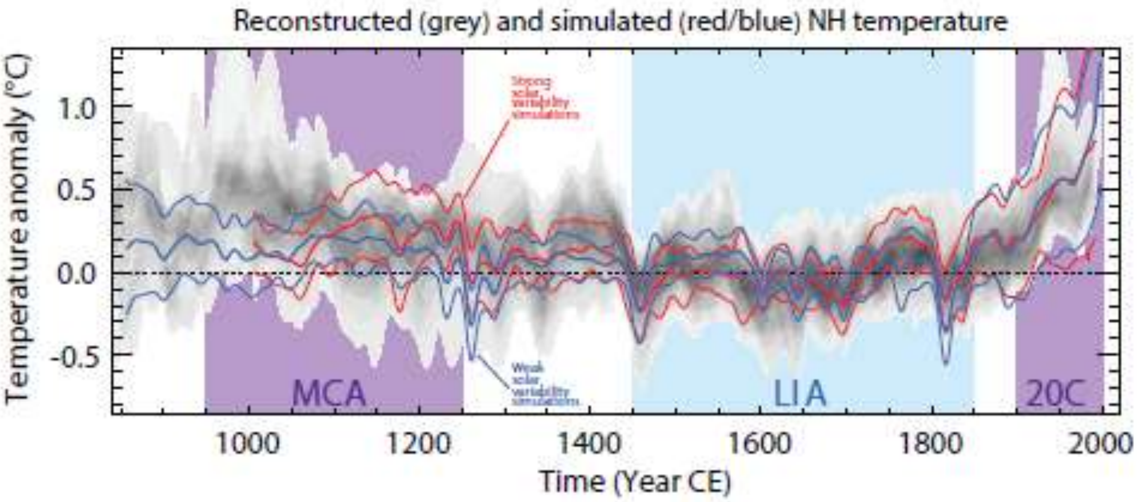


Figure 6.4: Comparison of climate model simulations and reconstructions of annual temperatures in the Northern Hemisphere over the last 1,150 years that are based on information from various paleoclimatic archives (tree rings, lake sediments, borehole temperatures, ice cores). Simulations shown by *colored lines* (*thick lines*: multi-model-mean; *thin lines*: multi-model 90% range; *red/blue lines*: models forced by stronger/weaker solar variability, though other forcings and model sensitivities also differ between the *red* and *blue* groups); overlap of reconstructed temperatures shown by *grey shading*; *darker grey* indicates more agreement between the various paleoclimate reconstructions. Distinct climate periods of the last millennium are indicated: Medieval Climate Anomaly (MCA), Little Ice Age (LIA), and 20th Century (20C). A significant temperature increase over the last 100 years can be identified. All data are expressed as anomalies from their 1500–1850 mean and smoothed with a 30-year filter. Figure from IPCC (2013), Fig. 5.8.

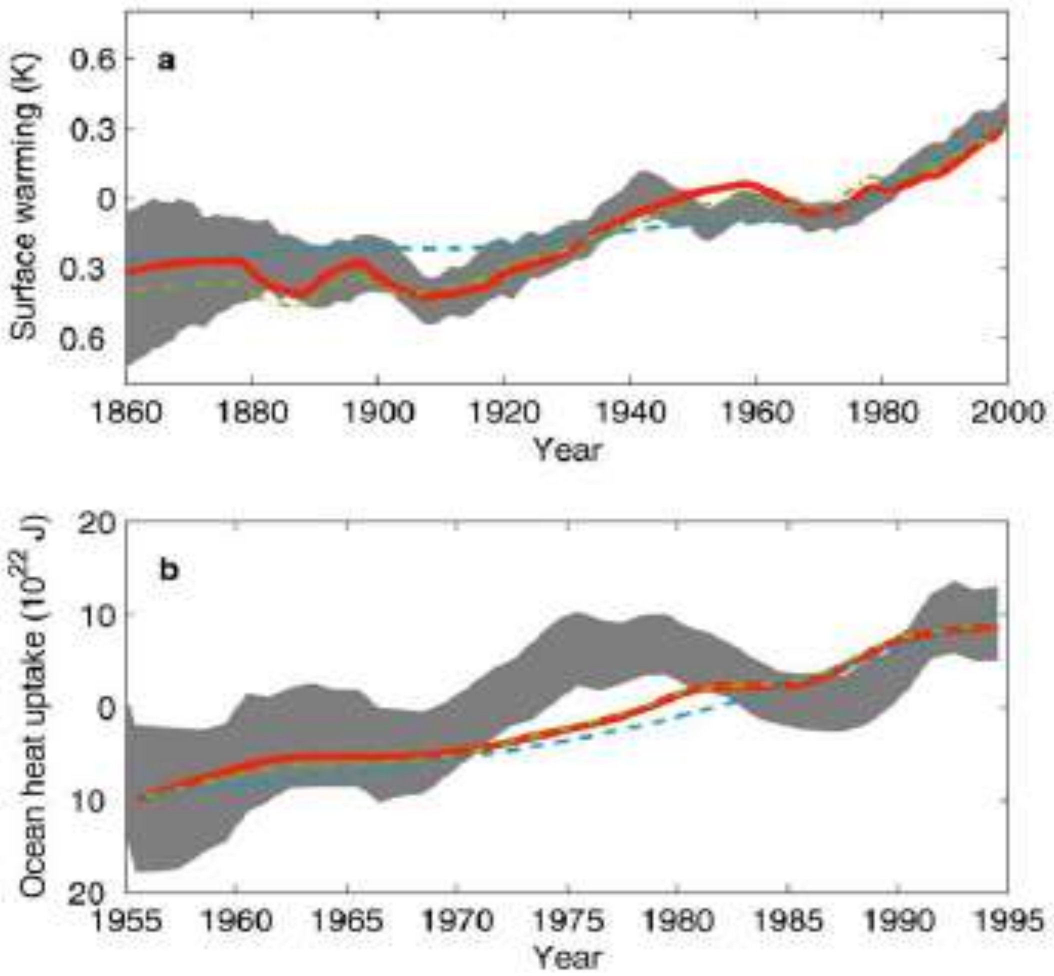


Figure 6.5: Changes in global mean temperature since 1860 a), and heat uptake in the ocean since 1955 b). *Grey bands* for observations and *lines* for different model runs. Figure from Knutti et al. (2003).

