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**M.A. GEOGRAPHY
SEMESTER I (CBCS)**

**GEOGRAPHY PAPER - I
ADVANCED STUDIES
IN PHYSICAL
GEOGRAPHY – I**

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Sem- I
Title of the Course – Advanced studies in
Physical Geography – I

Course Objectives:

1. To enhance the understanding of the students about geomorphic, atmospheric, oceanographic and hydrologic systems.
2. To make the students understand the interrelations between the various earth systems.
3. To reveal the evolutionary aspects of the lithosphere, atmosphere, ocean sphere and hydrosphere.

Course Outcomes:

- CO 1. The students will be able interpret and interconnect the various geologic, atmospheric, oceanographic and hydrologic phenomena.
- CO 2. Understand the history of the ocean, properties of sea water.
- CO 3. Understand and acquire knowledge on waves and tides.
- CO 4. Complete understanding of the calculation of the mean rainfall over basin
- CO 5. Understanding the concepts of rainfall runoff and groundwater

Detailed Syllabus:

Unit 1: The Earth System Science

(15 Hours)

- 1.1 The Earth System Science: The Earth - The origin and the evolution of the earth – big bang theory, formation of lithosphere of the Earth and plate tectonics
- 1.2 The Earth's interior: structure and composition, seismic waves and exploration for the earth's interior, deep drilling experiments
- 1.3 Geological time scale, geologic periods and climate change, recently proposed geological epoch (Anthropocene)
- 1.4 Earth's gravitational field - extent variation in magnitude - GRACE Mission; gravity and its effects on earth systems; Geomagnetism – extent magnitude and variations, dynamo effect, magnetic field reversals and effects

Unit 2: Atmosphere and climate (15 Hours)

- 2.1 Origin and evolution of structure and composition of the earth's atmosphere,
- 2.2 Relationship of Climatology with Meteorology, Weather elements and climatic controls
- 2.3 Insolation and heat Budget of the Earth, Temperature - Vertical, horizontal and seasonal variations,
- 2.4 Processes heat energy transfer; Inversion of temperature

Unit 3: Oceanography (15 Hours)

- 3.1 History of Oceanography- Understanding the ocean beginning with voyaging for trade and exploration, water, and ocean structure.
- 3.2 Ocean water- Thermal properties of ocean water - major dissolved nutrients and gasses, Light and Sound propagation in sea water, sea water and ocean water density.
- 3.3 Wave generation – growth and decay, Classification – factors influencing oceanic waves
- 3.4 Generation of tides – types of tides, tidal constituents.

Unit 4: Hydrology (15 Hours)

- 4.1 Hydrological cycle – scientific approaches - concept of watershed
- 4.2 Precipitation, Mean rainfall over drainage basin – calculation methods, characteristics of Rainstorm
- 4.3 Rainfall runoff control- Evapotranspiration, infiltration and runoff fluxes
- 4.4 Forms of sub-surface water, saturated formation.



THE EARTH SYSTEM SCIENCE

After going through this chapter, you will be able to understand the following features.

Unit Structure :

- 1.1 Objectives
- 1.2 The Earth System Science
- 1.3 Nature of Earth System Science
- 1.4 Scope of Earth System Science
- 1.5 The Earth - The Origin and The Evolution of The Earth
- 1.6 The Origin and The Evolution Of The Earth
- 1.7 Early Earth
- 1.8 Big Bang Theory
- 1.9 Formation of Lithosphere of The Earth
- 1.10 Theory of Plate Tectonics
- 1.11 The Earth's Interior
- 1.12 Structure and Composition of Earth's Interior
- 1.13 Seismic Waves and Exploration For The Earth's Interior
- 1.14 Deep Drilling Experiments
- 1.15 Geological Time Scale
- 1.16 Geologic Periods and Climate Change
- 1.17 Recently Proposed Geological Epoch (Anthropocene)
- 1.18 Earth's Gravitational Field - Extent Variation in Magnitude - Grace Mission
- 1.19 Gravity and Its Effects on Earth Systems
- 1.20 Geomagnetism – Extent Magnitude and Variations
- 1.21 Dynamo Effect, Magnetic Field Reversals and Effects
- 1.22 Summary
- 1.23 Sample Questions
- 1.24 References for Further Reading

1.1 OBJECTIVES

After learning this module, learners will be able to;

1. Understand theoretical background of evolution of the earth and formation of lithosphere.
2. Understand composition and structure of the earth's interior.
3. Demonstrate different field techniques used in empirical assessment of earth's interior and its dynamics.
4. Compare different geological periods and their characteristics.
5. Understand gravitational field of the earth and its effects on earth systems.
6. Demonstrate practical implications of earth's gravitational field.

1.2 THE EARTH SYSTEM SCIENCE

The study of the interrelated processes and interactions that occur in the Earth's atmosphere, hydrosphere, lithosphere, biosphere, and cryosphere (frozen ecosystems / environment) is known as Earth System Science (ESS), a multidisciplinary field. It came into being as a result of the realization that the Earth functions as a complex system with many interrelated and interacting parts. With the help of this all-encompassing method, scientists can comprehend the Earth as a dynamic being that is always changing. We examine the interdisciplinary character of Earth System Science and its significance in tackling urgent global concerns as we delve into its meaning, nature, scope, and value in this essay. An all-encompassing method for researching the Earth and its interrelated components is called "Earth System Science." It views the Earth as a multifaceted system made up of different subsystems, such as the biosphere, lithosphere, hydrosphere, atmosphere, and cryosphere. The complex feedback mechanisms among these subsystems combine to produce the dynamic behaviour of the Earth's environment. In order to obtain knowledge about Earth's history, present, and future conditions, ESS seeks to comprehend these interactions and processes.

