BLOCK 2

GLOBAL CLIMATE CHANGE – PAST AND FUTURE CLIMATE

BLOCK 2 INTRODUCTION

Earth is a constantly changing planet since its formation around 4.6 billion years ago and hence, its climate is also witnessing changes from time to time. We can know about the present climate by studying the components of the climate system. However, for understanding the current dynamics of climate and predicting its future state, it is necessary to have an understanding of present and past climate. In this block, the past and present climate have been discussed through sources of past climatic conditions, climate change during the Quaternary Period, and environmental indicators. With rising awareness about climate change due to both natural and human-induced factors, it has been projected that global warming would cause an increase in hot temperature extremes and occasional lower temperature extremes on daily as well as seasonal time scales. In this block, extreme weather events and future climatic conditions based on Representative Concentration Pathways are discussed.

Unit 5 "Account of Past Climate" deals with the climate of the past, sources of past climatic conditions and changes in climate during the Quaternary Period.

Unit 6 “Environmental Indicators and Instrumental Records” deals with the significance of instrumental records and proxy climate indicators in climate change studies.

Unit 7 "Climate Variability and Extreme Weather Events" deal with climate variability and extreme weather events.

Unit 8 “Predicting Future Climates” deals with emission scenarios of greenhouse gases.

OBJECTIVES

After studying this block, you should be able to:

- describe the sources of palaeoclimate information;
- discuss climate change during the Quaternary Period;
- explain the significance of instrumental records and proxy climate indicators;
- elucidate the contributions of proxy climate indicators to decipher the past climate;
- discuss the extreme weather events;
- explain the analogues from past climate;
- classify the different types of climate models; and
- explain the emission scenarios.

We hope that after studying this block, you will acquire an understanding of the past and future climate.

Wishing you success in this endeavour!

UNIT 5 ACCOUNT OF PAST CLIMATE

Structure

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5.1 INTRODUCTION

You know that climate is average weather, over a long period of time that covers a large area, even the whole planet. The weather represents hour to hour or day to day state of the atmosphere over a particular area. The atmosphere, ocean, snow and ice cover, land surface, rotation and revolution of earth, incoming solar radiation and biota are principal components of the climate and their interaction forms a system termed as climate system. You have already read about weather, climate and climate system while studying Unit 1 to 4 of the course. In fact, it is the climate system, which makes our planet Earth a habitable entity in the Universe.

The climate system evolves in time under the influence of its own internal dynamics like volcanic eruptions and due to changes in the external factors such as solar radiation and atmospheric composition. It is one of the oldest systems of the earth that has significantly contributed to the origin and evolution of life through ages. Earth is a constantly changing planet since its formation of around 4.6 billion years ago and hence, its climate is also witnessing the changes from time to time. We can know about the present climate by studying the components climate system. However, for understanding the current dynamics of climate and predicting its future state, it is necessary to have an understanding of present and past climate. In this unit, we will discuss the climate of the past, sources of past climatic conditions and changes in climate during Quaternary Period, when humans appeared as a dominant biotic element on the earth.

5.2 OBJECTIVES

After studying this unit, you should be able to:

- define palaeoclimate;
- differentiate between climate and palaeoclimate;
- describe the sources of palaeoclimate information; and
- discuss climate change during the Quaternary Period.

5.3 PALAEOCLIMATE

The term palaeoclimate refers to the climate of the past. As we have already stated in previous units that the science of studying the modern climate is termed as climatology. Similarly, the science dealing with the study of past climate is known as palaeoclimatology. The word palaeoclimatology is a combination of the Greek words "*Palaios*" - (ancient) + "*clima*"- (climate) + "*ology*" - (branch of learning) and therefore it refers to the study of the past climate. The scientists who study the past climate are known as palaeoclimatologists. They use natural environmental evidences or their proxies present on the earth's surface such as sediments, sedimentary layers, fossils (coral and tree growth rings), ice cores and radiocarbon to infer the climate of the past prior to the availability of recorded instrumental data of climate.

You may be surprised to know that changes in climate is neither unusual nor a new phenomenon. It is a natural process and Earth has already witnessed several cycles of climate change since its origin. Before discussing the earth's past climate, let us familiarise with the geologic time scale. Like the divisions of our time into years, months, weeks, days, hours, minutes and seconds; the geological time, covering entire span of Earth, is also divided into certain geologic time-units such as eon, era, period, epoch and age (Table 5.1). The duration of a particular time unit of the scale is determined by dating of rocks using radioactive methods. The boundary between two time units largely corresponds to sudden biotic events like origination or extinction of certain species.

Table 5.1: Summary of the geological time scale showing main time units

Eon	**Era**	**Period**	**Epoch**	**Time interval in million years (Ma)**
Phanerozoic	Cenozoic	Quaternary	Holocene	0.012 to present
			Pleistocene	2.58 to 0.012
		Neogene	Pliocene	5.333 to 2.58
			Miocene	23.03 to 5.333
		Palaeogene	Oligocene	33.9 to 23.03
			Eocene	56 to 33.9
			Palaeocene	66 to 56
	Mesozoic	Cretaceous		145 to 66
		Jurassic		201.3 to 145
		Triassic		251.9 to 201.3
	Palaeozoic	Permian		298.9 to 251.9
		Carboniferous		358.9 to 298.9
		Devonian		419.2 to 358.9

			Silurian		445.2 to 419.2
			Ordovician		485.4 to 445.2
			Cambrian		541 to 485.4
Precambrian	Proterozoic	Neoproterozoic			1000 to 541
		Mesoproterozoic			1600 to 1000
		Palaeoproterozoic			2500 to 1600
	Archaean	Neoarchaean			2800 to 2500
		Mesoarchaean			3200 to 2800
		Palaeoarchaean			3600 to 3200
		Eoarchaean			4000 to 3600
	Hadean	------			4600 to 4000

5.4 GLIMPSE OF EARTH'S CLIMATE THROUGH AGES

The rock record of the earth contains numerous clues of the past climate which shows that climate of the living planet earth is not uniform throughout its history, since time of origin nearly 4.6 billion years ago to present. As discussed before, fossils (tree rings, plant leaves, pollens and coral skeletons), ice cores, sedimentary layers and sediments are main substances containing proxy data for palaeoclimate. Further, the study of this proxy data also reveals that past climate of the earth had often altered by solar intensity, volcanic eruptions, lithospheric plate motion, weathering reactions as well as fluctuations of greenhouse gases and temperatures. Additionally, the changes in oceanic circulation patterns, cyclic variations in Earth's orbit around the Sun, extra-terrestrial (meteorite) impacts and biologic evolution also influenced Earth's past climate. It may be noted that the past climate of the earth is defined in term of non-glacial (infra- and inter-glacial) and glacial periods. Let us discuss the climate during Precambrian and Phanerozoic times.

5.4.1 Climate during Precambrian

During the Precambrian time (4.6 billion years to 540 million years ago), Earth's climate was warm and concentration of greenhouse gases like carbon dioxide, methane and water vapour were very high. The concentration of carbon dioxide was more than 18 times than its present levels and methane was above 1000 ppm. The oxygen was not present in the early atmosphere. After millions of years of the formation of the earth, temperature came down to certain degrees and water vapour of early atmosphere produced rains. As a consequence, the earth was provided with basic necessities such as soil, water and air for origination of life. It was around 3.5 billion years ago, the early forms of life such as cyanobacteria made their first appearance on the surface of the earth. These bacteria made their own food by using sun energy as a source of energy and released oxygen as a by-product of photosynthesis process. As a consequence, around 600 million years ago, enough oxygen was present in the atmosphere that led to development of multi-cellular organisms. The non-glacial and glacial stages have been recorded in Precambrian history of the Earth. The evidence consisting of sedimentary rocks formed by glaciers show that Earth was very cold possibly near to freezing point, during the latter part of the Precambrian times (Ruddiman, 2018). Four ice ages are known from the Precambrian: first ice age occurred in the Archaean eon around 2500 million years ago and three ice ages in the Proterozoic eon between 900 and 600 million years ago (Barry and Chorley, 2010).

5.4.2 Climate during Phanerozoic

In the Phanerozoic eon (540 to 0 million years ago), the concentration of carbon dioxide fluctuated greatly and decreased from 6000 ppm to reach its current levels. The carbon cycle greatly shaped the Phanerozoic climate and as a result diverse variation occurred in multi-cellular organisms and land plants (Beerling and Berner, 2005). It is noted that the climate shifted frequently between icehouse (glacial and non-glacial) and greenhouse conditions and temperatures greatly influenced by the natural processes including breaking and re-union of continental landmasses as well as extra-terrestrial impacts during the Phanerozoic time. The five great mass extinctions such as End Ordovician, End Devonian Permian/Triassic boundary, End Triassic and Cretaceous/Tertiary boundary had been recorded in the Phanerozoic history of life. All these mass extinctions are directly related to the wide spread changes to the past climate. Mass extinction is a phenomena where sudden and permanent loss of large number of species or groups of organisms on earth's surface. Three major ice ages are documented from the Phanerozoic eon, which occurred in the Ordovician period, during Carboniferous-Permian periods and Late Cenozoic era (Barry and Chorley, 2010).

5.5 SOURCES OF PALAEOCLIMATIC DATA

It must be noted that for studying modern climate, the climatologists (also known as climate scientists) can get a century old data. Can you think this data is sufficient to know the climate of the whole Earth, which is nearly 4.6 billion years old before present? The answer is certainly not. Therefore, the palaeoclimatologists used climate archives or proxies to unravel the past climate of the earth. The climate archives comprise earth's material and old documented records (e.g., historical records) that hold physical characteristics of the past environment. While studying climate archives, the climate of the past can be reconstructed. The main types of climate archives are:

- Historical data
- Archaeological data
- Geological record

5.5.1 Historical Data

It represents first source of information for reconstructing the past climate. It consists of documentary data. The logs of the farmers', diaries of travellers', ancient inscriptions, newspapers, paintings, artistic depictions, reports of the early weather observers and other public records are the sources of historical data. Apart from these, the legal document, written account, tax, economic and pictorial records containing information about land uses, landscape, societal collapse, construction material and biodiversity also provide important clues for reconstructing past/ancient climate. Additionally, any records consisting of information on the timings of forests and flowering of trees, occurrences of snowfall, rainfall, drought, famine and flood as well as migration of birds are also parts of historical data. Historical data provide both qualitative and quantitative information of the past climate. This data provide climatic information of the events recorded by the humans, for example, the Mesopotamian civilization of the Middle East, was considered to be the one of first civilizations to record events.

5.5.2 Archaeological data

Archaeology deals with the study of the past human cultures. It focuses on how people lived, worked, traded and moved in the past. The specialists of archaeology are known as archaeologists. They use archaeological data to know how the life style of prehistoric human is influenced by the climatic conditions. It is to be noted that archaeological data is considerable older than that of historical data, because archaeological data comprise a time of ancient cultures that are reconstructed on the basis of scientific analyses of numerous soil layers preserving human artifacts. In other words, archaeological time is based on the remains of human life and hence, not based on the record kept by humans as in the case of historical data (Krebs, 2007). An archaeological site is a place, where the evidences of past human activity are preserved and such evidences are a useful source of cultural and non-cultural (also described as environmental conditions) information, which together constitute the archaeological data (Reitz et al., 2008). The branch of archaeology dealing with the reconstruction of the past environment including climate is known as environmental archaeology. The following kinds of data, which may be useful of Palaeoclimatic study, are recovered from an archaeological site:

5.5.2.1 Rock layers, Minerals and Soil data

The chemical, physical and geological characteristics of rock layer, mineral and soil samples from any site provide many clues of the past climate. The grain-size analyses of sediment layers help to know the medium (wind, water, floods or glaciers) of their deposition and thus, useful to reconstruct the past climatic condition. The sequence of sediment layers of near shore archaeological sites give information of the sea level changes as they contain distinct layers of sediments deposited under marine to freshwater conditions.

5.5.2.2 Plant and Animal remains

The plant remains comprise any type of plant materials like wood, mature seeds, pollen, spores, fruits, flowers, leaves, stems, roots, bark, epidermis, fibers, stomata, starch grains, phytoliths, resins, lignin and lipids associated with any site. The animal remains comprise bones and teeth of mammals, fish skeletal remains and shells of invertebrates (molluscs, echinoderms, crustaceans, insects, foraminifers and protozoans). As we know that plant and animal life are largely controlled by climatic conditions, as a consequence, their remains will help us to known their food source and to reconstruct the climatic and environmental conditions of the past. The carbon, nitrogen and oxygen isotopic analyses of bone and shell remains give information about palaeodiets (terrestrial/aquatic), palaeotemperature (i.e. temperature of past) and seasonal patterns. The existence of mammoth (elephant) remains consisting of skins and bones clearly specify a cold climate. The presence of floral remains largely consisting of bouquets of wild flowers in the burial sites provides information about climate conditions prevailed at the time the society lived there. The sudden natural burial of a site preserving prehistoric humans and domesticated animals may have pointing towards the flooding phenomenon, which is related with rainfall and yield important clues of the past climate.

5.5.2.3 Artifacts

These are objects created, modified and used by humans. The various forms of pottery (intact or broken), tools made of stone, wood, bone and metal (arrow-heads, mace-heads and spears), decorative objects (jewellery and *figurines* or statuettes) and personal objects (clothing) constitute artifacts. It is considered that prehistoric humans used nearby available material for creating or manufacturing the artifacts. Thus, their study shed light on the past climate. For example, the presence of broken, blacked and burned clay pots in association with ash layers in an archaeological site is an indicative of the warm climate.

5.5.3 Geological Record

Geology is the science that deals with the study of the earth with reference to its origin, evolution, age, structure, composition and processes operating on it since its formation (about 4.6 billion years ago). The scientists who study the earth's materials are known as geologists. The earth's material consisting of different types of rocks (igneous, sedimentary and metamorphic), fossils, sediments and soils that are available to them (geologists) for study. This material is also termed as rock record and yields many proxies or indirect evidences to reconstruct the timeline of the earth's climate during the geological past. It may be noted that the geological record is much older than that of historical and archaeological data. The 4.6 billion years long history of earth witnessed numerous intervals of short and long term climatic fluctuations, which left many climatic proxies or natural archives preserved in the rock record. Some of the most important natural archives are sedimentary rock types, fossils, and ice core and cave deposits.

5.5.3.1 Sedimentary rock types

The sedimentary rocks are formed by the slow processes of deposition of sediments carried by rivers and streams into oceans and other water bodies (e.g., rivers or lakes) and after millions of years, the soft sediment got consolidated into stratified (layered) hard rocks. These rock bodies constitute the sedimentary rocks. Many climatically sensitive sedimentary rock types provide natural climatic archives as described below:

- **Glacial features:**

Some glacial features like striae, tillites and moraines are easily recognised in the field and serve as useful climate archive for cold, glacial climate of high latitudes and elevations. As the glacier moves, it erodes/breaks rocks lying at its base and transports them in the direction of flow, leaving behind deep scratches in the underlying rocks, which are made by rock fragments carried by glaciers and are termed as glacier striae. As the glacier advances, it drops a mixture of sediments consisting of boulders, pebbles, sand and mud, which later get settled by melt water of the glaciers and this heterogeneous mixture is known as till and when it lithified is known as tillites. As glaciers further advances, they form ridge-like deposits composed of unsorted mixture of fine rock particles to great boulders derived from the glacier are known as moraines. The drumlins, kames and eskers are other glacier features that also provide Palaeoclimatic information.