6.3 Types of Climate Models

The important components to be considered in constructing or understanding a model of the climate system are:

i. *Radiation:* the way in which the input and absorption of solar radiation by the atmosphere or ocean and the emission of infrared radiation are handled.

ii. *Dynamics:* the movement of energy around the globe by winds and ocean currents (specifically from low to high latitudes) and vertical movements (e.g. small-scale turbulence, convection and deep-water formation);

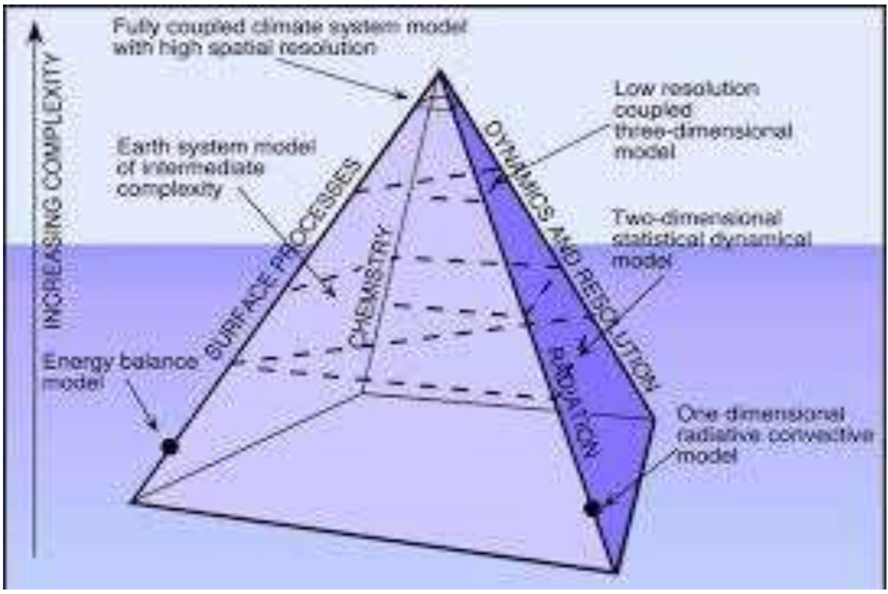
iii. *Surface processes:* inclusion of the effects of sea and land ice, snow, vegetation and the resultant change in albedo, emissivity and surface–atmosphere energy and moisture interchanges.

iv. *Chemistry:* the chemical composition of the atmosphere and the interactions with other components (e.g. carbon exchanges between ocean, land and atmosphere);

v. *Resolution in both time and space:* the time step of the model and the horizontal and vertical scales resolved.

The relative importance of these processes and the theoretical (as opposed to empirical) basis for parameterizations employed in their incorporation can be discussed using the climate modelling pyramid (Figure 6.6). The edges represent the basic elements of the models, with complexity shown increasing upwards. Around the base of the pyramid are the simpler climate models which incorporate only one primary process. There are four basic types of model.

Figure 6.6: The climate modelling pyramid. The position of a model on the pyramid indicates the complexity with which the four primary processes (dynamics, radiation, surface and oceans and chemistry) interact. Progression up the pyramid leads to greater interaction between each primary process.



The vertical axis is not intended to be quantitative. The position of various model types is indicated in the figure.

a) Energy balance models (EBMs) are zero- or one-dimensional models predicting the surface (strictly the sea-level) temperature as a function of the energy balance of the Earth. Simplified relationships are used to calculate the terms contributing to the energy balance in each latitude zone in the one-dimensional case.

b) One-dimensional models such as radiative–convective (RC) models and single column models (SCMs) focus on processes in the vertical. RC models compute the (usually global average) temperature profile by explicit modelling of radiative processes and a 'convective adjustment' which re-establishes a predetermined lapse rate. SCMs are single columns 'extracted' from a three-dimensional model and include all the processes that would be modelled in the three-dimensional version but without any of the horizontal energy transfers.

c) Dimensionally constrained models now take a wide variety of forms. The oldest are the statistical dynamical (SD) models, which deal explicitly with surface processes and dynamics in a zonally averaged framework and have a vertically resolved atmosphere. These models have been the starting point for the incorporation of reaction chemistry in global models and are still used in some Earth Models of Intermediate Complexity (EMICs).

d) Global circulation models (GCMs). The three-dimensional nature of the atmosphere and ocean is incorporated. These models can exist as fully coupled ocean–atmosphere models or 'coupled climate system models' or, for testing and evaluation, as independent ocean or atmospheric circulation models. These models attempt to simulate as many processes as possible and produce a three-dimensional picture of the time evolution of the state of the ocean and atmosphere. Vertical resolution is typically much finer than horizontal resolution but, even so, the number of layers is usually much less than the number of columns.

The vertical axis in Figure 6.6 shows increasing complexity (i.e. more processes included and linked together) and also indicates increasing resolution: models appearing higher up the pyramid tend to have higher spatial and temporal resolutions.

6.3.1 Dimensionally Constrained Climate Models

Dimensionally constrained climate models typically represent either two horizontal dimensions or the vertical plus one horizontal dimension. The latter were originally more common, combining the latitudinal dimension of the energy balance models with the vertical one of the radiative–convective models. These models also tended to include a more realistic parameterization of the latitudinal energy transports. In such models, the general circulation is assumed to be composed mainly of a cellular flow between latitudes, which is characterized using a combination of empirical and theoretical formulations. A set of statistics summarizes the wind speeds and directions while an eddy diffusion coefficient of the type used in EBMs governs energy transport. As a consequence of this approach, these models are called 'statistical dynamical' (SD) models. These 2D SDs can be considered as the first attempts at Earth modelling with intermediate complexity- the EMICs.

6.3.2 General Circulation Models

The aim of GCMs is the calculation of the full three-dimensional character of the atmosphere or ocean (Figure 6.2). The solution of a series of equations (Table 6.1) that describe the movement of energy, momentum and various tracers (e.g. water vapour in the atmosphere and salt in the oceans) and the conservation of mass is therefore required. Generally, the equations are solved to give the mass movement (i.e. wind field or ocean currents) at the next timestep, but models must also include processes such as cloud and sea ice formation and heat, moisture and salt transport.

The first step in obtaining a solution is to specify the atmospheric and oceanic conditions at a number of 'grid points', obtained by dividing the Earth's surface into a series of rectangles, so that a traditionally regular grid result (Figure 6.3). Conditions are specified at each grid point for the surface and several layers in the atmosphere and ocean. The resulting set of coupled non-linear equations is then solved a teach grid point using numerical techniques. Various techniques are available, but all use a timestep approach.

Table 6.1 Fundamental equations solved in GCMs

#	Equation
1.	*Conservation of energy* (the first law of thermodynamics) i.e., Input energy = increase in internal energy plus work done
2.	2. *Conservation of momentum* (Newton's second law of motion) i.e., Force =mass×acceleration
3.	*Conservation of mass* (the continuity equation) i.e., The sum of the gradients of the product of density and flow-speed in the three orthogonal directions is zero. This must be applied to air and moisture for the atmosphere and to water and salt for the oceans but can also be applied to other atmospheric and oceanic 'tracers' such as cloud liquid water.
4.	*Ideal gas law* (an approximation to the equation of state – atmosphere only) i.e. Pressure×volume is proportional to absolute temperature× density

6.3.3 Energy Balance Models

Balancing the planetary radiation budget

Balancing the planetary radiation budget offers a first, simple approximation to a model of the Earth's climate. The radiation fluxes and the equator-to-pole energy transport are the fundamental processes of the climate system incorporated in EBMs.

6.3.3.1 The structure of Energy Balance Models

The simplest method of considering the climate system of the Earth, and indeed of any planet, is in terms of its global energy balance. Viewing the Earth from outside, one observes an amount of radiation input which is balanced (in the long term) by an amount of radiation output. Since over 70 per cent of the energy which drives the climate system is first absorbed at the surface, the surface albedo will be predominant in controlling energy input to the climate system. The output of energy will be controlled by the temperature of the Earth but also by the transparency of the atmosphere to this outgoing thermal radiation. An EBM can take two very simple forms. The first form, the zero-dimensional model, considers the Earth as a single point in space having a global mean effective temperature. The second form of the EBM considers the temperature as being latitudinally resolved. Figure 6.7 illustrates these two approaches.

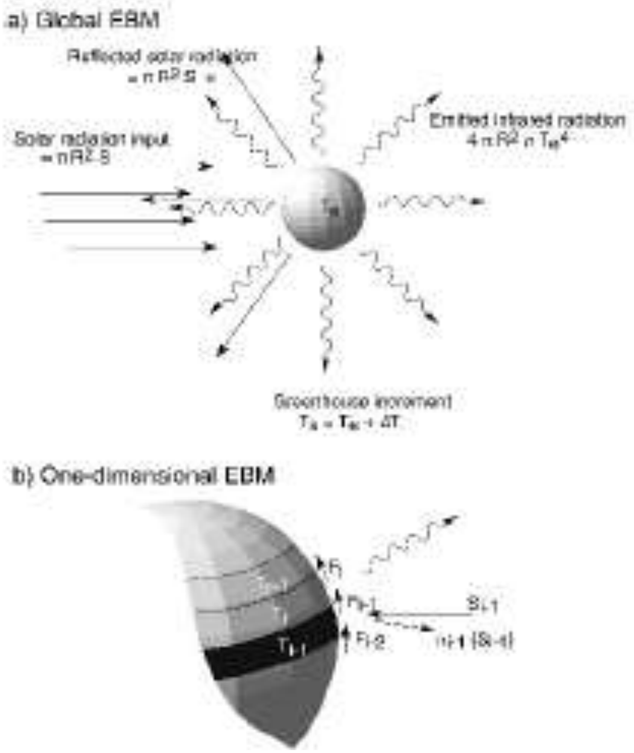


Figure 6.7 Energy transfers in (a) a global EBM and (b) a zonal EBM

6.3.4 One-Dimensional Radiative Convective Models

In earlier chapters, the importance of the greenhouse effect was noted. This effect is due to the absorption of the upwelling thermal infrared radiation that has been emitted by the surface of the Earth. If none of the gases in the Earth's atmosphere possessed absorption features in the wavelength region in which the Earth emits radiation, there would be no greenhouse addition and the surface temperature would be equal to the planetary effective radiative temperature (see Figure 6.7). The greenhouse absorbers not only affect the surface temperature, they also modify the atmospheric temperature by their absorption and emission of radiation. Radiative–convective models were developed primarily to allow examination of these radiative effects in the Earth's atmosphere.

Radiative–convective (RC) climate models are one-dimensional models like the EBMs described in Chapter 6. In this case, however, the dimension is the vertical. These models resolve many layers in the atmosphere and seek to compute atmospheric and surface temperatures. They can be used for sensitivity tests and, importantly, offer the opportunity to incorporate more complex radiation treatments than can be afforded in GCMs.

6.3.5 Dimensionally Constrained Climate Models

Dimensionally constrained climate models typically represent either two horizontal dimensions or the vertical plus one horizontal dimension. The latter were originally more common, combining the latitudinal dimension of the energy balance models with the vertical one of the radiative–convective models. These models also tended to include a more realistic parameterization of the latitudinal energy transports. In such models, the general circulation is assumed to be composed mainly of a cellular flow between latitudes, which is characterized using a combination of empirical and theoretical formulations. A set of statistics summarizes the wind speeds and directions while an eddy diffusion coefficient of the type used in EBMs governs energy transport. As a consequence of this approach, these models are called 'statistical dynamical' (SD) models. These 2D SDs can be considered as the first attempts at Earth modelling with intermediate complexity – the EMICs.

6.3.6 Sensitivity of Climate Models

An important stage in the development of climate models is a series of sensitivity tests. Modelers examine the behavior of their modelled climate system by altering one component and studying the effect of this change on the model's climate.

Equilibrium climatic states

As an example of a change in an internal variable we can consider the variation in the albedo, α, as a function of the mean global temperature in an EBM. Above a certain temperature, Tg, the planet is ice-free, and the value of the albedo is independent of temperature. As it becomes colder, we expect the albedo to increase as a direct result of increases in ice and snow cover. Eventually the Earth becomes completely ice-covered, at temperature Ti, and further cooling will produce no further albedo change. This could be expressed in the form

$$\alpha(T) = \alpha_i \text{..........................for } T \leq T_i$$

$$\alpha(T) = \alpha_g \text{..........................for } T \geq T_g$$

$$\alpha(T) = \alpha_g + b(T_g - T) \text{............for } T_i < T < T_g$$

Where, bis the rate of change of α as the temperature decreases. Ti is usually assumed to be 273K but may range between 263 and 283K. If we are concerned with equilibrium conditions (i.e., when the left-hand side of Equation (2.1) is zero) we can calculate R↑for a series of temperatures and R↓ for a series of albedos and show the results graphically. The points of intersection of the curves occur when emitted and absorbed radiation fluxes balance (i.e. R↓=R↑) which represent the equilibrium situations (Figure 2.7). Any slight imbalances between the fraction of the incident solar radiation, S, absorbed, S(1 -α (T)), and the emitted longwave flux at the top of the atmosphere, approximated by $\varepsilon\sigma T4$, where $\varepsilon$is the emissivity, lead to a change in the temperature of the system at the rate $\Delta T/Dt$, the changes serving to return the temperature to an equilibrium state. However, there are three equilibrium solutions, as shown in Figure 2.7: an ice-free Earth (1), a completely glaciated (or 'Snowball') Earth (3) and an Earth with some ice (2) (e.g. the present situation of the planet). All are possible.

6.4 Working with Climate Models

There is a wide variety of climate models with different characteristics and different applications. Even within one particular climate model type (e.g. three-dimensional models) there are many different features and stages of development. Moreover, because climate models share a commonality of purpose, it is possible, and often useful, to apply different climate model types to the same prediction task. The result of this profusion of model types and model characteristics is a bewildering array of models and model predictions. This array of predictions and predictive capability, combined with the continuing role of computer technology in model development, has prompted the climate modeling community to undertake a number of different initiatives that formalize some previously ad hoc practices. The community has developed a range of data interchange standards, has begun to generate a framework for the development of climate system models, and has initiated a series of model inter-comparisons and evaluations of performance. It is vital that anyone planning the use of climate model results, or embarking on a climate modelling project, is familiar with the development framework in which these models are produced.