- **Rock-types**

Some specific sedimentary rocks such as **calcretes**,which represent calcium carbonate accumulations, form due to the near surface evaporation of groundwater and **evaporates (**composed of rock salt also known as halite and gypsum) formed by evaporation of surface water can help to identify mid to low latitudes regions with arid, dry and warm climates. The **sandstone** resulted by lithification of desert dunes, is characterised by large scale cross-bedding tells us about desert likes condition and wind direction. The **varves** are lake deposits, consisting of alternating layers of coarse and fine grained sediments that have deposited in lakes. The lake receives coarse-grained sediments at the time when sediment supply is high possibly in summer season and fine-grained when sediment supply is low in winter season. Therefore, alternating coarse and fine grained layering of sediments are considered to be associated with cyclic seasonal variation. The **limestone** (carbonate) rocks rich in coral remains indicate warm water (tropical ocean) having temperature ranging from 21 to 29°C. The **coal-bearing sedimentary rocks** are indicative of humid tropical settings. **Laterites** are brownish to red nodular soils rich in iron, aluminum and manganese usually formed in hot and wet tropical climatic regions experiencing high rainfall.

5.5.3.2 Fossils

These are remains of the ancient life preserved in the sedimentary rocks. As we know that some organisms particularly animals and plants are highly dependent on environmental conditions and many of them are narrowly adapted to specific climatic conditions. As a consequence, their fossils provide valuable clues to know the climate of the past. The fossils of **reptiles** (e.g.,lizards or snakes) are good indicators of a warm climate because they cannot live in cold climate as their body is not able to maintain constant warm temperatures. The fossils of **plant cycads** indicate tropical and subtropical ancient climate because modern cycads occur in these climatic zones. The margins of plant leaf are excellent indicators of past climate, for example, fossil leaf with smooth margins are good indicators of tropical climate whereas leaf with toothed or lobed margins indicates cold climate.

The study of growth rings in trees and corals tell us about past seasonal variation. The trunk of a tree and skeleton of a sea coral contain numerous almost circular growth rings. In each season, a new ring adds and preserves weather conditions of the particular season. As they grow, many rings are added, which reflects season history of the area during the period of a tree or coral growth. The study of growth rings in a tree for inferring climate is known as **dendroclimatology**. The study of coral's growth rings is termed as **coral clock**. Based on growth rings of corals it is inferred that Earth's rate of rotation is decreasing slowly from ancient times due to the gravitation pull of the moon.

5.5.3.3 Ice Cores

They include cores of ice obtained from perennially cold areas where no or little melting occurs such as the Polar Regions, northern Greenland, high mountains of the Andes and the Himalaya by drilling glaciers and ice sheets. The ice cores obtained by drilling are used to study air bubbles, water and material trapped in them such as ancient atmospheric oxygen, hydrogen, carbon dioxide as well as dust and ash particles by various methods. Ice cores are useful source of past climate data of thousands of years ago.

5.5.3.4 Cave Deposits

These are calcium carbonate deposits consisting of speleothems (stalagmites, stalactites and flowstones) formed in a limestone cave and are a potential indicator of non-glacial terrestrial climate. The speleothems are secondary mineral deposits formed from groundwater within underground caverns. The speleothems possesses different types of annual laminas and preserve the seasonality. The oxygen and carbon stable isotopic analyses of each laminae tell us about the past rainfall, vegetation and other climatic factors. Cave deposits provide Palaeoclimatic evidences of around 30,000 years before present.

The reconstruction of the past climate involves the understanding and study of natural archives and the methods employed in their analysis. So, it is not necessary that our interpretation of proxy data is not always accurate. We should be aware about present day climatic relationships of various geological climate proxies and it will help us to overcome the difficulties associated with each climate proxy described above while inferring climatic information of the past.

Check Your Progress 1

Note: i) Use the space given below for your answers.

ii) Check your answers with those given at the end of the unit.

1) What is palaeoclimate?

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2) Which type of palaeoclimate does tillites indicate?

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3) Fossil leaf with smooth margins indicates ----------- palaeoclimate.

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5.6 CLIMATE OF THE QUATERNARY PERIOD

The Quaternary is the youngest period of the Cenozoic era and is divided into two epochs such as Pleistocene and Holocene (Table 5.1). It is a period of greater climate changes since the past 60 million years (Bradley, 2015). The climatic history of Earth since 2.58 million years ago to present is very dynamic because the large portion of the earth's surface particularly Northern Hemisphere, parts of Antarctica and high mountainous regions, repeatedly witnessed widespread glaciations. Therefore, this period is referred to as "the Great Ice Age". This age is not over yet, in fact, we are living in the inter-glacial (warm) stage of this age. The oxygen and carbon isotope ratios, growth rings in trees, cave and glacial features, lakes and dune deposits, microfossils, pollen grains and ice cores are climate proxies that are commonly utilised to reconstruct the climate of the Quaternary period.

5.6.1 Pleistocene

The Pleistocene epoch starts from 2.58 million years ago and ends at 11,700 years ago. Commonly, Epoch is a subdivision or time-unit of the geological time scale. The study of various climate proxies of the Pleistocene epoch clearly shows that it was a time of radical climate changes and emergence of humans (http://content.inflibnet.ac.in). At the close of the Pliocene and the beginning of the Pleistocene, there was shift in global climate at around 2.5 million years ago, as a consequence, climate became cooler and the genus *Homo* (i.e. humans) evolved from australopithecine (ape- and human-like primates) ancestors in response to climate change. In addition, the beginning of the Pleistocene is also marked by the first appearance of other mammalian genera: *Bos* (bovid), *Elephas* (elephant) and *Equus* (horse) (Mathur, 2005). The climate of the Pleistocene is characterised by an orderly sequence of inter-glacial–glacial–inter-glacial periods. During this epoch, the cold climate intensified, which led to the development of extensive ice sheets and mountain glaciers in high latitude and high altitude regions of the earth. It includes larger part of the Northern Hemisphere (USA, Canada, Greenland, Europe, Asia and northern Russia), Antarctica, South America and mountainous areas of the Rockies, Alps, Himalaya, Kilimanjaro and Mount Kenya. The maximum Pleistocene glaciations occurred in the Northern Hemisphere. Therefore, the massive ice sheets covering the parts of Eastern North America, Western North America, and Northern Europe are termed as the Laurentide ice sheet, Cordilleran ice sheet and Scandinavian ice sheet, respectively. It is interesting to note that during the Pleistocene epoch nearly 30% area of the earth's surface was covered by the ice sheets and glaciers, and around 20 alternate cycles of glacial–inter-glacial stages have been documented. The cold interval when glaciers are very extensive is known as glacial stage, and warm and dry interval between two intervening glacial stages when glaciers are less extensive is termed as inter-glacial stage.

In the Pleistocene, the tropical regions received maximum rainfall and experienced humid climate. The period of maximum rainfall is known as pluvial period and intervening period of dry climate between two successive pluvial periods is described as inter-pluvial period. The pluvial periods as stated above experienced maximum rainfall, caused the flooding in the rivers and streams and formed extensive flood plain deposits consisting of layers of sand, silt and gravel. It is observed that glacial–inter-glacial and pluvial–inter-pluvial intervals are interrelated. The deciduous and coniferous forests were more common during the warm period; however, grasses, lichens and mosses dominated land during the winter period.

Geologically, the Pleistocene epoch has been classified into three subdivisions: Lower, Middle and Upper. And, each of these subdivisions had experienced episodes of glacial–inter-glacial. Four glacial and three inter-glacial stages have been documented in the Pleistocene (Table 5.2).

Table 5.2: Glacial–inter-glacial periods of the Pleistocene

Epoch		**Glacial–inter-glacial stage**	
		Europe	**North America**
Holocene		Inter-glacial	Inter-glacial
Pleistocene	Upper (12,600 to 11,700 years ago	Wurm Glaciation	Wisconsinan Glaciation
		Riss-Wurm inter-glacial	Sangamonian inter-glacial
		Riss Glaciation	Illionian Glaciation
	Middle (78,100 to 12,600 years ago)	Mindel-Riss inter-glacial	Yarmouthian inter-glacial
		Mindel Glaciation	Kansan Glaciation
		Gunz-Mindel inter-glacial	Aftonian inter-glacial
	Lower (2.58 million to 78,100 years ago)	Gunz Glaciation	Nebraskan Glaciation
Pliocene			

The four pluvial periods such as Kageran, Kamasian, Kanjeran and Gamblian have been recorded from Africa and their occurrence were corresponding to the occurrences of Gunz, Mindel, Riss and Wurm European glacial stages. Many mammalian fauna such as woolly rhinoceros, woolly mammoth, Columbian mammoth, cave lion and rein deer adopted the cold climatic conditions.

5.6.2 Holocene

The Holocene is the current or recent interval of the geologic time scale (Table 5.1). It starts with the end of the last Pleistocene major glacial stage, about 11,700 years before present and continues to the present day. It is subdivided into three ages (Table 5.3). It is relatively a warm period during which human influences had been significantly altered the Earth system particularly its environment. Initially, humans altered Earth's environment by hunting, cutting down trees, farming (agriculture) and latterly, by establishing civilisation, building towns and cities, industries with burning of fossil fuels, extracting natural resources, and finally, by establishing huge networks of transportation and communication systems (Stanley, 2009). It is noted that humanity has broadly influenced the Holocene environment of earth, therefore, it is sometimes also known as Anthropocene. The term Anthropocene is an informal name and till date Holocene is a valid epoch.

Table 5.3: Holocene Time Scale

Period	Epoch	Age	Duration in years
Quaternary	Holocene	Meghalayan (Late)	4,200 to present
		Northgrippian (Middle)	8,200 to 4,200
		Greenlandian (Early)	11,700 to 8,200
	Pleistocene	Upper	12,600 to 11,700

The Anthropocene refers to 'Age of Man'. In simple words, the Anthropocene can be described as the geology of humanity, which focuses on the cumulative role of humans as geologic and geomorphic agents in altering the Earth's environment by multiple ways such as through agriculture, mining, industrialisation, urbanisation or globalisation. The word Anthropocene was extensively used in the scientific literature of China during the 1990s in informal way. In 2000, Paul Crutzen and Eugene Stoermer formally presented Anthropocene and also discussed it in the context of geological time scale. The Anthropocene is less popular concept as compared to the global warming (Syvitski, 2012). The Anthropocene is still an informal time unit and its beginning is still a matter of debate, but many workers believe that it began with the Industrial Revolution in Europe around 1800 years before present (Zalasiewicz and others, 2019).

The Holocene epoch is very important for us because it shows how Earth's environment reached to its present form. It also experienced varied cycles of climate change (Table 5.3). It should be noted that radiocarbon dating method (Carbon 14) with half-life 5,730 years serves as an excellent method for dating Holocene sediments and organic remains. The Early Holocene (11,700 to 8,200 years before present) was a time of global warming and moist conditions prevailed in tropical dessert areas. About three episodes of high sea level elevation were recorded during this interval based on remains of reef-building sea corals. The dry interval of the Early Holocene is described as Boreal period and wet as Atlantic period (Table 5.4). The Middle Holocenewas a time of high warming and global temperature rose by 4° to 5° C. During this interval, Arabia and India experienced higher monsoon circulation (Mathur, 2005). During the Early and Middle Holocene between 9,000 and 6,000 years before present, many continental glaciers disappeared. The dry and warm climate of the Middle Holocene is termed as Subboreal environmental period (Table 5.4). The Late Holocene (4,200 years before present to present) witnessed rapid warming and cooling intervals. Between 1445 to 1700 AD, the Arctic region covered by ice and many glaciers advanced which gave rise to Little Ice Age. The record shows that climate is fluctuating in the Late Holocene. The wet and cool climate of Late Holocene is named as Subatlantic environmental period.

Table 5.4: Holocene climate (modified after Mathur, 2005)

Epoch	Glacial stage	Environmental period	Age based carbon 14 method (in years before present)	Climate
Holocene	Post glacial	Subatlantic	2,500 to 0	Wet and cool
		Subboreal	5,000 to 2,500	Dry and warm
		Atlantic	8,000 to 5,000	Wet and warm
		Boreal	10,000 to 8,000	Dry and warm
Pleistocene	Late glacial			

In nutshell, we live in the Holocene. This epoch possesses relatively high sea level, minimal ice covers (which are still extensive in Polar Regions and high elevation of the mountainous regions), mid-latitude deciduous forest and huge expansion of human population (Bloom, 2009). The modern and industrial society of humans have continuously been altering earth's environment by burning fossil fuels and adding high concentration of carbon dioxide as a byproduct of fossil fuels combustion into the atmosphere. It is altering the climate system and, thus, causing the global warming.

Check Your Progress 2

Note: a) Use the space given below for your answers.

b) Check your answers with those given at the end of the unit.

1) The Pleistocene epoch starts from ……… and ends at ………………. .

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2) List the four Pleistocene glacial and three inter-glacial stages of the Europe.

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5.7 LET US SUM UP

In this unit, you have learnt the following:

- Palaeoclimate is the science dealing with the study of past climate.
- Palaeoclimatologists used climate archives or proxies to unravel the past climate of the Earth.
- Historical data, archaeological data and geological record are the main climate archives
- The logs of the farmers', dairies of travellers', ancient inscriptions, newspapers, paintings, artistic depictions, reports of the early weather observers and other public records are the sources of historical data.
- Rock layers, minerals, soil, remains of plant and animal, and artifacts are the main sources of archaeological data.
- The geological record consisting of sedimentary rock types (sandstones, evaporates, calcretes, tillites), fossils, ice cores and cave deposits yield clues of past climate.
- The Pleistocene epoch starts from 2.58 million years ago and ends at 11,700 years and it is period of extensive glaciations particularly in the Northern Hemisphere, Antarctica, South America and mountainous areas of the Rockies, Alps, Himalaya, Kilimanjaro and Mount Kenya.
- Four glacial and three inter-glacial stages are known from the Europe and North America during Pleistocene epoch.
- The Holocene is the epoch where we live. It starts with the end of the last Pleistocene major glacial stage, about 11,700 years before present and

continues to the present day.

- The Holocene is relatively a warm period during which humans have significantly altered the Earth's environment.
- The "Anthropocene" refers to 'Age of Man' describes geology of humanity and focuses on the cumulative role of humans as geologic and geomorphic agents in altering the Earth's environment by multiple ways.

5.8 KEY WORD

Proxy: A proxy climate indicator is a record that is interpreted, using physical and biophysical principles, to represent some combination of climate related variations back in time. Climate-related data derived in this way are referred to as proxy data. Proxy data can be calibrated to provide quantitative climate information.

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5.10 ANSWERS TO CHECK YOUR PROGRESS

Check Your Progress - I

1) The term palaeoclimate refers to the climate of the past. The science of studying the modern climate is termed as climatology, similarly, the science dealing with the studying of past climate is known as palaeoclimatology. The word palaeoclimatology is a combination of the Greek words "*Palaios*" - (ancient) + "*clima*"- (climate) + "*ology*" - (branch of learning) and therefore it refers to the study of past climate.

2) Tillites are lithified glacial deposits and indicate a cold glacial climate.