6.5 Data Interchange

Much of the early development of climate models was undertaken in well-resourced government laboratories such as the United Kingdom Meteorological Office and GFDL. These establishments developed monolithic frameworks for their models. Models were focused on the computer architecture available and tailored to the local data storage system. Data formats were invariably unique to the model, often with compression or other techniques used to manage the use of the limited non-volatile storage space (what we now know as 'disk space'). For example, to save space, a modeller might combine two different variables in a single two-dimensional field, with special 'decoding' instructions required to understand the significance of the 'odd' numbers in regions of (say) sea ice. The digital archives so created necessarily had an accompanying paper archive that explained the intricacies of the stored files. With limited interoperability of computer systems and the lack of direct network connections, data interchange between computer systems was a cumbersome and technically involved process. As computer systems developed, the infrastructure for data interchange and interoperability also developed. The development of the UnixTM operating system and its near siblings and their near universal implementation on modern computers and the rapid development of high-speed data communications have been the key enabling factors in the growth of model inter-comparisons.

New technologies for data interchange amplified the problems associated with monolithic development. For inter-comparisons to be successful, some standard for data interchange and documentation must be developed. One such standard is the NetCDF (Network Common Data Format) file standard developed by Unidata as a means for data transfer between Unidata applications. The concept is implemented as a library of computer 'functions' that can be assembled by a user to access or create NetCDF files. The files are self-describing, machine-independent datasets that can be readily interchanged between users without the need for supplementary materials. The files can contain data of different types, multiple variables as well as ancillary data or descriptive text. This philosophy is intended to reduce errors arising from misinterpreting data and reduces the costly effort associated with conversion between data formats.

Data management is, however, a growing part of the climate modeller's skill set. Modellers must manage datasets produced by their model (perhaps several Gb per simulated year) and also manage observational datasets used for validation and forcing. The exponential growth of this data volume, as model resolutions and integration times have increased, has led to the development of various distributed data technologies. Instead of modellers transferring data from one machine to another, the NetCDF libraries have been recently extended to function in a distributed manner. Originally designed for oceanographic data, the OPeNDAP/DODS data access protocol simplifies data distribution and is a protocol for requesting and transporting data across the Internet, based on the client–server model. Data are distributed without regard to local storage format. Anyone with a digital data archive can configure their archive as an OPeNDAP/DODS server and make it available to clients in the science community. OPeNDAP/DODS is a community-driven project and is based on the idea that datasets are often best distributed by their creators. This allows for appropriate updating and documentation of changes and saves the need for multiple copies of data (potentially differently described) being stored at multiple locations. Data can be accessed at remote locations and these remote data analysis and visualization systems can be modified to be OPeNDAP/DODS clients, retrieving data at the application level, instead of requiring the user to collect and store copies of a dataset.

6.6 Earth System Modelling Framework

The history of the climate modelling community, which grew up around, and in support of, models developed at large institutions, has also affected the level to which modelling developments have propagated through the community. Amodeller at one institution, developing a new cloud parameterization scheme for example, cannot easily transfer this scheme to another model. If a modelling group decides to implement such a scheme in their model, it is likely that significant code development will need to be undertaken. Even if the module can be compiled on the adopter's computer, there are likely to be problems integrating the new scheme with a different model grid or time stepping scheme. There may also be aspects of the new module that implicitly require a specific environment to be available at the developer's institution (e.g. particular disk and tape storage technologies).

The desire to improve collaboration and reduce development time, together with the development of climate model inter-comparisons, has meant an increased demand for interchangeability of model components. Modellers are keen to test the performance of their atmospheric models with different ocean model schemes and different land-surface schemes. To this end, the development of an Earth System Modelling Framework (ESMF) has been proposed, to enhance interoperability and performance of large modelling ventures. The motivation for ESMF is three-fold: (i) climate models are increasingly composed of highly specialized modules contributing to a modelling 'system'; (ii) computer hardware and software are becoming increasingly complex as high-performance computing relies more heavily on massively parallel systems and scalable computing architectures such as the 'Earth Simulator'; and (iii) a number of modelling frameworks have been developed that encourage interoperability and reuse of software. ESMF is likely to make significant headway in promoting exchange of model components. Not only does such a scheme make interchange between large organizations possible, but modelling innovations by smaller groups (typically university groups) can be readily implemented into large coupled modelling projects without expensive recoding, making model development a truly distributed process.

At its most basic, ESMF provides a means for assembling geophysical component models into applications. This is best illustrated by means of an example. If a modelling group wishes to create an ESMF component model from (say) their land surface scheme, a number of steps are involved. The ESMF architecture is characterized by a 'sandwich' design (Figure 6.1). The three components are illustrated in Figure 6.1a for the ESMF application. The superstructure provides a shell to encompass the user's code and an infrastructure layer provides foundation components that users can use to speed construction and ensure consistent behaviour. For example, the ESMF clock 'objects' provide a consistent notion of time between components. This is an important aspect of model coupling, since different model components may operate on different timesteps. The encapsulation of legacy code within ESMF means that modern object-oriented techniques can be applied where traditional programming techniques would normally prohibit such an approach. ESMF could be used to link three models with very different grid structures. Because each developer would have created an ESMF application from her or his code, coupling becomes relatively straightforward. A spectral atmospheric model could be connected to a finite grid ocean model and a land-surface scheme configured as a 'mosaic' grid. Figure 6.1b illustrates how the infrastructure layer organizes grid information in a hierarchical manner. A 'field' contains much more than the data; it also contains metadata about the variable (e.g. humidity). The 'grid' class contains information about the physical grid and information about how computations can be made.

Although the addition of extra code inevitably results in reduced model performance, the ESMF project has a goal of showing less than 10 per cent degradation in performance of the model. The first version of ESMF was released in 2003 and development is set to continue into 2005.

6.7 Model Evaluation

All models of the climate system must face evaluation as part of their development. Computer systems in the 1960s and 1970s had very limited interoperability and networking capability and, because of these limitations on the exchange of model output, early modellers had to be satisfied with comparisons to observed data where available. Inter-model comparisons were frequently restricted to 'eyeball' evaluations of differences. The advent of interoperable computer networks since those early comparisons has led to increased data interchange between modelling groups, to the development of protocols for evaluation of models and to organized model inter-comparison projects (MIPs).

Evaluation of climate models can produce a range of outcomes that have been grouped as (i) predictions that are unreasonable; (ii) predictions that are so reasonable as to be already known; (iii) unexpected predictions, which can be readily understood and accepted; or (iv) predictions that, while being reasonable, identify novel outcomes that challenge current theories. Normal practice in model development would screen out all developments producing unreasonable results, and there is little benefit in inter-comparison of results that are totally reasonable and well known. Thus, the inter-comparisons and group evaluations tend to try to focus on results in categories (iii) and (iv): new predictions that are consistent with theory and those that challenge existing ideas.

The process of comparison of model predictions and group evaluation is complex as it has to encompass models and modelling groups from around the world and has to be organized so that comparable results are being compared. To facilitate the process of model evaluation and inter-comparison, the WCRP's Working Group on Numerical Experimentation (WGNE) categorized inter-comparisons into three levels (Figure 6.2). Level 1, the simplest, uses any available model results and a common diagnostic set. The IPCC assessments are Level 1 inter-comparisons. Level 2 requires that the simulations are made according to pre-specified, identical conditions, that common diagnostics are employed and that there is a common diagnostic set against which all the predictions are evaluated. Level 3, the 'best' inter-comparison process, requires, in addition to the requirements of the lower two levels, that all the models employ the same resolution and that the inter-comparison includes the use of some common routines or code modules.

Until the 1990s, inter-comparisons were conducted at Level 1. The Atmospheric Model Inter-comparison Project initiative (begun in the early 1990s) has spawned around 30 different MIPs which are inter-comparisons at Level 2 – some of these are described in the following sections. At the time of writing, there are no Level 3 inter-comparisons, although some of the Level 2 inter-comparisons are planned later to develop common code modules. The Earth System Modelling Framework (ESMF), discussed in Section 6.3, will provide a robust methodology for Level 3 inter-comparisons, with interchangeable code modules.

6.8 Inter-comparisons facilitated by technology

Most of the recent climate model inter-comparisons have only been possible because of the advent of global telecommunications and the accompanying data interchange standards. The Internet is an essential part of a Level 2 or higher inter-comparison. Typically, a coordinating group is identified, and this group takes responsibility for the provision of the agreed model simulation instructions, including the experimental design and the forcing data based on either email discussions or a faceto-face workshop. The coordinating group typically also provides independent data against which to compare the model results and facilitates model inter-comparisons by providing quality control procedures and a central electronic results and data 'library', which can be accessed by all the participating modelling groups. The demands associated with providing these facilities are quite considerable. This is one of the reasons why Level 2 inter-comparisons have so far been restricted to specific aspects of the whole climate system. The following sections review, as examples, inter-comparisons of atmospheric and coupled models, radiation schemes, land-surface schemes and ocean carbon models.

6.9 AMIP and CMIP

AMIP, the Atmospheric Model Inter-comparison Project, was established in 1989 and moved into its second stage (AMIP II) in 1996. It focuses on structured (Level 2) inter-comparisons of the atmospheric component of global climate models. Participating models use prescribed ocean surface temperatures and sea ice extents as well as agreed values of the solar constant

(1365Wm-2) and the atmospheric concentration of CO_2 (345 ppmv) as input to a fixed length simulation. The simulation period for AMIP I was from 1 January 1979 to 31 December 1988 and that for AMIP II from 1 January 1978 to 1 March 1996. The prescribed forcings did not extend to the use of common surface elevation information nor, in AMIP I, to an agreed spinup procedure, although for AMIP II there was such a recommended procedure.

All participating model groups (around 30–40) were required to submit output in an agreed format, but there was no requirement for a particular resolution. The results from these global atmospheric simulations have been reported in various of the IPCC Assessments as a partial demonstration of the validity of GCMs.

The Coupled Model Inter-comparison Project (CMIP) aims to extend the analysis of AMIP to coupled models. The project is ongoing and involves collecting both 'control run' simulations from available coupled models (18 at the time of writing) and from enhanced CO_2 experiments, with a specified increase in CO_2 of 1 per cent per annum. The models in CMIP are models of the atmosphere and ocean that include interactive sea ice and simulate the physical climate system, given only a small number of external boundary conditions such as the solar 'constant' and atmospheric concentrations of radiatively active gases and aerosols.

6.10 Historical evolution of climate models

There is, today, a wide range of climate models available for the variety of simulation tasks associated with improving understanding of the climate system and predicting future (and past) climate changes. Currently the most highly developed tools available for climate assessment are the global climate models (GCMs) and the earth models of intermediate complexity (EMICs). These models, based on knowledge of physics, chemistry, biology, as well as economics and social science, portray this understanding in simplified representations, called parameterizations, of the processes they are designed to characterize. In a climate model, an atmospheric component is coupled to a model of the ocean, a representation of the biota and sometimes characterization of technological trends and food and water resources. The term GCM is nowadays taken to mean at least fully three-dimensional models of the atmosphere and oceans coupled together. If only the atmospheric (or oceanic) component is represented, the acronym AGCM (atmospheric GCM) or OGCM (oceanic GCM) is used. The difference in response (or equilibration) times of, for example, the ice masses and the carbon cycle compared to the atmosphere (Table-6.2) means that different components are explicitly incorporated into different climate model types.

Table 6.2. Representative equilibration times for components of the Earth's climate system

Climatic domain	s	Equivalent
Atmosphere		
Free	10^6	11 days
Boundary layer	10^5	24 h
Hydrosphere		
Ocean mixed layer	10^6–10^7	Months–years
Deep ocean	10^{10}–10^{11}	300–3000 years
Lakes and rivers	10^6	11 days
Cryosphere		
Snow and surface ice layer	105	24 h
Sea ice	10^6–10^{10}	Days–100s of years
Mountain glaciers	10^{10}	300 years
Ice sheets	10^{12}	3000 years
Biosphere		
Soil/vegetation	10^6–10^{10}	11 days–100s of years
Lithosphere	10^{15}	30 million years

For long time-scale simulations of future and past climates, the EMICs are used, while for periods of days and decades to a century or two, GCMs are employed. Although a few GCM integrations have extended over 10000 years or more (Broccoli, 2000), the main focus of GCM studies continues to be on the decadal to century scale. This review is organized in a roughly historical narrative, which is summarized in Table-6.3. This 40-year story of numerical climate modelling does not, however, fit tidily into either an evolutionary structure or allow a neat sectionalizing into systems' and components' descriptions. This is the result of two, sometimes competing, factors: increased computer power and sparsity of observations. First, the development of numerical climate modelling has always been dependent on the state of development of the numerical platforms, i.e. the computer. This interdependence, for climate modelers needs have also prompted computational developments, is a tangled affair, which has, at some points, seen computation undertaken without clear motives other than to use the power. At the same time, scientists challenging the 'received wisdom' have always disputed the predictions of numerical models and even their underpinning premises. These debates and disputes have, quite naturally, often been tied up with the issues of funding, influence and publicity.