3) Tropical

Check Your Progress-II

1) 2.58 million years ago; 11,700 years ago.

2) The four European glacial stages are the Gunz, Mindel, Riss and Wurm. The three inter-glacial stages are the Gunz-Mindel, Mindel-Riss and Riss-Wurm.

UNIT 6 ENVIRONMENTAL INDICATORS AND INSTRUMENTAL RECORDS

Structure

6.1 Introduction
6.2 Objectives
6.3 Factors affecting the Earth's Climate System
6.3.1 Internal Forcing
6.3.2 External Forcing
6.3.2.1 Human Influences
6.3.2.2 Orbital Variations
6.3.2.3 Solar Output
6.3.2.4 Volcanism
6.3.2.5 Plate Tectonics
6.3.2.6 Other Mechanisms
6.4 The Measurement of Climate Change
6.4.1 Instrumental Records
6.4.2 Proxy Records
6.5 Annual Resolution Data from Proxy Record
6.5.1 Speleothems
6.5.2 Corals as Palaeoclimate Proxy
6.5.3 Dendrochronology
6.6 Centennial to Millennial Scale Data from Proxy Records
6.6.1 Palynology as a Proxy Record
6.6.2 Stable Isotopes
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6.1 INTRODUCTION

Climate change is one of the serious issues being faced by humanity across the globe. Climate change has a wide-range of effects on the environment, socio-economic life influencing several sectors like water resources, agriculture and food security, human health, terrestrial ecosystems, biodiversity and coastal zones (https://unfccc.int/resource/docs/publications/impacts.pdf). According to the published reports during the last 100 years Earth's average temperature has raised by more than 1.4^0F with much of this occurred during the last 35-40 years (NRC, 2012). There are ample evidences of such warming that brought out unpredicted drought and anomalous rainfall, impacting the floral and faunal diversity pattern in diversified geographical parts of world. The 4% - 12% variability of daily monsoon rainfall in India is expected to be with 1^0C of warming. There is a chance of 13% - 50% change in variability which will take place if greenhouse gases continue to be emitted unabated. Over the last century, atmospheric concentrations of carbon dioxide increased from a pre-industrial value of 278 parts per million to 379 parts per million in 2005 (NRC, 2011). As a result of global warming, with relatively small rise in the average temperature, the type, frequency and intensity of extreme events, such as tropical cyclones, droughts, floods and heavy precipitation events are expected to increase.

Changes in rainfall pattern are likely to lead to flooding or drought conditions. Melting of glaciers can result into flooding and soil erosion. A shift in crop growing seasons is witnessed and expected at large scale with rising temperatures which will pose great threat to food security and may result in the widespread of diseases. With a 2° C rise in temperature, there is a risk of loss of 30% of habit and habitats resulting into the extinction of species especially in the coral reefs, boreal forests, Mediterranean region and mountains. Increasing sea levels pose grave danger to the coastal life and increase great risk of storm surge, inundation and wave damage to coastlines, particularly in small island states and countries with low lying deltas. A rise in extreme events will have effects on health and lives as well as associated environmental and economic impacts. Through this unit, you will be learning various facets of environmental indicators and instrumental records.

6.2 OBJECTIVES

After studying this unit, you will be able to:

- explain the significance of instrumental records and proxy climate indicator; and
- elucidate the contributions of proxy climate indicator to decipher the past climate.

6.3 FACTORS AFFECTING THE EARTH'S CLIMATE SYSTEM

Climate induced changes have severely impacted various biotic and abiotic components of ecosystem and thus, resulted into the altered nature of Earth's climate system. Biotic processes, variations in solar radiation received by the Earth, long-term changes in the tilt of the Earth and its orbit around the sun, plate tectonics and volcanic eruptions, human activities play a vital role in governing the Earth's climate system. According to the World Metrological Department (WMD) climate is the average of weather conditions at a place for at least a period of 30 years. A deviation in the mean standard of climate for a longer period of time (i.e., millions of years) is called climate change. Climate is a complex system of interactions between various components of earth like atmosphere, hydrosphere, cryosphere, land surface and biosphere (IPCC 2007). There are several internal and external factors that influence and affects the climate of the Earth. Thus, it becomes necessary to understand these components, functioning and their influence in altering the climate dynamics and behavioral analysis of these external and internal forcing to understand the climate change at spatial and temporal scale.

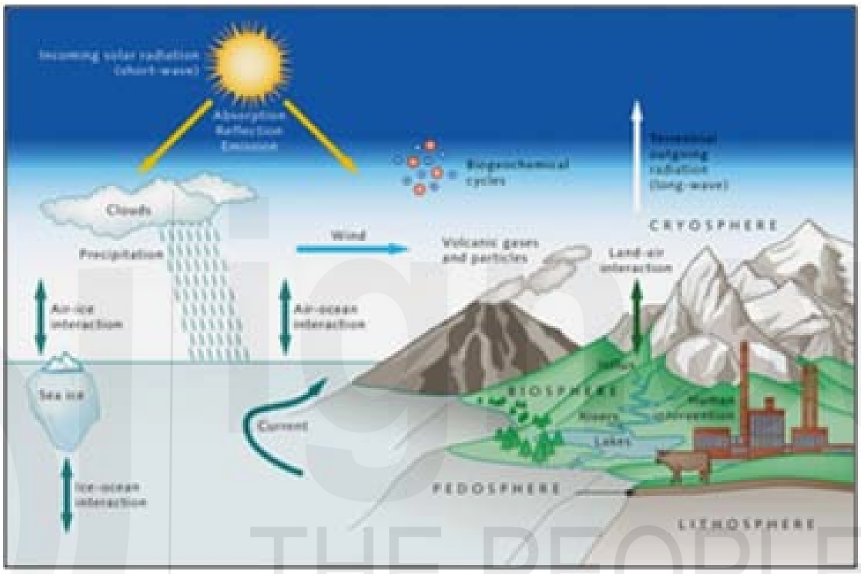

Fig. 6.1. Factors affecting Earth's climate system

(source:https://worldoceanreview.com/en/wor-1/climate-system/earth-climate-system/)

6.3.1 Internal forcing

Internal forcing are the natural processes that operate from within the climate system like the ocean and atmospheric interactions and interaction among the biotic (living) components. The ocean and atmosphere work together and result in internal climate variability that lasts from years to decades. By redistributing heat between the deep ocean and the atmosphere and altering the cloud/water vapor, sea ice distribution, these circulations affect global average surface temperature and the total energy budget of the earth. While living components play a vital role in albedo, evapo-transpiration, cloud formation, weathering, water and carbon cycle, etc.

6.3.2 External forcing

Anthropogenic impacts like increased emissions of greenhouse gases and dust along with natural processes like changes in solar output, Earth's orbit, volcano eruptions, etc. act as the external forces that affects the climate of the Earth.

6.3.2.1 Human influences

Human induced pressures in the form of agriculture, land clearance, shifting cultivation, deforestation, urbanization and industrialization have resulted into the irreversible changes like increase in the amount of greenhouse gases, ozone depletion, production of methane, etc. and have badly impacted the microclimate, and measures of climate variables

6.3.2.2 Orbital variations

Orbital variation plays a vital role in governing the climate system of Earth. The shape of the Earth's orbit changes every 100,000 years, it varies from being elliptical to nearly circular and then back. Slight variations in Earth's motion led to changes in the seasonal distribution of sunlight reaching the Earth's surface and its distribution across the globe. Milankovitch cycle (a resultant of combination of Earth's eccentricity, changes in the tilt angle of Earth's axis of rotation, and precession of Earth's axis) is notable to understand the past climate change and various climatic episodes of glacial and interglacial cycles in geological past.

6.3.2.3 Solar output

The Sun is the ultimate source of most of the energy that drives the biological and physical processes around us. Earth-Sun orbital relationship has a direct impact on geographical distribution of the Sun's energy over the Earth's surface. Other sources include geothermal energy from the Earth's core, tidal energy from the Moon and heat from the decay of radioactive compounds. Both long- and short-term variations in solar intensity are evidenced to affect global climate. Over the time-scale of millions of years, the change in solar intensity is a critical factor influencing climate (Schroder et al. 2008). Review of studies shows that solar output played an influential role in triggering the geological events like Little Ice, marked by relative cooling and greater glacier from 1550 to 1850 AD (Miles et al. 2004).

6.3.2.4 Volcanism

The volcanic eruptions that can inject over 100,000 tons of SO_2 into the stratosphere are considered to affect the Earth's climate (Wignall, 2001). Due to the optical properties of SO_2 and sulfate aerosols, a global layer of sulfuric acid haze is created which results in cooling conditions by partially blocking the transmission of solar radiation to the Earth's surface for several years (Graff et al. 1997). For instance, eruption of Mount Pinatubo in 1991, affected the climate substantially, and subsequently global temperatures decreased by about 0.5 °C (0.9 °F) for up to three years (IPCC 2007). This resulted in reduction of surface temperatures in 1991–93 which is equivalent to a reduction in net radiation of 4 watts per square meter (AGU, 2011).

Volcanoes also contribute in the extended carbon cycle. A large amount of carbon dioxide is released for very long (geological) time period to counteract the uptake by sedimentary rocks and other geological carbon dioxide sinks. A review of published studies indicates that annual volcanic emissions of carbon dioxide, including amounts released from mid-ocean ridges, volcanic arcs, and hot spot volcanoes, are only the equivalent of 3 to 5 days of human-caused output (Bruckschen et al., 1999; IPCC, 2007; AGU, 2011; AAS, 2017)

6.3.2.5 Plate tectonics

Over a wide range of timescale, horizontal and vertical displacements of tectonic plates reconfigure global land and ocean areas and generate varying topography which affect the global and local patterns of climate and atmosphere-ocean circulation (Atri & Melott, 2014). There are several factors associated with the role of plate tectonics in climate change like the position and size of the continents, geometry of the oceans and patterns of ocean circulation. The locations of the seas are important in controlling the transfer of heat and moisture across the globe, and therefore, in determining global climate. For example, formation of the Isthmus of Panama about 5 million years ago closed the direct mixing of Atlantic and Pacific Oceans. This strongly affected the ocean dynamics of Gulf Stream and may have led to Northern Hemisphere ice cover (Sindbaek, 2007; Demenocal, 2001).

6.3.2.6 Other mechanisms

The Earth receives an influx of ionized particles known as cosmic rays from a variety of external sources, including the Sun. There is a hypothesis that an increase in the cosmic ray flux would increase the ionization in the atmosphere, leading to greater cloud cover which in turn would cool the surface.

6.4 THE MEASUREMENT OF CLIMATE CHANGE

6.4.1 Instrumental records

A climate element, is any one of the various properties or conditions of the atmosphere which together specify the physical state of the climate at a given place, for a particular period of time (Linacre, 1992). To understand the dynamics of climate change and associated events, it is necessary to have a better understanding of the present scenario of climate by studying and observing the factors controlling or contributing in climate change. In this regard, multi-disciplinary and interdisciplinary studies (oceanography, meteorology, geomorphology, geology and pale climatology) give good amount of quantitative and qualitative information. This information along with the observational and instrumental records from diversified geographical location contribute a lot in making predictive climatic models. Analysis of instrumental records of common climate elements such as temperature, precipitation (rain, snow and hail), humidity, wind, sunshine and atmospheric pressure taken together proved to be very useful to specify the physical state of the climate at a given place, for a certain period of time. Such records of climate elements collected over time are known as "time series" (enviropedia). Temperature data gives an insight into Earth's surface and sea surface temperature (SST). Precipitation data in the form of rainfall, snowfall, etc. is yet another important factor that shows relative climate variation, including humidity, water balance and water quality etc. Vegetation studies pertaining to loss, increase or change in biomass reflect the ecosystem change under varied climatic regimes. Sea level measurements help in tracing the shore line fluctuation. Solar activity influence climate, primarily through changes in the intensity of solar radiation. Volcanic eruptions, like solar radiation, can alter climate due to the aerosols that are emitted into the atmosphere and alter climate patterns. Chemical composition of air or water can be measured by tracking levels of greenhouse gases such as carbon dioxide and methane, and measuring ratios of oxygen isotopes. Studies show that there is a strong correlation between the percent of carbon dioxide in the atmosphere and the Earth's mean temperature.

But these available instrumental weather records are spanning for short time period in most parts of the country and they do not provide benchmark information to discriminate between natural and human-induced climatic impact. Since climate, in general, shows high spatial and temporal variability, long-term climate records from different geographic regions of the country are required so that we can have a better insight into the climate change. In this connection, high-resolution long-term proxy records are required. There exists inconsistency in the amplitude of climate records derived from different proxies therefore multi-proxy approach proved to be better because the individual records could be cross-verified and robust climate reconstructions can be derived. Such high-resolution proxy climate records spanning centuries to millennia would be useful to understand the natural course of climate, climate sensitivity to forcing, spatial variability, lead and lag relationship, recurrence behavior of extreme climate events and their ecological impact.

6.4.2 Proxy records

It is not possible for us to travel back in time to understand and measure temperatures, rainfall and other environmental conditions. Thus, we need to rely on various proxies from ancient geological materials to understand the conditions locked up in. There are many such proxies like ice cores, tree rings, sub-fossil pollen, boreholes, corals, lake, ocean sediments, and Speleothems that proved to be very useful to mankind to understand the long term vegetation and climate dynamics at spatial and temporal scale. Thus, multi-proxy study is needed to resolve several issues related to present, past and future directions in climate change studies.

6.5 ANNUAL RESOLUTION DATA FROM PROXY RECORD

Since the proxy records gives an indirect information about the past climate, temperature, and rainfall, etc. each proxy responds variably to the changing climatic scenario and thus record palaeoclimate data accordingly. The finer the resolution of data the more information we gather from it. Among the various proxies used in palaeoclimate studies, some of the proxies that give annual resolution data includes Speleothems, corals and tree rings.

6.5.1 Speleothems

The word Speleothems is a Greek word 'Spelaion' meaning cave and 'thema' meaning deposit through flowing, dripping, or seeping water (Moore, 1952; Schwarcz, 1986). Thus, they may be defined as the mineral deposits formed in karstic caves, where the water table is significantly lowered, and favoring air exchange with atmosphere. On the basis of competition between the dynamics of the water and the crystal growth habits of the constituent minerals, they attain different shapes viz. stalagmites and stalactites or slablike deposits known as flowstones (Sasowsky, 2012). Stalactites are the deposits which hang from the ceilings of caves, they often have a hollow core, with growth occurring around the central orifice. On the other hand, stalagmites are solid and grow incrementally at the drip site. They are primarily composed of calcium carbonate, precipitated from groundwater that has percolated through the adjacent carbonate host rock. The most commonly occurring minerals are calcite, aragonite, and gypsum (Sasowsky, 2012). Certain trace elements may also be present that often gives the deposit a characteristic color. Deposition of a Speleothems results from evaporation of water or degassing of carbon dioxide from water droplets.

Under the high seasonal climatic variations inside (humidity, CO_2 partial pressure, air ventilation) or outside (precipitation, temperature, snow melting) the cave. For example, annual laminas are formed in the Speleothems (Fairchild and Treble 2009, Bradley, 2015; Tan et al. 2006; Baker et al. 2008). Therefore, Speleothems have the potential to record past climate with annual resolution.

Annual laminas in Speleothems: In Speleothems four types of laminas have been reported.