Table 6.3: Historical evolution of climate models

Decade and landmark papers	Climate model status
≤1969	
Manabe and Möller (1961)	Numerical weather forecasts extended
Manabe and Strickler (1964)	RC models developed
Sellers (1969)	Dynamics and radiation virtually separate
Budyko (1969)	EBMs newly described
1969–1981	
Manabe and Bryan (1969)	Multi-layer oceans added to GCMs
Green (1970), Stone (1973)	SD models developed
Manabe and Wetherald (1975)	Greenhouse modelling with GCMs
CLIMAP (1981)	Palaeo datasets first employed for 'validation'
1981–1989	
Hansen *et al.* (1981)	GCMs becoming predominant model type
Sellers *et al.* (1986)	Surge in computational power and capacity
Oort and Peixoto (1983)	Satellites generate global observations
Luther *et al.* (1988)	Model intercomparisons suggested
1989–1999	
Houghton *et al.* (1990)	Simpler models required by IPCC
Semtner and Chervin (1992)	OAGCMs established but need flux correction
Flato and Hibler (1992)	Sea-ice and land-surface components evolving
Cubasch *et al.* (1994)	First ocean–atmosphere coupled ensemble
Santer *et al.* (1996)	Validation and attribution first described
2000s	
? ? ?	EMICs as important as GCMs Past climate simulations re-emerging for testing Observational need driven by evaluation demand Policy needs a major driver of numerical models

6.11 General Circulation Models (GCMs)

The aim of GCMs is the calculation of the full three-dimensional character of the climate comprising at least the global atmosphere and the oceans. If a model were to be constructed which included the entirety of our knowledge on the atmosphere-ocean system, it would not be possible to run it on even the fastest computer. For this reason, even GCMs, currently the most complicated numerical models, can only be simplifications of our current knowledge of the climate system. GCMs are the direct descendants of the numerical weather prediction models, the basis of which is the representation of the climate system as a series of differential equations representing the many processes in the atmosphere and oceans. The solution of these equations (Table 6.8) that describe the movement of energy, momentum and various tracers (e.g. water vapor in the atmosphere and salt in the oceans) and the conservation of mass, is, therefore, required. Generally, the equations are solved to give the mass movement (i.e. wind field or ocean currents) at the next time step, but models must also include processes such as cloud and sea-ice formation, and heat, moisture, momentum and salt transport. Treatments of individual components are generally complex, although the general process is the same for all aspects of the climate system. The first step in obtaining a solution is to specify the atmospheric, oceanic and surface conditions at a number of 'grid points', obtained by dividing the Earth's surface into a series of patches, so that a global grid result. Conditions are specified at each patch for the surface and multiple layers in the atmosphere and ocean. The resulting set of coupled non-linear equations are then solved at each patch using numerical techniques. Various techniques are available, but all use a timestep approach (e.g. Haltiner and Williams, 1980; Hansen et al., 1983; Hack, 1992). Computational techniques divide atmospheric models into two main groups: spectral models and grid models. Spectral models (Bourke et al., 1977; Boer et al., 1984), make use of fast Fourier transforms (FFT) to conduct part of the calculation in a wave formulation; whereas grid point models (Manabe et al., 1979; Hansen et al., 1983; Mitchell et al., 1995) make use of a straightforward rectangular grid.

Table 6.4: Fundamental equations solved in GCMs

1. *Conservation of energy* (the first law of thermodynamics), i.e. Input energy = increase in internal energy plus work done
2. *Conservation of momentum* (Newton's second law of motion), i.e. Force = mass × acceleration
3. *Conservation of mass* (the continuity equation), i.e. The sum of the gradients of the product of density and flow-speed in the three orthogonal directions is zero. This must be applied to air and moisture for the atmosphere and to water and salt for the oceans, but can also be applied to other oceanic 'tracers' and to cloud liquid water
4. *Ideal gas law* (an approximation to the equation of state—atmosphere only), i.e. Pressure × volume = gas constant × absolute temperature

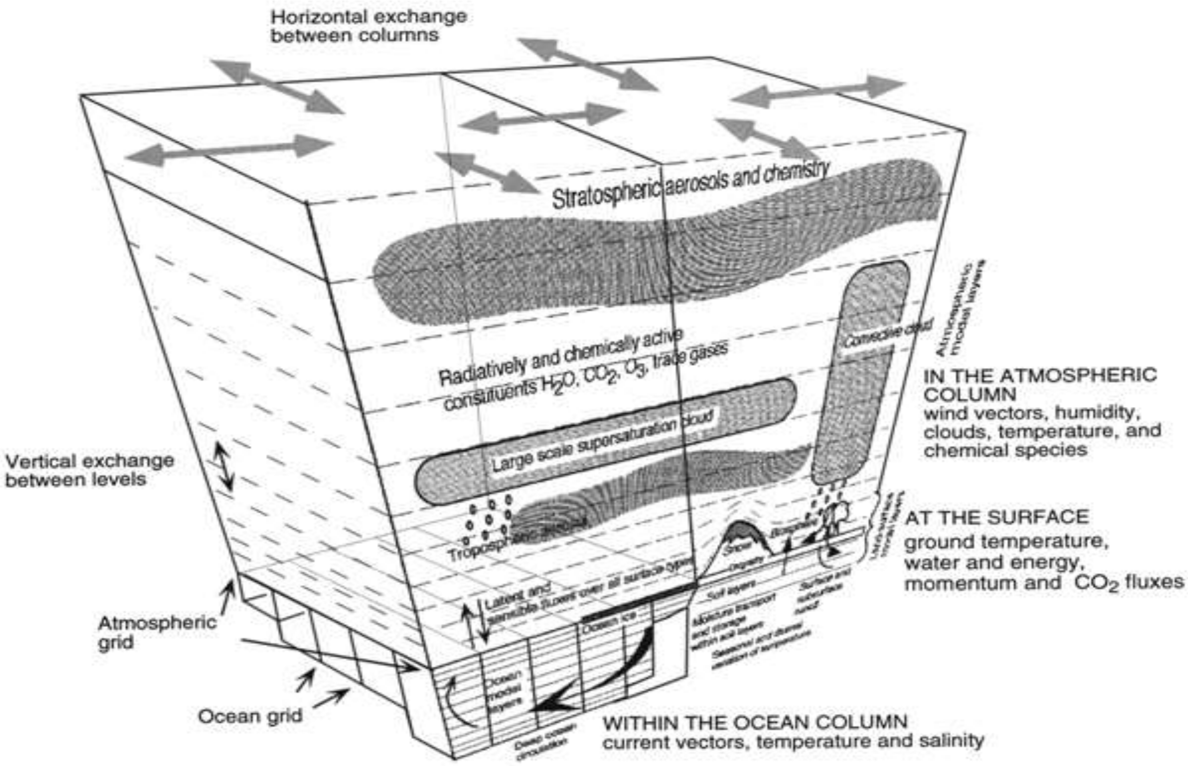


Fig. 6.8: The basic characteristics and processes within a GCM, showing the manner in which the atmosphere andocean are split into columns. Both atmosphere and ocean are modelled as a set of interacting columns distributed across the Earth's surface. The resolutions of the atmosphere and ocean models are often different because the processes differ and have different time-scales and equilibration times. Typically, many types of cloud and land surface are treated. In this example, soil moisture is modelled in a number of layers and tropospheric and stratospheric aerosols are included.