1) Fluorescent laminas: They are observed by using conventional mercury light-source UV reflected-light microscopy and confocal laser fluorescent microscopy (Shopov et al. 1994; Orland et al. 2012)

2) Visible laminas: They are observed using conventional transmitted and reflected-light microscopy (Genty and Quinif 1996)

3) Calcite-aragonite couplets: They show seasonal alternations of calcite and aragonite growth layers (Railsback et al. 1994)

4) Geochemical laminas: It is defined by the annual variability of their chemical constituents such as stable isotopes ($\delta^{18}O$, $\delta^{13}C$) and trace elements (e.g., Mg, Sr, Ba) (Johnson et al. 2006).

The number of layers formed are counted in a Speleothems and are then compared with the duration of growth measured independently by radiometric dating techniques viz., ^{230}Th dating is most commonly used for the late Pleistocene samples (Baker et al. 1993; Tan et al. 2000), while with ^{210}Pb and ^{226}Ra methods samples younger than 150 years can be dated (Baskaran and Iliffe 1993; Condomines and Rihs 2006) or with the atomic bomb testing 14C signature that characterizes the last 50 years (Genty et al. 1998; Mattey et al. 2008).

6.5.2 Corals as palaeoclimate proxy

Coral reefs have been a part of the Earth's oceans for millions of years and are very sensitive to changes in climate. By extracting calcium carbonate from the ocean waters, they form skeleton like structure. When the water temperature changes, calcium carbonate densities in the skeletons also change. Studies shows that the coral formed in the summer has a different density than coral formed in the winter. This creates seasonal growth rings on the coral (like rings on a tree). These rings are used to determine the temperature of the water, and the season in which the coral grew and by studying the growth bands, coral samples can be dated to an exact year and season. The density of the coral skeleton, or how many minerals are present in a piece of a certain size, changes with temperature.

Check Your Progress 1

Note: i) Use the space given below for your answers.

ii) Check your answers with those given at the end of the unit

1) What are Speleothems?

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2) How coral act as palaeoclimate proxy?

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6.5.3 Dendrochronology (Tree rings study)

Climate change during the past 1000 years is important to reconstruct as it can be correlated with the historical archives and extent to which climate affected civilizations can be deduced. Of the several proxies used for paleoclimate (e.g., ice cores, lake sediments, corals and Speleothems) reconstructions, tree rings have special advantages: they record seasonal monsoonal variability, they preserve continuous record and can be easily dated using ring-counting. An individual tree ring records contemporaneous climate changes in the year of formation over the life-span of the tree. Cross correlation and matching of ring patterns of different (dead, archived and growing) trees of the same climate regime can extend the climate reconstructions to past several thousands of years. Significant contributions to climate science within the last decade have firmly established tree-rings as valuable sources of proxy data for evaluating long-term climate variability/trends and as useful tools for developing long-term records of extreme climatic events [Mann et al., 1999]. Previous monsoon reconstructions using tree rings were based on ring width. The analogy used was: trees from high latitude or altitude regions, with wider (narrower) rings correspond to higher (lower) temperature/ precipitation (Managave and Ramesh, 2012). However, the presumably simple relation between width and climate is rather complex and is influenced by non-climatic factors such as light availability, topography, soil type and forest thinning, ecological parameters and also genetic variability among trees of the same species (e.g., Kress et al. [2009], Fritts [1976]). Paleoclimate proxies are affected by ecological parameters and considered to be better measures for climate reconstruction. Tree cellulose $\delta\ ^{18}O$ is more sensitive to rainfall fluctuations as compared to ring-width and ring density [Sano et al., 2010]. Several researches and reviews on tree rings isotopes by Farquhar et al. (1989), Ramesh et al. (1986), Dawson et al. (2002), McCarroll and Loader (2004), Managave and Ramesh (2012) highlight that oxygen and hydrogen of cellulose from individual growth rings can be used as proxies for climatic parameters such as rainfall, humidity and temperature. The oxygen isotope composition of plants is influenced by various physiological and climate processes. It is mainly controlled by $\delta\ ^{18}O$ of the source water, the level of ^{18}O enrichment in leaf due to evaporation, biochemical fractionation of ^{18}O due to synthesis of sucrose in the leaf and the isotopic exchange between carbohydrate and xylem water during cellulose synthesis. The $\delta\ ^{18}O$ of rainfall is inversely related to the amount of precipitation in the tropics (Dansgaard, 1964; Rozanski et al., 1993; Schmidt et al., 2007; Yadava and Ramesh, 2007) hence tree cellulose $\delta\ ^{18}O$ is a powerful tool to reconstruct past monsoon rainfall.

Dendrochronology is the science which belongs to the study of trees' annual growth rings, or in a more scientific way dendrochronology (dendros: trees or growth ring of trees, chronos: time or past event, logy: the study of) is the study and dating of trees annual growth rings to understand the past event and processes. Trees are the natural archives and have the potential to reflect the past atmospheric conditions through annual growth-rings. Tree-ring study could be useful to understand the different aspect of environment like climate, ecology, geophysical process, etc. To study the different disciplines of dendrochronology, it has been divided into several branches based on various parameters and the important applications are as follows:

a) Dendroclimatology: Developing records of past climate using living and dead tree-annual growth rings.

b) Dendrohydrology: Developing records of past water availability and flooding.

c) Dendroarchaeology: Dating of Archaeological dwellings.

d) Dendrogeomorphology: Dating of land movements in the past in the form of landslide, creeping and debris flow.

e) Dendroglaciology: Dating of glacial movement and fluctuations in the past.

f) Dendrovolcanology: Dating of volcanic eruptions in the past.

g) Dendrochemistry: Monitoring of the chemical composition of the soil.

h) Dendroecology: Determine the ecological process in terms of tree-line movements, etc.

i) Dendropyrochrnonology: Dating of forest fires in the past.

j) Dendroentomology: Reconstruction of population level of insects in the past.

k) Dedromastecology: Reconstruction of trees fruiting events.

Dendroclimatology is a special branch of dendrochronology. Development of past climatic records with the help of annual tree-growth rings is called Dendroclimatology. Trees' annual growth rings are studied to understand the past climatic fluctuations and environmental process prevailing over the region. Atmospheric conditions and influence of climate can be observed in tree rings by variation in ring-width. This tree-growth and climate relationship was first recognised by the Leonardo da Vinci in sixteenth century (Stallings et. al, 1937). However annual tree-ring development and wood structure were studied to the mid-1800s when Hartig' son and others published their research paper (Schweingruber, 1988). Hartig's son Robert had also studied anatomy and ecology of tree-rings in the end of nineteenth century and date the damage by insects, hail and frost in trees (Schweingruber, 1988). Andrew E. Douglass was the pioneer worker of this science and known as the "Father of Dendrochronology". He realized that the narrow rings of trees formed during the dry years and the variation in tree-ring pattern can be used to cross-date different sites of tree-ring sequence and to exactly fit them into the calendar year. In the twentieth century, tree-ring study became a useful tool and has been used widely in the world to understand past climatic process. H. C. Fritts (1976) introduced statistical procedures for the reconstruction of past climate on the basis of climatic signal preserved in the tree-ring sequences.

Annual growth-rings are actually secondary xylem and one ring consists of earlywood and latewood. The light and large sized cell which forms during the spring season are called as earlywood and comparatively small in size and dark in colour cells are developed during summer period called latewood. Dendroclimatic studies require trees which produce annual growth ring like conifers including some broad leaf trees are highly useful for the climatic reconstructions. To understand the climate growth relationship, trees from the climate sensitive sites are used where tree-growth is directly influenced by the climatic parameters such as temperature and precipitation. Generally steep slopes, where water table is far from the tree roots are used due to negligible influence of water logging on trees and increasing dependency over climate. Trees grown over such condition are very vulnerable to climate change and therefore very sensitive too. Methodology consists of that two-increment core sample perpendicular to the natural slope from a tree generally taken and for the coring in trees breast height (~1.4m) is used. Increment cores are very fragile and to support the sample wooden frames are used to hold the cores safely and this process is known as mounting of tree-ring samples. Mounted samples are air dried for few days on room temperature and then surfaces are polished with different grit of abrasive to make cross-surface visible under microscope. To assign true calendar year to each ring's skeleton, plot method is used to cross date tree-ring sequence of each sample (Stokes and Smiley, 1968). Using dated samples, tree-ring chronologies developed from each site and climatic signal with the help of metrological data in the chronologies identified. Calibration and verification analysis are performed and ultimately climatic variable is reconstructed.

The tree-ring based climatic reconstruction provides valuable window to look in the past to understand the climatic variability. Actually, in the era of global warming, climate is continuously changing and there is huge temporal and spatial difference exist in a regional scale. Observational record from all over the globe shows that temperature is continuously increasing whereas precipitation shows heterogeneity in the trend. Earth's climate is changing since long back but in the last ~150 years, the anthropogenic activity enhances the variability and due to the influence of anthropogenic practices, climatic observational records show turbulence in their normal pattern. The instrumental records are restricted our understanding in terms of climatic changes in past because of the availability of very sparse and patchy climatic data. Meteorological data records go up-to last one and half century which are not sufficient to understand long term climatic changes. In the absence of proper network of metrological station, tree-ring data have potential to supplement the existing records up-to the last millennium and more.

Resolution of tree ring data is very high and this character makes it unique among the other climatic proxies.

Several tropical and temperate tree species growing in different climatic zones in India with distinct seasonality are known to have datable growth rings. Early studies on tree-rings in India were aimed to understand tree productivity and rotation cycles (Gamble, 1902). Chowdhury (1939, 1940a, b) first attempted to study the effect of environmental factors on growth-ring formation in several species. However, climatic aspect of tree-ring studies in India began only around late 1970s (Pant, 1979). Since then, subsequent tree-ring studies have indicated enormous dendroclimatic potential of different species and several chronologies and reconstructions developed (Yadav et al., 2004, 2006, 2014a, 2014b, 2015, 2017; Misra et al., 2015).

6.6 CENTENNIAL TO MILLENNIAL SCALE DATA FROM PROXY RECORDS

To understand the long-term climate and vegetation dynamics and to understand the influence of human being in altering the landscape dynamics, etc. we need to look into the proxy records that can help in reconstructing the geological past, whether its climate, vegetation, ecosystem or human interference. The proxies that give annual resolution data fetch good information about the changing landscape dynamics for the past few thousand years. But to have the long-term information, we have to rely on proxies that gives information from centennial to millennial scale. So as the gap in the data sparsity at spatial and temporal scale could be filled and a better scenario for further research and policy framing could be done. In this connection, palynological analysis from the sub-surface sediment samples from lakes, swaps, wetlands and ocean cores proved to be very potential archive to reconstruct the wide spectrum of knowledge about the past climate and vegetation relationship as well as the socio-economic status of the past societies.

6.6.1 Palynology as a proxy record

Since the early 1990s, palynology (study of pollen/spores, diatom, phytoliths, etc.) has been used to address several issues like vegetation dynamics, landscape evolution, agriculture, socio-economic status, past dietary pattern, etc. from a wide variety of sediment samples collected from diversified geographical location across the globe.

Analyses of pollen, diatoms and phytoliths data and identification of other organic remains from lacustrine sediments at close interval from the sediment profile would portray the pattern of vegetation changes. The identification of the spores/pollen, diatom and phytoliths help not only in the reconstruction of climate based on changes of past vegetation but also provide great help in understanding the advent of agriculture and role of the various anthropogenic impacts on vegetation dynamics vis-à-vis climate change in a region. This can be done on the basis of morphological variation (in pollen) between wild vs cultivated grasses, abrupt decline in tree taxa in the landscape, records of weeds known to be associated with the cultivation and forest clearance. In a study from Kolleru lake by Misra et al., (2013), palynological investigation showed that during early to mid-Holocene time, Kolleru lake was a part of sea and under the varying sea level and other geological processes and human interference, it got disconnected from the sea and eventually turned into the present-day fresh water lake. Presence of rice phytoliths and record of cultural pollen (more than 40µ) recorded during 6000 years BP indicate towards the paddy cultivation and agricultural practice in the vicinity of the study area. Diatoms being very sensitive to pH and salinity variation will reflect into the past salinity variation, present and past ecological status of wetlands and associated fresh environment etc., in the region.

Application of phytolith as climatic proxy is based on different ecological preferences of the C_3 and C_4 type. C_4 type of plants favour conditions of aridity and low soil moisture whereas the C_3 plants dominate areas of higher soil moisture (Tieszen et al., 1979). These changes are linked with climatic changes in respect to time scale provided by C-14 dates (both conventional and AMS) of corresponding sediments analyzed.

6.6.2 Stable isotopes

Plants vary not only on the morphological basis but also vary in their methods of food preparation. Thus, the perennial grasses are be classified as either C_3 or C_4 plants. These terms refer to the different pathways that plants use to capture carbon dioxide during photosynthesis. Thus, on the basis of the photosynthetic pathway, the plants are broadly classified as -

1) C_3 Plants: The majority of plants (85%), for example are rice, wheat, soybeans are C_3. They have no special features to combat photorespiration and the first stable compound formed is 3 carbon compound. They are adapted to cool season establishment and growth in either wet or dry environments. C_3 species also tend to generate less bulk than C_4 species. C_3 grasses are known for their greater tolerance of frost compared to C_4 grasses.

2) C_4 Plants: C_4 plants initially produce a 4-carbon molecule that then enters the C_3 cycle. Plants are more adapted to warm or hot seasonal conditions under moist or dry environments.

3) CAM: In some plants, as an adaptation to arid conditions, carbon fixation pathway varies. In such plants to reduce evapo-transpiration, stomataremain closed during the day, but open at night to collect carbon dioxide (CO_2) which is stored as the four-carbon acid malate in vacuoles at night, and then in the daytime, the malate is transported to chloroplasts where it is converted back to CO_2, to get utilized during photosynthesis.

Even the isotopic signatures of the C_3 and C_4 plant varies. The C_3 plants have $\delta^{13}C$ in the range of 22.6‰ to 22.8‰, whereas the C_4 types of plants have $\delta^{13}C$ values in the range of sample 211‰ to 213‰ (Smith and Epstein, 1971; O'Leary, 1988). In a lacustrine system, both terrestrial and aquatic plants contribute to the organic matter. To understand the autochthonous and allochthonous inputs in the region, C/N ratio is very useful and would be used. It is known that autochthonous organic matter comprising aquatic plants and algae has a C/N ratio of less than 10, whereas allochthonous organic matter comprising terrestrial plants has a C/N ratio normally higher than 20 and may be up to 200 (Meybeck, 1982; Hedges et al., 1986, in Talbot and Johannessen, 1992).

6.6.3 Biomarkers analysis

Among the various proxies used in palaeoclimate studies, use of biomarkers has increased for the last few decades and has been widely used to address several issues related to palaeo-humidity, palaeo-temperature, palaeo-vegetation, wet and humid phases, etc. A typical biomarker molecule is made up of a hundred or so covalently-bound atoms of carbon and hydrogen, sometimes also including oxygen, nitrogen, etc., (Eglinton and Eglinton, 2008). These biosynthesized molecules released from precursor organism directly, or upon its death get readily dispersed in the environment. Dispersion of biomarkers is greatly influenced by their entrapment within mineral matrices such as shell, teeth, bone etc., or encapsulation in resistant biopolymer matrices such as cell walls, leaf and insect cuticles and pollen grains, or packaging in environmentally ephemeral entities such as fecal pellets, "marine snow" or other detrital debris and colloidal matter (e.g., humic acids) (Eglinton and Eglinton, 2008). Thus, the number of carbon atoms varies from source to source.

6.6.4 Ancient DNA

Among the various emerging potential proxies, ancient DNA proved to be very useful to scientific as well as archaeological community to resolve several issues related to origin, evolution, dispersal, and migration of plants and humans in ancient past. It plays a vital role in identification of the samples that are morphologically difficult to identify. Sedimentary DNA is also been in use to know about the past vegetation scenarios and thus climate of several sites across globe. Like other fields, this field also requires lot of standard protocol right from the site selection, sample collection, storage to data generation and interpretation. Avoiding the contamination of the samples is the pre requisite for DNA analysis.

6.7 LET US SUM UP

Climate change is one of the serious issues being faced by humanity across the globe. Climate change has a wide-range of effects on the environment, socio-economic life influencing several sectors like water resources, agriculture and food security, human health, terrestrial ecosystems, biodiversity and coastal zones. To understand the dynamics of climate change and associated events, it is necessary to have a better understanding of the present scenario of climate by studying and observing the factors controlling or contributing in climate change. In this regard, multi-disciplinary and interdisciplinary studies (oceanography, meteorology, geomorphology, geology and pale climatology) give good amount of quantitative and qualitative information. This information along with the observational and instrumental records from diversified geographical location contribute a lot in making predictive climatic models. Analysis of instrumental records of common climate elements such as temperature, precipitation (rain, snow and hail), humidity, wind, sunshine and atmospheric pressure taken together proved to be very useful to specify the physical state of the climate at a given place, for a certain period of time. Nevertheless, available instrumental weather records are spanning for short time period in most parts of the country and they do not provide benchmark information to discriminate between natural and human-induced climatic impact. Since climate, in general, shows high spatial and temporal variability, long-term climate records from different geographic regions of the country are required so that we can have a better insight into the climate change. In this regard, high-resolution long-term proxy records are required. We have seen that proxies like ice cores, tree rings, sub-fossil pollen, boreholes, corals, lake, ocean sediments, and Speleothems had proved to be very useful to mankind to understand the long term vegetation and climate dynamics at spatial and temporal scale.

Acknowledgement:

Authors would like to thank Director, BSIP for necessary facilities. Misra S acknowledges DST Fast Track project YSS/2015/001193 for the available facilities under this project.

6.8 KEY WORD

Proxy: A proxy climate indicator is a record that is interpreted, using physical and biophysical principles, to represent some combination of climate related variations back in time. Climate-related data derived in this way are referred to as proxy data.

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6.10 ANSWERS TO CHECK YOUR PROGRESS

Check Your Progress 1

1) Speleothems are defined as the mineral deposits formed in karstic caves, where the water table is significantly lowered, and favoring air exchange with atmosphere. On the basis of competition between the dynamics of the water and the crystal growth habits of the constituent minerals, they attain different shapes namely stalagmites and stalactites or slab-like deposits known as flowstones. Stalactites are the deposits which hang from the ceilings of caves, they often have a hollow core, with growth occurring around the central orifice. Stalagmites are solid and grow incrementally at the drip site.

2) Coral reefs are very sensitive to changes in climate. Corals by extracting calcium carbonate from the ocean waters, they form skeleton like structure. When the water temperature changes, calcium carbonate densities in the skeletons also change. It has been reported that the coral formed in the summer has a different density than coral formed in the winter. This creates seasonal growth rings on the coral (like rings on a tree). These rings are used to determine the temperature of the water, and the season in which the coral grew and by studying the growth bands, coral samples can be dated to an exact year and season. The density of the coral skeleton, or how many minerals are present in a piece of a certain size, changes with temperature.

Check Your Progress 2

1) Dendrochronology is the science which belongs to the study of trees' annual growth rings. In other words, dendrochronology is defined as the study and dating of trees annual growth rings to understand the past event and processes. Trees are the natural archives and have the potential to reflect the past atmospheric conditions through annual growth-rings. Tree-ring study could be useful to understand the different aspect of environment like climate, ecology, geophysical process, etc.

2) Dendroclimatology is a special branch of dendrochronology. Development of past climatic records with the help of annual tree-growth rings is called Dendroclimatology. Trees' annual growth rings are studied to understand the past climatic fluctuations and environmental process prevailing over the region. Atmospheric conditions and influence of climate can be observed in tree rings by variation in ring-width.

UNIT 7 CLIMATE VARIABILITY AND EXTREME WEATHER EVENTS

Structure

7.1 Introduction
7.2 Objectives
7.3 Climate Change
7.4 Extreme Weather Events
7.5 Drought
7.6 Extreme Heat
7.7 Extreme Precipitation
7.8 Tropical cyclones/Hurricanes
7.9 Extratropical storms/Tornadoes
7.10 Wildfires
7.11 Let Us Sum Up
7.12 Key Words
7.13 Suggested Further Reading/References
7.14 Answers to Check Your Progress

7.1 INTRODUCTION

It has been observed that in recent years, there has been an increase in frequency and magnitude of extreme weather events. These weather events are considered extreme if they differ from similar weather events of that area by 90-95%. Further, to identify the weather events of a region, their historical record of weather is examined. Examples include unusually high or low temperature, precipitation, winds or any other parameters such as wildfires, droughts and floods.

With rising awareness about climate change due to both natural and human-induced factors, it has been projected that global warming would cause and increase in hot temperature extremes and occasional lower temperature extreme on daily as well as seasonal time scales. Under RCP8.5 (Representative Concentration Pathway), by the end of the 21st century, a current 20-year high temperature event will occur more frequently on land and a current 20-year low temperature event will become very rare.

A new scientific approach known as 'extreme event attribution' is being practiced where computer models are used to simulate weather conditions and different scenarios are compared to identify how global warming or any other factor has affected extreme weather events. Attribution scientists aim to quantify the extent of human-induced climate change alters the likelihood and intensity of extreme weather events. An example of extreme event attribution of Hurricane Harvey in Texas in 2017 is very high rainfall of 60 inches that worsened the flooding and increased the likelihood of storm.

The website Carbon Brief has published an update of its attribution studies titled "Attribution of Extreme Weather Events in the Context of Climate Change" (Fig. 7.1) that have looked into the impact of climate change on extreme weather events around the world. The vertical axis corresponds to the confidence in attribution science and the horizontal axis indicates the level of understanding of how climate affects that type of event.

Fig. 7.1: Attribution of Extreme Weather Events in the Context of Climate Change (Source: NAS, 2016)

It is pertinent to mention that many scientists are of the opinion that global climate change has led to increase in frequency and magnitude of extreme weather events such as heat waves, droughts, floods, storms etc. Further, anthropogenic role in climate change has further aggravated the occurrence and intensity of extreme weather events. For example, sea level rise due to climate change adversely affects the coastal storms. Further, rising global temperatures due to global warming pose additional stress on areas affected by drought due to higher temperatures. All these examples point towards the role of climate change in increasing the intensity and frequency of extreme weather events. Through this unit, we would be discussing climate variability and extreme weather events.

7.2 OBJECTIVES

After studying this unit, you should be able to:

- define the extreme weather event; and
- discuss the extreme weather events.

7.3 CLIMATE CHANGE

Climate change refers to the change in the normal weather patterns around the world for an extended period of time. Many evidences such as rising sea level, shifting of tree lines, loss of sea ice, increased frequency of heat waves and drought, shrinking of glaciers and so on, indicate towards changing climate of the Earth. The United Nations has set up an organization known as Intergovernmental Panel on Climate Change (IPCC) for assessing the science related to climate change. IPCC is of the opinion that the extent of climate change effects on individual regions will vary over time depending on the adaptation capacity of the community as well as the environment of that region. Further, the temperature increase forecasted by IPCC is 1-3°C all over the globe, which would be beneficial for some regions while disadvantageous for a few. However, the disadvantages far outweigh the positive effects of climate change.

Further, it is projected that global climate will continue to change even beyond this century depending on the amount of greenhouse gases emitted globally, that heat up the earth's atmosphere by preventing passage of longwave radiations back to the space; and also, by earth's response to those greenhouse gas emissions.

7.4 EXTREME WEATHER EVENTS

The definition of an extreme event is quite varied depending on the impacts caused by these events or on the basis of magnitude and intensity of these events. It may range from droughts, tsunamis and earthquakes to epidemics or explosion as well. These extreme events have been gaining greater attention in the last few years due to increase in frequency and magnitude of extreme weather and climate events; as well as due to increase in vulnerability due to high population growth, lifestyle changes and urbanization in regions which should ideally have been buffer zones during the onset of disaster such as floods. Examples include building settlement areas on river banks or in coastal regions prone to tsunamis or cyclones.

If we look at the chronology of the development of the term 'extreme event', it was first used for rainfall intensity and frequency in a report by the National Weather Service, earlier known as U.S. Weather Bureau (U.S. Weather Service, 1959). The word 'extreme' has been derived from the Latin 'extremus' meaning "utmost" while 'event' originates from the Latin 'evenire' meaning "to come" (Weekley, 1921). Thus, extreme refers to the process of rare occurrence or of low probability or as outliers to the normal condition; while event describes a non-stationary situation. Thus, an extreme weather event refers to the occurrence of a very high or very low value of a weather variable as compared to its threshold level in a specific region. This is illustrated in the form of extreme weather and climate events such as heat waves and drought which are a manifestation of climate change. Over the last three decades, the world has witnessed prolonged droughts, excessive precipitation, frequent floods, fewer colder days and higher temperatures. This is often attributed to human-induced climate changes. Many factors influence extreme weather events.

Various mechanisms have been developed all over the world to assess the extreme weather events. For example, U.S Records is a tool that lists daily, monthly and all-time data for weather stations located across the United States. Besides, the National Climate Extremes Committee (NCEC) was established in 1997 in US to study the extreme events and ponder upon the meteorological measurements by NOAA (National Oceanic and Atmospheric Administration) and State Climate Extremes Committee (SCEC) in 2006 to evaluate the climatological records of individual states in US. International Best Track Archive for Climate Stewardship (IBTrACS) provides information pertaining to the distribution, frequency, and intensity of tropical cyclones worldwide. Also, various reports such as Special Reports on Extreme Climate Events and Global Hazards Report focus on extreme events around the world. NOAA's National Centres for Environmental Information (NCEI) hosts and provides public access to abundant environmental information on Earth that includes atmospheric, coastal, oceanic and geophysical data.

In the following section, let’s study some extreme weather events arising out of climate change.

7.5 DROUGHT

Drought is a climate anomaly characterized by temporary reduction in water or moisture availability significantly below the normal amount for a specific period. This could be due to a single factor of insufficient or irregular rainfall, or a higher water need or a combination of multiple factors. The reason for concern of drought is that if it persists for longer periods, it can cause adverse effects on humans, vegetation, livestock as well as ecological systems that undergo drought. Globally, drought is the second-most geographically extensive hazard after floods of the earth’s land area. The percent of area affected by serious drought has doubled since 1970. In recent years, droughts have been occurring frequently, and their impacts are being aggravated by the rise in water demand and the variability in hydro-meteorological variables due to climate change.

In general, four types of drought are recognised: meteorological drought, hydrological drought, agricultural drought and socioeconomic drought. Meteorological drought is defined as a lack of precipitation over a region for a period of time. Hydrological drought is related to a period with inadequate surface and subsurface water resources for established water uses of a given water resources management system. Agricultural drought, usually, refers to a period with declining soil moisture and consequent crop failure. This does not include any reference to surface water resources A decline of soil moisture depends on several factors which are affected by meteorological and hydrological droughts along with differences between actual evapotranspiration and potential evapotranspiration. Socio-economic drought is associated with failure of water resources systems to meet water demands and thus associating droughts with supply of and demand for water. Socio-economic drought occurs when the demand for water exceeds supply as a result of a weather-related shortfall in water supply. In rainfed areas, drylands are more prone to 'drought'. Severe drought can affect livestock and crops in agriculture; leading to food price instability, famine; water transport system; roadways; increase the probability of wildfires; scarcity of hydropower and thus additional energy stress coupled with increased electricity demand. Resilience towards drought can be built by conserving water, enhancing water efficiency, stormwater management, emergency planning for drought, and planting drought-resistant crops.

Various mechanisms have been explained regarding contribution of climate change to drought. The first and foremost factor in this is the erratic monsoon patterns and its deviation from the normal or predicted rainfall. Further, lesser rainfall coupled with higher temperatures create moisture stress in plants due to increased evapotranspiration. As a result, the amount of water needed for evapotranspiration exceeds the total amount of moisture available in soil. Further, it has also been hypothesized that droughts can persist through a “positive feedback,” where dry soils and reduced plant cover can further hamper precipitation in an already dry area.

Further, it is estimated that relatively wet places, such as the tropics, and higher latitudes will get wetter, while relatively dry places in the subtropics will become drier. The recent studies on droughts in United States indicate that 81% of area suffered severe economic drought.

In the Indian context, every year since 2015, the country has faced severe drought in many states. It has been estimated that during the last year (2019), about 42% of geographical area of the country faced severe drought and about 50 million people were severely affected by drought. According to the Drought Early Warning System, Rajasthan, Bihar, Jharkhand, Gujarat, Maharashtra, Tamil Nadu and Telangana were the states worst affected by drought. In 2019, 44% of India’s area was under drought of one type or the other due to scanty rainfall, delay in monsoons and increased heatwaves. Even in 2020, almost one-fifth of India's districts faced drought-like conditions as per reports by India Meteorological Department (IMD).

7.6 EXTREME HEAT

It has been observed that all over the world, the frequency and intensity of hot days has been increasing in the last few decades; while the number of cold days annually has been decreasing. Further, if greenhouse gas emissions are not significantly reduced, the coldest and warmest daily temperatures are expected to increase by at least 5 degrees F in most areas of United States.

The National Climate Assessment estimates the annual number of days with a heat index above 100 degrees F will double, and days with a heat index above 105 degrees F will triple, nationwide, when compared to the end of the 20th century. Figure 7.2 represents the projected changes in the number of days per year in United States with a maximum temperature above 90°F and a minimum temperature below 32°F. Changes are the difference between the average for mid-century (2036–2065) and the average for near-present (1976–2005) under the higher scenario (RCP8.5). This map depicts a weighted multi-modal mean of 32 climate model projections.