Modelling the full three-dimensional nature of the ocean is more difficult than capturing the atmosphere because the scales of motion which exist in the oceans are much smaller than those in the atmosphere (ocean eddies are around 10–50 km, cf. around 1000 km for atmospheric eddies), and the ocean also takes very much longer to respond than the atmosphere to changed forcing. The smaller scales demand a smaller grid size. Hence, there are very many more points at which computations must be made. The dynamics of the ocean are governed by the amount of radiation, which is available at the surface, and by the wind stresses imposed by the atmosphere, but the flow of ocean currents is also constrained by the positions and shapes of the continents. The formation of oceanic deep water is closely coupled through salinity to the formation and growth of sea-ice so that ocean dynamics demands effective inclusion of sea-ice dynamics and thermodynamics. The Antarctic circumpolar current, for example, is largely controlled by topography, and errors in the path of this current can result in significant errors in sea surface temperature. Furthermore, deep water circulation of the ocean can take hundreds or even thousands of years to complete, so that ocean models which include these dynamic processes often have to be asynchronously coupled with atmospheric components to provide the most detailed models of the physical climate system. Ocean models are generally constructed on a rectangular grid, as the sharp discontinuities at the edge of oceans make them unsuited to the spectral techniques which are used for some models of the atmosphere.

Earth models of intermediate complexity (EMICs)

The sliding criteria from sub-grid variability to frozen (or specified) boundary conditions for global climate models and EMICs are shown in Figure 9. Within the EMICs, modelers intentionally adopt simple approaches to selected processes; for example, interactions between the surface and the near-surface layer of the atmosphere. Detailed consideration of the transfer processes at the surface of the Earth are computationally too demanding for explicit inclusion in EMICs but are included in GCMs. Achieving the most beneficial trade-off between calculated, sub-grid variation and boundary specification defines the art of climate modelling. Some modellers have used the approach of nesting a regional model within a global model to provide high resolution simulations of a particular region. Results from such studies are dependent on the quality of the global scale model used to supply the regional boundary conditions and upon the verity of the nesting procedure. Aspects of the physical character of the climate system deemed to be critically important in GCMs, such as the radiation fluxes at the Earth's surface, are parameterized in EMICs. Cloud amount may be made to be dependent on surface temperature, and surface albedo regarded as constant for a given latitude: remarkably reminiscent of the early EBMs. Atmospheric dynamics are often not modelled explicitly in EMICs. Instead, simple parameterizations such as a 'diffusion' approximation are employed to parameterize heat transport: the same approach as used in 2D SDs.

There are also EMICs which involve an energy-moisture balance model coupled to an OGCM and a number of both thermodynamic and dynamic/thermodynamic sea-ice models Schnellnhuber (1999) provides an overview of the system-wide approach employed by EMICs. The power of these EMICs is that they can be applied to very wide-ranging timescales. Thus, while one or two GCMs and a number of EMICs have been used to try to investigate the last glacial maximum (LGM), as well as the collapse of the ocean conveyor ingreenhouse warming experiments, both now being recognized as an important aspect of climate model evaluation/validation, only an EMIC has been used to evaluate the effect of historical land cover change over hundreds of years.

SESSION 7: APPLIED CLIMATOLOGY

7.1 Introduction

An Atmospheric Science often subdivide study of complexity of gaseous envelope that surrounds the earth into specific areas of interest. One such division identifies the fields of meteorology and climatology. Meteorology is a science that deals with motion and the phenomena of the atmosphere with a view to both forecasting weather and explaining the processes involved. It deals largely with status of atmosphere over a short period of time and utilizes physical principles to attain its goal. Climatology is the study of atmospheric conditions over a longer period of time. It includes the study of different kinds of weather that occur at a place. Dynamic change in the atmosphere brings about variation and occasionally great extremes that must be treated on the long term as well as the short-term basis. As a result, climatology may be defined as the aggregate of weather at a place over a given time period. There is diversity of approaches available in climate studies. Figure 7.1. Illustrates the major subgroups of climatology, the approaches that can be used in their implementation, and the scales at which the work can be completed.

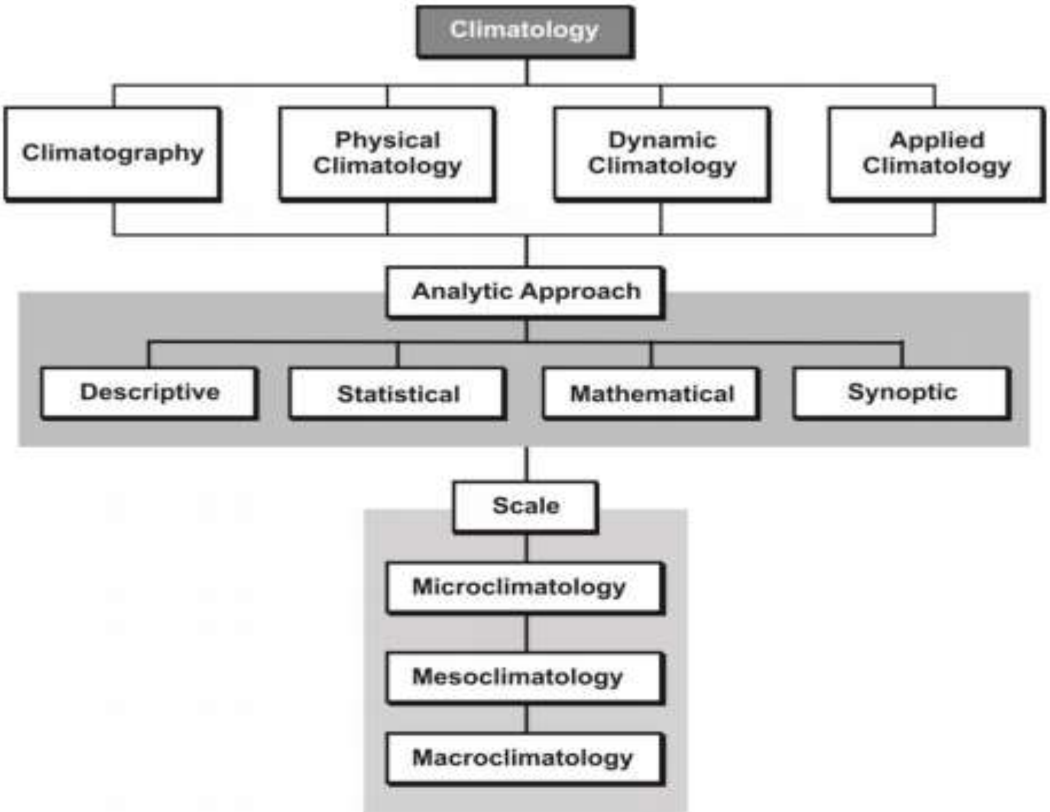


Figure 7.1: Subgroups, Analytical methods and scales of climatic study

Climatographic consists of the basic presentation of data and its verbal or cartographic description.

Physical Climatology deals largely with the energy exchanges and physical components.

Dynamic Climatology is more concerned with atmospheric motion and exchanges that lead to and result from that motion.

Applied Climatology is the scientific application of climatic data to specific problems within such areas of forestry, agriculture, and industry. It can involve the application of climatic data and theory of other disciplines, such as geomorphology and soil science.

7.2 Urban Climatology

Urban and rural environments differ substantially in their micro-climate. These climatic differences are primarily caused by the alteration of the Earth's surface by human construction and the release of artificially created energy into the environment.