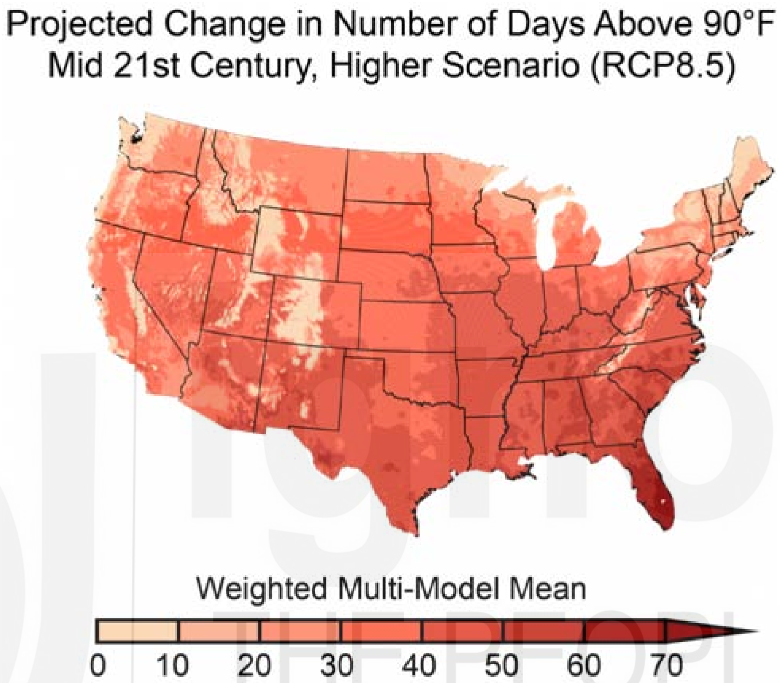

Fig. 7.2: Projected changes in the number of days per year in United States (CICS-NC and NOAA NCEI by Russel Vose, available in Climate Science Special Report).

In the Indian context, extreme heat events have been occurring frequently in the last decade. Various heat events have been recorded that have been linked to anthropogenic reasons contributing to climate change. Last year in the month of May and June (2019), a severe heat wave was recorded in India with highest temperatures reaching 50.8°C in Churu, Rajasthan. Many casualties were reported in Northern and eastern cities of India during summer season due to these heat waves. This led to severe drought and extreme water scarcity in many parts of India. Some other examples include heat wave in Ahmedabad in 2010 that killed about 1000 people and another heat wave in 2015 caused about 2300 casualties in whole of India. In the same year, a huge heat wave killed thousands of people in Andhra Pradesh and Telangana. So far, the highest temperatures during extreme heat waves have been recorded in the year 2016 with temperatures reaching 51°C in Phalodi in north-western India.

The threats posed by extreme heat waves include increase in frequency and intensity of droughts; wildfires; heat island effect in urban areas due to elevated temperatures in built-up areas of cities; impact on human health such as dehydration, diarrhoea, fatigue, heat stroke, heat stress, unconsciousness and even death, cardiovascular and respiratory symptoms; economic losses and increase in pollution levels, thus, affecting the air quality. This is particularly damaging to crop productivity, livestock, higher energy consumption due to excessive use of air-conditioners and refrigerators.

As a result, it becomes imperative to chalk out resilience pathways for minimising the heat impacts. These include:

- Creating heat preparedness plans;
- Recognising populations vulnerable to extreme heat;
- Installing cool and green roofs and cool pavement to reduce the urban heat island effect;
- Increasing land area under plantation to reduce the temperature of urban area; and
- Utilizing energy efficiency to reduce electricity demand.

It is believed that in 2003, the European heat wave killed about 35000-70000 people. In India, most of the heat waves occur during the summer months of May and June. In 2015, it was estimated that heat waves caused death toll of more than 2400 people in the country. This number has been increasing ever since with India seeing the hottest 32 days during May-June months in 2019. In 2020, Churu in Rajasthan state recorded the highest temperatures (50°C) during summertime. The Indian Meteorological Department had categorized Core Heatwave Zones (CHZs) that included Rajasthan, Punjab, Haryana, Delhi, Madhya Pradesh, Uttar Pradesh, Coastal Andhra Pradesh and Orissa besides other regions of the country.

7.7 EXTREME PRECIPITATION

Extreme precipitation events have become more common since the 1950s in many regions of the world. It is predicted that with increasing global warming, the trend of extreme precipitation would continue since warmer air can hold greater amount of water vapour. This would probably lead to more moisture retention by warmer air and further lead to intense precipitation. However, intense precipitation may or may not lead to increase in total precipitation. Various climate models predict a decrease in rainfall and increase in length of dry periods. The heavy events are defined as the top 1% of all daily events.

Many climate models project that all over the globe, the wet places would get wetter while the dry ones would become even drier due to spatial and temporal variability in extreme precipitation events. Further, these models also indicate a relatively widespread intensification of heavy precipitation events in response to global warming and increase in greenhouse gases.

However, the complexities of extreme events should be kept in mind while studying these models since they tend to simplify these processes due to assumptions in these models.

Threats posed by heavy precipitation

Some of the most imminent threats posed by heavy precipitation is the prospect of flooding. This is further exacerbated in urban areas where stormwater flow pollutants like heavy metals, pesticides and other nutrients such as nitrogen and phosphorus increase and runs off into sewerage and aquatic ecosystems, thus, damaging the water quality. It is estimated that from 1980 to 2009, floods caused more than 500,000 deaths and affected more than 2.8 billion people all over the world. Some recent examples include heavy rains in Maryland in July 2016 of about six inches falling during two hours, and a year's worth of rainfall (17 inches) was received in Colorado in September 2013 causing severe economic losses. India is one of the worst floods affected countries, being second in the world and accounts for one fifth of global death count due to floods. India receives 75% of rains during the monsoon season (June to September). As a result, almost all the rivers are flooded during this time resulting in sediment deposition, drainage congestion, invading into the main land. More than 8 million hectares of land in India are annually affected by floods. The flood prone area in India constitutes about 40 million hectares. Other examples include Uttarakhand floods due to cloudburst that caused great loss to life and property in June 2013. Every year during monsoons, the city of Mumbai gets flooded due to very old drainage network system and increase in impermeable surfaces due to heavy construction of roads, pavements and buildings in the city. According to meteorological records from the Santacruz Observatory in Mumbai, this year, 82.5 inches of rain fell in the city between July 10 and August 7, 2020.

Various types of floods have been recognised:

- Flash floods: These can be caused by short-duration intense precipitation, dam or levee failure, or collapse of debris and ice jams. The flash floods in Uttarakhand in June 2013 due to multiple cloud bursts in a single day caused massive landslides and has been known to be the worst disaster in the country after 2004 tsunami incident.

- Urban flooding: Caused by immediate runoff from impervious surfaces such as roads, pavement, parking lots, and buildings by short-duration very heavy precipitation. Flash floods and urban flooding are directly linked to heavy precipitation and are expected to increase as a result of increases in heavy precipitation events.

- River flooding: It occurs when surface water as a result of precipitation drained from a watershed into a stream or a river exceeds channel capacity, overflows the banks and inundates adjacent low-lying areas.

- Coastal flooding: It is predominantly caused by storm surges as a result of increase in heavy rainfall and sea level rise that push seawater towards the shore. Storm surge can cause inland flooding leading to deaths, damage to infrastructure, and severe beach erosion.

In addition to flooding, heavy precipitation also increases the risk of landslides. Every year, the states of Himachal Pradesh and Uttarakhand face landslides due to heavy rains in the region. The Garhwal Himalayas tragedy of 16-17 June, 2013 was one of the worst disasters of the last century owing to unprecedented rainfall. The extreme rainfall coupled with bursting of moraine-dammed Chorabari lake caused heavy floods in Mandakini river that led to flash floods and devastation in downstream areas of Kedarnath, Rambara and Gaurikund.

Resilience to extreme precipitation event

The impacts of heavy precipitation can be reduced by the following steps:

- Building infrastructure on higher platforms so that they are less prone to flooding.
- Applying flood control infrastructure.
- Replacing the use of pavement and concrete with permeable surfaces
- Providing insurance and incentives to the victims affected by floods and landslides.
- Wastewater systems need to be separated from stormwater systems.

Check Your Progress 1

Note: i) Use the space given below for your answers.

ii) Check your answers with those given at the end of the unit.

1) What are potential threats caused by extreme heat event?

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2) How can resilience be built for an extreme precipitation event?

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7.8 TROPICAL CYCLONES/HURRICANES

A hurricane is a low-pressure storm system that develops in the tropics or subtropics; hence, is known as tropical cyclones. In the Northern Hemisphere, these storms rotate counter-clockwise and clockwise in southern hemisphere. Stronger systems are called “hurricanes” or “typhoons,” while weaker tropical cyclones are called “tropical depressions” or “tropical storms.” Tropical cyclones, are known as hurricanes in the Atlantic Ocean or typhoons in the Pacific Ocean. Predicting these cyclones/ hurricanes has been quite uncertain; it is only with the advent of recent remote sensing techniques and satellite data that the study of these cyclones and hurricanes has developed to a great extent.

It is believed by climate scientists that a warmer and moist atmosphere would increase the magnitude and intensity of hurricanes. Further, increased temperatures would lead to sea level rise, and higher rainfall; that would lead to increased coastal storms and thus, flooding. However, the impact of global warming on frequency of hurricane is uncertain. Various factors have been shown to influence these hurricanes as a result of higher local sea surface temperatures, including natural variability, human-induced emissions of heat-trapping gases, and particulate pollution. Quantifying the relative contributions of natural and human-caused factors is an active focus of research.

Further, the cyclones are very sensitive to natural climate variability, that in turn, affects the ocean basins. Modelling the tropical cyclones is a difficult task due to the grid size of numerical climate simulation models ranging from a few tens to several hundred kilometres.

Threats Posed by Hurricanes

- Economic losses due to hurricanes are enormous. Four of the 10 costliest hurricanes on record in the United States occurred in 2017 and 2018. Hurricane Katrina (2005) remains the most expensive hurricane on record costing $168 billion (2020 dollars).
- Risk to property and infrastructure in coastal areas is huge.
- There is a great threat to human lives during a hurricane. About 1800 deaths during Hurricane Katrina and 2981 deaths during Hurricane Maria in 2018 have been reported.
- Besides, hurricanes damage energy systems, water and sewer systems and transportation structures.

In 2020, various hurricanes such as Hurricane Hanna that made landfall in Texas followed by Hurricane Isaias and then Hurricane Laura, Hurricane Sally and Hurricane Eta were the most prominent one besides various tropical storm that occurred in Atlantic Ocean. A total of 30 storms were recorded in 2020 with the strongest storm being Storm Iota with maximum wind speeds of 260km/hr. Out of these 30 storms, 13 developed into hurricanes with total fatalities of more than 431 and total economic losses of more than $46.906 billion USD have been reported. It is pertinent to mention that the Atlantic Hurricane season started on June 01 and ended on November 30 this year. It was by far the most active and seventh costliest recorded Atlantic hurricane season in terms of economic losses.

Resilience can be built by:

- Preserving coastal wetlands and coral reefs to minimize the impacts of storm surge.
- improving vulnerable buildings to reduce flood damage.
- Developing an evacuation plan to minimize the adverse impacts.

7.9 EXTRATROPICAL STORMS/TORNADOES

Research indicates that storms have increased in frequency and intensity since the 1950s coupled with the intensity and frequency of tornadoes, hail, and thunderstorm. Storms are related to atmospheric circulations which corresponds to temperature difference between the equator and the poles.

If we look into the temperature gradient between the poles and the equator, the melting of ice at the poles due to climate change results in greater warming at the poles; thus, decreasing the temperature difference between equator and poles. Further, warming is higher at the top of the troposphere, thus, strengthening the temperature gradient. The difference between the troposphere of upper tropics and the lower Arctic results in the atmospheric dynamics of the mid-latitudes, such as depressions and storms. Climate variability further adds to the formation of storms. However, it is pertinent to mention here that not all depressions turn into storms, hence, further adding to the uncertainty. The impact of atmospheric instability and wind shear on the formation of tornadoes needs to be studied.

Threats posed by tornadoes

The most important threats from tornadoes is the damage due to high speed winds that carry debris along with them. As per the projections of NOAA, about 1,200 tornadoes occur across the country annually. Although the casualties have decreased rapidly in the last few years due to better early warning systems and satellite images; however, the damages caused still need detailed minimization strategies.

Communities can increase their resilience and reduce the impacts from tornadoes by:

- Adopting more stringent building codes in tornado-prone areas.
- Continuing to support research on severe weather forecasts.
- Heeding watches and warnings when they are issued, and ensuring that

individuals can be reached by emergency alert systems.

7.10 WILDFIRES

Many studies have linked an increase in wildfire activity to global warming. In addition, the risk of a fire could depend on past forest management, natural climate variability, human activities, and other factors, in addition to human-caused climate change. Determining how much climate change contributes to extreme weather events such as wildfires continues to be studied.

Climate change has been a key factor either directly or indirectly, in increasing the risk and extent of wildfires in the world. Various factors contribute to increased risk of wildfire, such as temperature, soil moisture, dry conditions, increased drought scenario, presence of vegetation and other potential fuel such as organic matter that burns up easily (e.g., dried leaves, twigs etc.). Some of the examples include frequent bushfires in Australia of which the highest number of deaths and casualties were reported in the 2009 Black Saturday bushfires in the state of Victoria. The most recent examples include burning of the Seshachalam forest area very close to the holy city of Tirupati in South India in March, 2020 and the lightening sparked wildfires in the state of California in August 2020 which has burnt lakhs of acres of land.

The effects of wildfire are manifold:

- Economic aspects: Wildfires cause severe economic losses as funds are required for suppression of fires.
- Public health: Wildfire cause risk to life, property and public health; Smoke reduces air quality and can cause eye and respiratory illness.
- Damage to environment: Wildfires can damage ecosystem and release large amounts of gases such as carbon dioxide into the atmosphere, thus, adding further to climate change.

Resilience towards wildfires can be developed by:

- Avoiding buildings and infrastructure in fire-prone areas.
- Working on increasing the spacing between residential areas and forest areas.
- Including fire-resistant materials in buildings.
- Increasing resources allocated to firefighting and fire prevention and minimizing damage due to fires.

Many of these extreme events are inter-related and cannot be studied in isolation. For example, highest rainfall was recorded from a single event during Hurricane Harvey at Houston in August 2017.

Check Your Progress 2

Note: i) Use the space given below for your answers.

ii) Check your answers with those given at the end of the unit.

1) What are the contributing factors to a wildfire event?

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2) Is it best to study extreme events in isolation or a holistic manner?

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7.11 LET US SUM UP

To sum up, the study of extreme weather events is very challenging due to uncertainties in climate change. Most of the climate models have their own limitations, which in turn, make the study of extreme weather events in relation to climate change a huge scientific challenge. Although attempts are being made all over the world by various research groups for improvement of climate models, increasing the network of observation stations and simulation of extreme events; still a lot needs to be done to improve research output and predictability of extreme events and thus, climate change. Further, every time anthropogenic inputs should not be blamed for every extreme event occurring; many a times nature follows its own course which is beyond the control of humans. However, efforts should be made to minimize the impacts of humans on probability of extreme event.

Abbreviations

USGCRP	U.S. Global Change Research Program
GCMs	General Circulation Models
EBMs	Energy Balance Models
WCRP	World Climate Research Programme
NOAA	National Oceanic and Atmospheric Administration
RCP	Representative Concentration Pathway

NAS	National Academy of Sciences
NCEC	National Climate Extremes Committee
IBTrACS	International Best Track Archive for Climate Stewardship
NCEI	National Centers for Environmental Information

7.12 KEY WORDS

Drought: A period of abnormally dry weather long enough to cause a serious hydrological imbalance. A period with an abnormal precipitation deficit is defined as a meteorological drought. A megadrought is a very lengthy and pervasive drought, lasting much longer than normal, usually a decade or more.

Storm surge: The temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions. The storm surge is defined as being the excess above the level expected from the tidal variation alone at that time and place

7.13 SUGGESTED FURTHER READING/REFERENCES

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Web Links

- American Meteorological Society – Explaining Extreme Events in 2016 from a Climate Perspective (https://watermark.silverchair.com/bams-explainingextremeevents2016_1.pdf)
- http://www.c2es.org/content/drought-and-climate-change/
- http://www.c2es.org/content/extreme-precipitation-and-climate-change/
- http://www.c2es.org/content/heat-waves-and-climate-change/
- https://nca2014.globalchange.gov/highlights/report-findings/extreme-weather
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- Weekley, E. (1921). Extreme An etymological dictionary of modern English, John Murray, London.

7.14 ANSWERS TO CHECK YOUR PROGRESS

Check Your Progress 1

1) The threats posed by extreme heat waves include increase in frequency and intensity of droughts; wildfires; heat island effect in urban areas due to elevated temperatures in built-up areas of cities; impact on human health such as dehydration, diarrhoea, fatigue, heat stroke, heat stress, unconsciousness and even death, cardiovascular and respiratory symptoms; economic losses and increase in pollution levels

2) Building infrastructure on higher platforms so that they are less prone to flooding; Applying flood control infrastructure; Replacing the use of pavement and concrete with permeable surfaces; Providing insurance and incentives to the victims affected by floods and landslides.

Check Your Progress 2

1) Contributing factors to wildfire event are forest management, natural climate variability, human activities, and other factors, in addition to human-caused climate change.

2) Many of these extreme events are inter-related and cannot be studied in isolation. E.g., tsunamis are triggered by earthquakes; while floods or landslides are triggered by heavy precipitation.

UNIT 8 PREDICTING FUTURE CLIMATES

Structure

8.1 Introduction

8.2 Objectives

8.3 Analogues from Past Climate

8.4 Climate Models

8.5 Types of Climate Models

8.5.1 Energy Balance Models (EBMs)

8.5.2 Zero-Dimensional Models

8.5.3 One-Dimensional Models

8.5.4 Radiative Convective Models

8.5.5 General Circulation Models (GCMs)

8.5.5.1 Diagnostic Climate Modelling

8.5.5.2. Prognostic Climate Modelling

8.5.6 Coupled Atmosphere-Ocean General Circulation Models

8.6 Greenhouse Gas Emission Scenarios

8.6.1 The A1 Family

8.6.2 The A2 Family

8.6.3 The B1 Family

8.6.4 The B2 Family

8.7 Time Dependent Models

8.8 Representative Concentration Pathways (RCPs)

8.8.1 RCP8.5

8.8.2 RCP6

8.8.3 RCP4.5

8.8.4 RCP2.6

8.9 Let Us Sum Up

8.10 Key Words

8.11 Suggested Further Reading/References

8.12 Answers to Check Your Progress

8.1 INTRODUCTION

In recent years, there has been a growing concern about climate change all across the globe. The increasing average global temperatures, the rising of sea level and submerging of low-lying islands, the loss of biodiversity and shrinking of hotspots all over the world have led to increasing distress about the changing climate. Historically speaking, ever since the origin of the

Earth, it is not the first time that the climate is changing; however, the enhanced anthropogenic contribution to climate change is what makes the entire scenario worrisome. As a result, scientists all over the world are thinking of various strategies to understand the phenomenon of climate change, to gain an insight about its implications and also to quantify the changing climate by means of models. It is where the role of climate models comes into picture. These models attempt to quantify the changing climate by using physical laws of radiation and energy; and studying the radiation behaviour and flux at the surface of the Earth. So, there may be regional or global climate models to quantify the extent of change that the Earth is undergoing in terms of climate; and also include clouds and aerosols in more complex models for understanding their dual role in radiative forcing of the Earth, that eventually leads to climate change. Various emission scenarios of greenhouse gases are also discussed in this unit that have been reported by the Intergovernmental Panel on Climate Change (IPCC).

8.2 OBJECTIVES

After studying this unit, you should be able to:

- explain the analogues from past climate;
- classify the different types of climate models; and
- explain the emission scenarios.

8.3 ANALOGUES FROM PAST CLIMATE

As per IPCC Report (2007), rapid climate changes have been observed in the recent past and are further expected to increase in the near future. The analogues approach is a novel method of testing the ground realities to the outputs of climate models. In this approach, the analogues tool connects the sites that are analogous (similar) to climates at sites across other geographic locations, implying climates across space as well as time (means with respect to historical or projected future climates). For example, if any place in the world has the present climate that is similar to the future predicted climate elsewhere; then these two sites can provide interesting observations on adaptation strategies to be followed for mitigating or at least minimizing the adverse effects of predicted climate change in future. This approach is usually helpful for complex systems that face difficulty in climate models. But this approach holds true only if climate is the driving force behind the observations in differences at the two sites. In a holistic way, the analogues approach can help to relate global models with targeted field studies (Ramírez-Villegas et al., 2011) to explore mechanism of adaptation. Such comparisons between sites can be used to enable farmers to develop a knowledge framework for realising the future of site-specific agricultural output. The analogues tool, coupled with field studies link mathematical climate models with existing farm technologies. The analogues methodology can use historical data to understand the case studies where the success or failure of adaptation mechanism can be identified.

In this approach, users specify a location known as the 'reference' location'; variables such as rainfall and temperature; and, one or more climate scenarios for future-related analyses (e.g., 2020, 2030, or 2050), an SRES emissions scenario (IPCC 2000, Moss et al. 2010), and a global climate model (GCM) (IPCC 2007, PCMDI 2007). The temporal data for variables ranges from hourly to yearly basis including daily or monthly data. When the tool finds suitable global present-day analogues for the 2050 climate of a given reference site A, the analogues tool would first use the forecast the climate scenario and then compare the present-day climate for all sites where data exist with A's projected climate. The result is then compared using dissimilarity index. Not only climatic, but other variables such as soils, crops, and socioeconomic characteristics are also considered. The outputs are generated for any geographic region at any resolution equal to or above 1 km, depending on the amount of data, the computational power and the spatial resolution of the data.

8.4 CLIMATE MODELS

A model is a qualitative and/or quantitative representation of objects or phenomenon. Computer models that simulate Earth's climate are called as General Circulation Models (GCMs). Climate models use physical parameters and processes as input to simulate past climate and predict future climatic conditions. Various workers call climate models as an extension of weather forecasting; except that the primary focus on time duration lies on decades, rather than hours. These models represent mathematically the five components of climate system- atmosphere, hydrosphere, lithosphere, cryosphere and biosphere based on physical and chemical principles of thermodynamics, fluid dynamics, radiative transfer and biological interactions. In recent years, inclusion of clouds and carbon cycle in climate models has also been emphasized. Thus, these models can be used to simulate changes in temperature, rainfall, winds and oceanic circulations over long periods. However, these models being based on assumptions and mathematical algorithms have certain limitations in simulating the Earth's climate which is complex and in dynamic state of flux. Nevertheless, these models have improved greatly in the last few years to provide better insight into future climate. The accuracy of these models can be tested by assessing their ability to simulate past or present climates. The climate models are an important tool for understanding how climate might change, rather than will change, based on quantitative and scientific measurements. Normally, *"scientists validate their models by comparing them against real-world observations or testing against past changes in the Earth's climate ('hindcasts') such as temperature, rainfall, snow, hurricane formation, sea ice extent and many other climate variables. Also, it has been observed that the average of all models can be more accurate than most individual models* *in terms of higher reliability and consistency when several independent models are combined"* (https://www.carbonbrief.org/qa-how-do-climate-models-work).

8.5 TYPES OF CLIMATE MODELS

The best models of climate change have been used by Intergovernmental Panel on Climate Change (IPCC) to develop climate change scenarios. The two primary models used to project changes in climate were developed at Canadian Climate Centre, and Hadley Centre in United Kingdom.

Other climate models have been developed at:

A) National Centre for Atmospheric Research

B) NOAA's Geophysical Fluid Dynamics Laboratory

C) NASA's Goddard Institute for Space Studies

D) Max Planck Institute for Meteorology in Germany

Although these models work on similar principles; however, the output from these models vary based on inputs provided for these models as well as the uncertainties in emissions of greenhouse gases. For example, the Hadley model projects wetter climate than Canadian model; while the latter projects higher temperatures over US. In general, almost all climate models predict higher increase in temperature at regions in middle to high latitudes since the melted ice and snow in these regions decrease reflectance; thus, allowing for greater absorption of heat in these regions. These models predict that the net effect of adding greenhouse gases and fossil fuel combustion results in producing a warmer climate. IPCC anticipates a warming of 1.1°C to 6.4°C between 1900 and 2100. Thus, it becomes imperative to understand the differences in model projections for interpreting the results from the models. Some models have been discussed below:

8.5.1 Energy Balance Models (EBMs)

These models calculate surface temperature as a variable for climate by considering the balance between incoming solar energy and outgoing solar energy in the form of heat released back to space.

8.5.2 Zero-dimensional Models

These models considerthe entire Earth as a whole unit; essentially, as a single point. For example, a simple radiant heat transfer model that treats the earth as a single point and averages outgoing energy.

8.5.3 One-dimensional Models

Besides treating Earth as a one unit, these models includethe transfer of energy across different latitudes of the Earth's surface. Further, one-dimensional model can be represented by the following equation:

$$(1-\alpha)S\pi r^2 = 4\pi r^2 esT^4$$

where,

$(1-\alpha)S\pi r^2$refers to the incoming energy from the sun

$4\pi r^2 esT^4$represents the outgoing energy from the sun calculated from Stefan Boltzman's constant using constant radiative temperature T

S is the solar constant = 1367W/m^2

$\alpha$is Earth's average albedo (~ 0.3)

r is the Earth's radius, approximately 6.371×10^{6}m

e is effective emissivity of earth, about 0.612

s is Stefan Boltzman's Constant, approximately 5.67×10^{-8}JK^{-4}m^{-2}s^{-1}

T is the Radiative temperature (K).

If we factor out πr^2, then

$$(1-\alpha)S = 4esT^4$$

The above equation represents the effective radiative temperature of the Earth and yields an average Earth temperature of 288K. This model determines the effect of changes in solar output or albedo or earth's emissivity on surface temperature. However, these one-dimensional models do not look into the issue of temperature distribution on Earth or the factors responsible for circulation of energy about the Earth.

8.5.4 Radiative Convective Models

These models are refinement of one-dimensional model that they can determine the effects of varying concentrations of greenhouse gases on emissivity and hence the surface temperature. Further, these models simulate the transfer of energy through the altitudes of the atmosphere by Radiative transfer or convection for transport of heat. Radiative Convective Models can calculate the temperature and humidity of different layers of the atmosphere.

8.5.5 General Circulation Models (GCMs)

These models are also called Global Climate Models, and are four – dimensional (4-D) models (including time as a parameter) which simulate the climate based on physical laws, the flows of air and water in the atmosphere and/or the oceans, as well as the transfer of heat. Earlier GCMs focussed on only one component of atmosphere, may be only atmosphere or oceans.

The first general circulation climate model combining both atmospheric and oceanic processes was developed by NOAA Geophysical Fluid Dynamics Laboratory in 1960s. Early GCMs only simulated one aspect of the Earth system – such as in "atmosphere-only" or "ocean-only" models – but they did this in three dimensions, incorporating many kilometres of height in the atmosphere or depth of the oceans in dozens of model layers.

A global climate model (GCM) is a complex mathematical representation of the major climate system components mentioned below:

A) The atmospheric component- simulates clouds and aerosols.

B) The land surface component- vegetation, snow cover, and water bodies.

C) The ocean component- simulates current movement and biogeochemistry

D) The sea ice component- It modulates solar radiation absorption and air-sea heat and water exchanges.

These climate models divide the globe into a three-dimensional grid of cells, and equations for each component (atmosphere, land surface, ocean, and sea ice) are calculated on the global grid for a set of climate variables such as temperature; as well as exchange fluxes of heat, water, and momentum. The grid size is dependent upon the computing power and the capability of the computer to solve these equations. If the resolution is fine, that means higher number of grid cells are required; while for farther spaced grid cells, lesser calculations are required; but even the details are less comprehensive.

Further, there are two types of processes within climate models - simulated and parameterized. Simulated processes are larger than grid-scale and based on principles such as conservation of energy, mass, and momentum. An example of a simulated process is the model representing tropical cyclones and storm activity. Parameterized processes represent processes that are smaller than grid scale, and use both scientific principles as well as use of observational data. An example of a parameterized process is model that represents cloud and aerosol composition.

For parameterisation of climate models, the Earth is divided into grid cells and the average climate for each grid cell is calculated. However, various processes such as height of landscape or presence of clouds occur at much smaller scale than the size of grid, and hence may be overlooked. To rectify such errors in a model, these variables are "parameterised", implying that their values are defined in the computer code rather than being calculated by the model itself. A few examples include scattering by aerosols, snow cover, evaporation, condensation, soil properties, rain, surface roughness and so on.

In many cases, it is not possible to narrow down parameterised variables into a single value, so the model needs to include estimation. Scientists run tests with the model to find the value – or range of values – that allows the model to give the best representation of the climate. Examples for the same include tuning model for albedo, sea ice extent and absolute temperatures.

After tuning, the next important step in a climate model is reducing the 'biases' generated as a result of deviations of simulations from the observed climate. These biases occur because models are a simplification of the climate system and the large-scale grid cells that global models use can miss the detail of the local climate. This generally occurs in case of regional or local simulations. Typically, bias correction is applied only to model output, but in the past, it has also been used within runs of models.

As such, GCMs are critical tools to improve the understanding and prediction of climate change. The uses for climate modelling include diagnosis and prognosis.

8.5.5.1 Diagnostic Climate modelling

It includes detection and attribution.

a) Detection

It is the process of demonstrating that climate has changed in some defined sense without providing a reason for that change.

b) Attribution

It is the process of establishing the most likely causes for the detected change with some defined level of confidence.

An example of diagnostic climate modelling is the role of anthropogenic forcing in 20th century climate change.

8.5.5.2 Prognostic climate modelling

It predicts future climate, such as global warming trends, using current or historic data (ocean structure, radiative forcing, etc.) as a basis. Timescales for projection include seasonal/inter-annual variability, decadal prediction, and 21st century scenarios.

Thus, although we are well aware of the fact the computation of climate modelling is very intensive; however, complex algorithms and increased computing power would help in better simulations and parameterized processes, as well as reliable climate change projections.

8.5.6 Coupled atmosphere-ocean general circulation models

The coupled models are sophisticated as they factor in multiple models. The purpose of the coupled models is to represent the functioning of climate system in an inclusive manner. For instance, the coupled atmosphere-ocean general circulation models (or "AOGCMs") can at best simulate the exchange of heat and freshwater between the land and ocean surface and the air above.

A major concern with climate models is that with the diversity of climate models, it becomes difficult to compare the results of different models since the approach of each model is difficult. As a result, Coupled Model Inter-comparison Project ("CMIP") has been developed as a framework for climate model experiments, to analyse and validate GCMs. These are coupled atmosphere-ocean GCMs that aim to bring an improvement and homogeneity into all the climate models. Earlier, CMIP focused on modelling atmospheric CO_2 concentrations; later it incorporated more detailed Representative Concentration Pathways ('RCPs'). To rule out the differences in the output using different models, the results of various models are loaded on a central web portal, managed by the Program for Climate Model Diagnosis and Intercomparison (PCMDI) that can be freely accessed by scientists all over the world. The Working Group on Coupled Modelling committee is responsible for CMIP. It is a constituent of the World Climate Research Programme (WCRP) based at the World Meteorological Organization in Geneva. Currently, CMIP6 is underway that comprises of 21 individual Model Intercomparison Projects, or "MIPs".