Energy Characteristics of Urban Areas

In a city, concrete, asphalt, and glass replace natural vegetation, and vertical surfaces of buildings are added to the normally flat natural rural landscape. Urban surfaces generally have a lower albedo, greater heat conduction, and more heat storage than the surfaces they replaced. The geometry of city buildings causes the absorption of a greater quantity of available incoming solar radiation and outgoing terrestrial infrared radiation. Even in early morning and late afternoon the urban areas are intercepting and absorbing radiation on their vertical surfaces. In urban areas, large amounts of heat energy are added to the local energy balance through transportation, industrial activity, and the heating of buildings. In winter, the amount of heat generated from the burning of fossil fuels in New York City is 2.5 times greater than the heat absorbed from the Sun. Finally, in rural areas, evaporation and transpiration from various natural surfaces act to cool the land surface and local atmosphere. In urban locations, drainage systems have been created to quickly remove surface water. Thus, little water is available for cooling.

Observed Climate of Cities

Urban areas tend to be warmer than the surrounding countryside. These differences in temperature are best observed at night under stable conditions when atmospheric mixing is at a minimum. Climatologists call this phenomenon the urban heat. The urban heat island is strongest at the city center where population densities are highest and industrial activity is at a maximum. The heat island effect has been described in many cities around the world, and temperature differences between city and country can be as high as 6° Celsius.

Wind in urban areas is generally calmer than those in rural areas. This reduction in velocity is due the frictional effects of the city's vertical surfaces. However, some street and building configurations within a city can channel the wind and increase its velocity through a venture effect. Certain parts of downtown Chicago and Winnipeg are noted for their unusually high wind speeds.

Climatologists have measured about up to 10% more rainfall in urban areas. This increase may be due to the combined effect of particulate air pollution and increased convectional uplift. Air pollution may enhance rainfall by increasing the number of condensation nuclei through the atmospheric addition of smoke and dust particles. The additional generation of heat within the city increases the number of convection currents over that surface. Convection is required to initiate the development of thunderstorms.

7.3 Climate Change Study

Climate change occurs when changes in Earth's climate system result in new weather patterns that remain in place for an extended period of time. This length of time can be as short as a few decades to as long as millions of years. The climate system receives nearly all of its energy from the sun. The climate system also gives off energy to outer space. The balance of incoming and outgoing energy, and the passage of the energy through the climate system, determines Earth's energy budget. When the incoming energy is greater than the outgoing energy, earth's energy budget is positive, and the climate system is warming. If more energy goes out, the energy budget is negative and earth experiences cooling. Climate change also influences the average sea level.

Modern climate change is driven by the human emissions of greenhouse gas from the burning of fossil fuel driving up global mean surface temperatures. Rising temperatures are only one aspect of modern climate change though, with includes observed changes in precipitation, storm tracks and cloudiness. Warmer temperatures are driving further changes in the climate system, such as the widespread melt of glaciers, sea level rise and shifts in flora and fauna.

7.4 Weather forecasting

A more complicated way of making a forecast, the analog technique requires remembering a previous weather event which is expected to be mimicked by an upcoming event. What makes it a difficult technique to use is that there is rarely a perfect analog for an event in the future. Some call this type of forecasting pattern recognition, which remains a useful method of observing rainfall over data voids such as oceans with knowledge of how satellite imagery relates to precipitation rates over land, as well as the forecasting of precipitation amounts and distribution in the future. A variation on this theme is used in medium range forecasting, which is known as teleconnections, when systems in other locations are used to help pin down the location of a system within the surrounding regime. One method of using teleconnections are by using climate indices such as ENSO-related phenomena.

7.5 Climatic Geomorphology

Climatic geomorphology is the study of the role of climate in shaping landforms and the earth-surface processes. An approach used in climatic geomorphology is to study relict landforms to infer ancient climates. Being often concerned about past climates climatic geomorphology considered sometimes to be an aspect of historical geology. Since landscape features in one region might have evolved under climates different from those of the present, studying climatically disparate regions might help understand present-day landscapes.

7.5.1 Desert Geomorphology

Desert geomorphology or the geomorphology of arid and semi-arid lands shares many landsforms and processes with more humid regions. One distinctive feature is the sparse or lacking vegetation cover, which influences fluvial and slope processes, related to wind and salt activity. Early work on desert geomorphology was done by Western explorers of the colonies of their respective countries in Africa (French West Africa, German South West Africa, Western Egypt), in frontier regions of their own countries (American West, Australian Outback) or in the deserts of foreign countries such as the Ottoman Empire, the Russian Empire and China. Since the 1970s desert geomorphology in Earth has served to find analogues to Martian landscapes.

7.5.2 Periglacial Geomorphology

As a discipline periglacial geomorphology is close but different to Quaternary science and geocryology. Periglacial geomorphology is concerned with non-glacial cold-climate landforms in areas with and without permafrost. Albeit the definition of what a periglacial zone is not clear-cut a conservative estimate is that a quarter of Earth's land surface has periglacial conditions. Beyond this quarter an additional quarter or fifth or Earth's land surface had periglacial conditions at some time during the Pleistocene.

7.5.3 Tropical Geomorphology

If the tropics is defined as the area between 35° N and 35° S, then about 60% of Earth's surface lies within this zone. During most of the 20th century tropical geomorphology was neglected due to a bias towards temperate climates, and when dealt with it was highlighted as ‘exotic. Tropical geomorphology does mainly differ from other areas in the intensities and rates at which surface processes operate, and not by the type of processes. The tropics are characterized by particular climates, that may be dry or humid. Relative to temperate zones the tropics contain areas of high temperatures, high rainfall intensities and high evapotranspiration all of which are climatic features relevant for surface processes. Another characteristic, that is not related to present-day climate per see, is that a large portion of the tropics have a low relief which was inherited from the continent of Gondwana.

Reference:

1. https://www.environmentalscience.org/careers
2. https://banglapedia.org/index.php?title=Monsoon
3. https://earthhow.com/koppen-climate-classification/
4. Are cyclones formed in the Bay different?
5. The Daily star, 12:00 AM, October 29, 2014 / LAST MODIFIED: 01:53 AM, March 08, 2015
6. USGS, Science for a changing world, What is a landslide and what causes one?
7. Climate%20of%20Bangladesh%20-%20Wikipedia.html
8. seasonal%20variation.html
9. 9.Climate%20%20%20meteorology%20%20%20Britannica.com.html
10. 10.Dhaka, %20Bangladesh%20%20Detailed%20climate%20information%20and%20monthly%20weather%20forecast%20%20%20Weather%20Atlas.html
    11.VolcanoesandClimateChange,Volcanoes%20and%20Climate%20Change%20%20%20Earthdata.html
11. 12. IMO Paper: Participation in the WMO voluntary observing ships scheme,https://www.pame.is/projects/arctic-marine-shipping/amsa/voluntary-observing-ship-vos-scheme
12. 13. Climate%20%20%20meteorology%20%20%20Britannica.com.html
13. Climatology%20%20The%20Science%20of%20Global%20Weather%20Systems%20over%20the%20Long%20Term%20%20%20EnvironmentalScience.org.html.