Check Your Progress 1

Note: i) Use the space given below for your answers.

ii) Check your answers with those given at the end of the unit.

1) What are zero-dimensional Models?

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2) What is the objective of CMIP?

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8.6 GREENHOUSE GAS EMISSION SCENARIOS

Different climate models project different values for rise in temperature, by next decade or next 50 to 100 years. This extreme gap between various climate models could be attributed to two factors:

- Climate models are unable to factor in the effects of clouds. The clouds are composed of an important greenhouse gas called water vapour, that traps the heat; as well as exert cooling effect by blocking sun's rays from reaching the earth's surface. Therefore, it is not clear as to which of the dual role these clouds play in modifying the climate. Thus, inclusion of these clouds generates some error in results, which may amount to 1 to 2°C error on a prediction for 2100.

- Further, a second aspect that needs to be taken into account is not only the current amount of greenhouse gases; but also, the amount of greenhouse gases that would be added to the atmosphere due to anthropogenic inputs.

Since such an impact of clouds and greenhouse gases would vary according to different human inputs; therefore, scientists are using the term "**emission scenarios"**, to describe the behaviour of greenhouse gases emissions. The Intergovernmental Panel on Climate Change (IPCC) was jointly established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) to "assess the scientific, technical and socio-economic information relevant for the understanding of the risk of human-induced climate change". Since its inception, the IPCC has produced a series of comprehensive Assessment Reports on the state of understanding of causes of climate change, its potential impacts and options for response strategies. It prepared also Special Reports, Technical Papers, methodologies and guidelines. These IPCC publications have become standard work of reference, widely used by policymakers, scientists and other experts. In 1992, the IPCC released emission scenarios to be used for driving global circulation models to develop climate change scenarios. IPCC has developed emission scenarios for long term in 1990 and 1992. The Special Report on Emissions Scenarios (SRES) was published by the Intergovernmental Panel on Climate Change (IPCC) in 2000. The greenhouse gas emissions scenarios described in the Report have been used to make projections of possible future climate change. IPCC has in fact described about 40 scenarios which are grouped mainly into four main families - A1, A2, B1, B2; and they reflect a particular trajectory (evolution) of humanity, and the important hypothesis (concerning demography, agricultural practices, technology spreading, etc.) are then turned into "food production" and "consumption of energy" using models.

The IS92 scenarios were the first global scenarios to provide estimates for the greenhouse gases. Therefore, the IPCC decided in 1996 to develop a new set of emissions scenarios which will be of broader use than the IS92 scenarios. The new scenarios provide also input for evaluating climatic and environmental consequences of future greenhouse gas emissions and for assessing alternative mitigation and adaptation strategies.

8.6.1 The A1 family

The A1 family is based on the following hypothesis:

- Increased economic growth;
- the world population that peaks in mid-century and declines thereafter;
- introduction of new and efficient technologies;
- underlying theme converge between regions;

- social and cultural interactions increase rapidly;
- A1 scenario family describes alternative directions of technological change in the energy system; that are distinguished by their technological emphasis:
- fossil intensive (A1FI),
- non-fossil energy sources (A1T), or
- Balance across all sources (A1B).

This A1 family scenario explains that there would be increased energy consumption and exhausting of limits for fossil fuels (except coal). Besides, the atmospheric CO_2 concentration in 2100 comes close to 1100 ppm.

8.6.2 The A2 family

The A2 family is based on the following hypothesis:

- Continuously increasing world population;
- Evolution of the world in a heterogeneous manner;
- economic growth is region oriented;
- spreading of new efficient technologies is slower and are very different depending on the region of the world;
- The underlying theme is self-reliance and preservation of local identities.

8.6.3 The B1 family

The B1 family is based on the following hypothesis:

- the world peaks in mid-century and declines thereafter;
- the economic structures directed towards service and information technologies;
- rapid dissemination of new, clean and efficient technologies; and
- addressing economic, social and environmental problems without any supplementary climate initiative.

Hence, this scenario suggests significant additional resources in oil and gas compared to present times, and development of nuclear energy. Also, it predicts the atmospheric concentration of CO_2 in 2100 near about 450 ppm.

8.6.4 The B2 family

The B2 family exemplifies a world where:

- World population reaches 10 billion people by 2100.
- In this family of scenarios, the sustainability from the spheres of economic, social and environmental perspectives are emphasised through local solutions;

- Economic development is intermediate;
- Oriented towards environmental protection and social equity, it focuses on local and regional levels; and
- Development and transfer of efficient technologies in B2 family is quite uneven.

The atmospheric carbon dioxide concentration in this scenario reaches about 740 ppm.

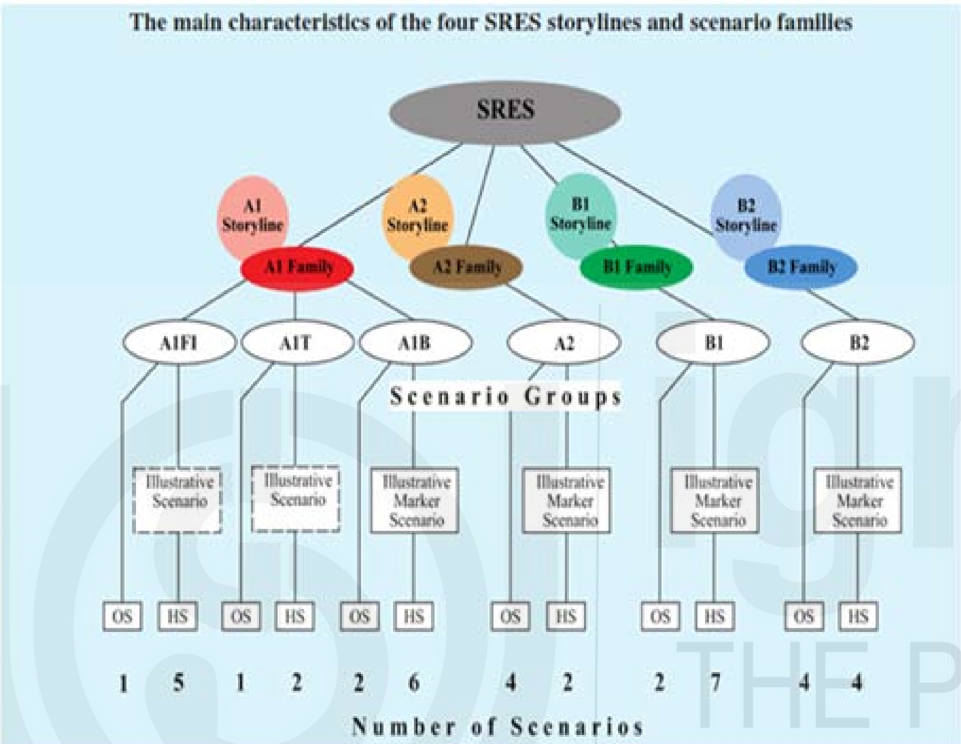

Fig. 8.1 Schematic illustration of SRES scenarios (A Special Report of IPCC Working Group III, IPCC, 2000)

8.7 TIME DEPENDENT MODELS

The emissions and radiative forcing scenarios described include a component of time: i.e., by what quantity would the climate change and what would be the time duration for the same. However, the magnitude of human-induced climate change depends more on the net carbon emitted into the atmosphere rather than average annual emissions.

Analysing all the above scenarios reveals that none of them account for extreme events such as nuclear war or a massive outbreak. Further, though they are in limited numbers, these scenarios lead to very different patterns for the greenhouse gases emissions and concentrations during the coming century. *The IS92a scenario is an older scenario that was used for the 1995* IPCC *report.* For a given emission scenario, the various models do not differ by more than 1 to 2 °C for the predicted temperature increase in 2100.

In effect, different social, economic and technological developments have a strong impact on emission trends, and the scenarios provide important understanding about relationship between environmental quality and development choices. This will greatly aid policy builders and decision makers for appropriate climate interventions.

8.8 REPRESENTATIVE CONCENTRATION PATHWAYS (RCPs)

Representative Concentration Pathways (RCPs) are a set of scenarios that have been used in IPCC Fifth Assessment Report (AR5) for predicting future climate scenario based on climate models. Since these models were developed to represent possible future concentration of greenhouse gas emissions by including a pathway that represents the trajectory of GHG emissions to reach a particular radiative forcing by 2100; hence the name Representative Concentration Pathways. Radiative forcing is a measure of the energy that is absorbed and retained in the atmosphere by greenhouse gases and aerosols. Thus, it can be positive (heating) or negative (cooling) and is affected by concentration of greenhouse gases and aerosols, changes in land cover and total solar irradiance. RCP was adopted by IPCC in its Fifth Assessment Report (AR5) that superseded Special Report on Emissions Scenarios (SRES) projections based on socio-economic scenarios that were used in Third and Fourth IPCC Assessment Reports. The basic difference lies in the fact that RCPs fix the emissions trajectory and resultant radiative forcing rather than the socio-economic circumstances. Thus, these RCPs can then be used to test policy decisions on mitigation and adaptation to climate change. There are the following four pathways based on the amount of radiative forcing produced by greenhouse gases till 2100 (https://www.environment.gov.au/system/files/resources/492978e6-d26b-4202-ae51-5eba10c0b51a/files/wa-rcp-fact-sheet.pdf).

8.8.1 RCP8.5

- According to this pathway, the radiative forcing reaches greater than 8.5 W/m^2 by 2100.
- Atmospheric carbon dioxide concentrations in 2100 would be 936 ppm (used as input in most model simulations).
- The average temperature increase for 2081-2100, relative to 1850-1900 baseline as per this model is 4.3°C while the likely range of temperature increase is 3.2-5.4°C.
- The average global mean sea level rise for 2081-2100, relative to 1986-2005 is 0.63 m while the probable range is 0.45-0.82m.
- It is based on minimum efforts to reduce emissions.

8.8.2 RCP6

- In this intermediate stabilisation pathway, the radiative forcing is stabilised at approximately 6 W/m^2 after 2100.

- Atmospheric carbon dioxide concentrations in 2100 would be 670 ppm (used as input in most model simulations).
- The average temperature increase for 2081-2100 relative to 1850-1900 baseline as per this model is 2.8°C while the likely range of temperature is 2.0-3.7°C.
- The average global mean sea level rise for 2081-2100 relative to 1986-2005 is 0.48 m while the probable range is 0.33-0.63m
- It requires strong mitigation efforts, with early participation from all emitters followed by active removal of atmospheric carbon dioxide.

8.8.3 RCP4.5

- In this intermediate stabilisation pathway, the radiative forcing is stabilised at approximately 4.5 W/m^2 after 2100.
- Atmospheric carbon dioxide concentrations in 2100 would be 538 ppm (used as input in most model simulations).
- The average temperature increase for 2081-2100 relative to 1850-1900 baseline as per this model is 2.4°C while the likely range of temperature is 1.7-3.2°C.
- The average global mean sea level rise for 2081-2100 relative to 1986-2005 is 0.47 m while the probable range is 0.32-0.63m.

8.8.4 RCP2.6

- In this pathway, the radiative forcing peaks at approximately 3 $W\ m^{-2}$ before 2100 and then declines.
- Atmospheric carbon dioxide concentrations in 2100 would be 421ppm (used as input in most model simulations).
- The average temperature increase for 2081-2100 relative to 1850-1900 baseline as per this model is 1.6°C while the likely range of temperature is 0.9-2.3°C
- The average global mean sea level rise for 2081-2100 relative to 1986-2005 is 0.40m while the probable range is 0.26-0.55m.
- It is also referred to as RCP3-PD. (PD stands for Peak and Decline).
- RCP2.6 aims to keep warming likely below 2°C above pre-industrial temperatures.

Check Your Progress 2

Note: i) Use the space given below for your answers.

ii) Check your answers with those given at the end of the unit.

1) What is emission scenario?

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2) What are the four main families of emission scenario?

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8.9 LET US SUM UP

The increasing average global temperatures, the rising of sea level and submerging of low-lying islands, the loss of biodiversity and shrinking of hotspots all over the world have led to increasing distress about the changing climate. The complexity in the climate change issue compelled the scientists all over the world to device strategies to understand the phenomenon of climate change, to gain an insight about its implications and also to quantify the changing climate by means of models. In this regard, the climate models are very important. The climate models attempt to quantify the changing climate by using physical laws of radiation and energy; and studying the radiation behaviour and flux at the surface of the Earth. There are variety of models that include regional or global climate models to quantify the extent of change that the Earth is undergoing in terms of climate.

We have studied in this unit about the role of climate models in predicting the future climate. Further, we have discussed the importance of climate analogues in climate change studies, and emission scenarios.

Acronyms

IPCC:	Intergovernmental Panel on Climate Change
SRES:	Special Report on Emissions Scenarios
GCMs:	General Circulation Models
EBMs:	Energy Balance Models
GFDL:	Geophysical Fluid Dynamics Laboratory
AOGCMs:	Atmosphere-ocean general circulation models
CMIP:	Model Inter-comparison Project
RCPs:	Representative Concentration Pathways

WCRP: World Climate Research Programme

UNEP: United Nations Environment Programme

8.10 KEY WORDS

Climate Models: A model is a qualitative and/or quantitative representation of objects or phenomenon. Computer models that simulate Earth's climate are called as General Circulation Models (GCMs). Climate models use physical parameters and processes as input to simulate past climate and predict future climatic conditions.

Energy Balance Models (EBMs): Energy Balance Modelscalculate surface temperature as a variable for climate by considering the balance between incoming solar energy and outgoing solar energy in the form of heat released back to space.

Detection: Detection of change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense, without providing a reason for that change.

Attribution: Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with an assignment of statistical confidence.

Emission scenario: A plausible representation of the future development of emissions of substances that are potentially radiatively active based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socio-economic development, technological change) and their key relationships. Concentration scenarios, derived from emission scenarios, are used as input to a climate model to compute climate projections.

Representative Concentration Pathways (RCPs): Scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases and aerosols and chemically active gases, as well as land use/land cover.

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Web Links

https://jancovici.com/en/climate-change/predicting-the-future/what-is-an-emission-scenario-is-it-important-for-the-future/

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https://www.environment.gov.au/system/files/resources/492978e6-d26b-4202-ae51-5eba10c0b51a/files/wa-rcp-fact-sheet.pdf

https://www.gfdl.noaa.gov/blog_held/time-dependent-climate-sensitivity/

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8.12 ANSWERS TO CHECK YOUR PROGRESS

Check Your Progress 1

1) These models considerthe entire Earth as a whole unit; or as a single point. For example, a simple radiant heat transfer model that treats the

earth as a single point and averages outgoing energy

2) Coupled Model Intercomparison Project (CMIP) has been developed as a framework for climate model experiments, to analyse and validate GCMs; and bring an improvement and homogeneity into all the climate models.

Check Your Progress 2

1) The behaviour of greenhouse gases as modelled by climate models is emission scenario.

2) The four main families of emission scenario are A1, A2, B1, B2; and reflects a particular evolution of humanity, and the main hypothesis concerning demography, agricultural practices and technology spreading.