1.3 NATURE OF EARTH SYSTEM SCIENCE

The Earth System's nature Science is by its very nature interdisciplinary, incorporating ideas and methods from other scientific fields such as biology, chemistry, physics, geology, meteorology, oceanography, ecology, and mathematics. The Earth system is interdisciplinary in nature, which is necessary for a thorough understanding of it since it involves intricate interactions and feedback loops that are beyond the scope of individual disciplines. A systems thinking approach is also embraced by ESS, which views the Earth as a complex system whose emergent qualities come from the interactions of its constituent parts. This method places a strong emphasis on how interrelated Earth's subsystems are and how important it is to examine them holistically as opposed to separately.

Further more, Earth System Science is characterized by its dynamic and evolving nature. It recognizes that the Earth is not static but undergoes continuous changes over various spatial and temporal scales. These changes can be natural, such as climate variability and geological processes, or anthropogenic, resulting from human activities such as deforestation, urbanization, and fossil fuel combustion.

1.4 SCOPE OF EARTH SYSTEM SCIENCE

The Earth System Science is vast and encompasses a wide range of topics and phenomena. Some key areas of study within ESS include:

- **Climate Dynamics** : ESS investigates the complex interactions between the atmosphere, oceans, land surfaces, and ice masses that drive Earth's climate system. This includes studying processes such as atmospheric circulation, ocean currents, greenhouse gas concentrations, and feedback mechanisms that influence climate variability and change.
- **Biogeochemical Cycles** : ESS examines the cycling of essential elements such as carbon, nitrogen, phosphorus, and water between the atmosphere, biosphere, hydrosphere, and lithosphere. Understanding these biogeochemical cycles is crucial for assessing ecosystem health, nutrient cycling, and the impact of human activities on the environment.
- **Earth Surface Processes** : ESS studies the processes shaping the Earth's surface, including erosion, weathering, sediment transport, and landform development. This involves examining the interactions between geological, hydrological, and biological processes that influence landscape evolution and land use patterns.
- **Ecology and Biodiversity**: ESS explores the interactions between organisms and their environment, including ecosystem dynamics, species distribution, and biodiversity patterns. This includes studying the impacts of environmental change, habitat destruction, and invasive species on ecosystems and species populations.
- **Natural Hazards** : ESS investigates natural hazards such as earthquakes, volcanic eruptions, tsunamis, hurricanes, and floods, examining the underlying processes and factors that contribute to their occurrence and impact. This includes assessing hazard risks, developing early warning systems, and implementing mitigation strategies to reduce vulnerability.
- **Human-Environment Interactions** : ESS examines the interactions between human societies and the environment, including the impact of human activities on Earth's systems and the feedback loops that result. This includes studying issues such as land use change, deforestation, pollution, resource depletion, and climate change adaptation and mitigation strategies.

- **Significance of Earth System Science :** Earth System Science plays a crucial role in addressing some of the most pressing global challenges facing humanity. Its significance can be understood in several key aspects.
- **Understanding Climate Change :** ESS provides essential insights into the drivers and impacts of climate change, helping to inform climate mitigation and adaptation strategies. By studying the complex interactions within the Earth's climate system, researchers can better understand the causes of climate variability and change, assess future climate scenarios, and develop policies to mitigate greenhouse gas emissions and reduce the impacts of climate change on ecosystems and societies.
- **Sustainable Resource Management :** ESS contributes to sustainable resource management by providing knowledge about the Earth's natural systems and processes. This includes understanding the availability and distribution of water, energy, minerals, and other resources, as well as assessing the impacts of resource extraction and consumption on the environment. By integrating ecological, social, and economic considerations, ESS helps inform policies and practices aimed at promoting resource conservation, ecosystem resilience, and sustainable development.
- **Predicting Natural Hazards :** ESS plays a vital role in predicting and mitigating the impacts of natural hazards such as earthquakes, tsunamis, hurricanes, and floods. By studying the underlying processes and factors that contribute to hazard occurrence, researchers can develop models and early warning systems to forecast and mitigate the impacts of these events. This includes monitoring geological and atmospheric phenomena, assessing hazard risks, and implementing measures to enhance resilience and reduce vulnerability in at-risk communities.
- **Conservation and Biodiversity :** ESS contributes to conservation efforts by providing insights into ecosystem dynamics, species distribution, and biodiversity patterns. By understanding the complex interactions between organisms and their environment, researchers can identify key habitats, species, and ecosystems that require protection. This includes studying the impacts of habitat destruction, climate change, pollution, and invasive species on biodiversity, as well as developing strategies for conservation and restoration.
- **Informing Policy and Decision-Making :** ESS informs policy and decision-making at local, national, and global levels by providing scientific knowledge and evidence-based insights into environmental issues. By integrating interdisciplinary research findings, policymakers can develop informed policies and strategies to address challenges such as climate change, natural hazards, resource management, and biodiversity conservation. This includes incorporating ESS principles

into environmental laws, regulations, and international agreements to promote sustainable development and environmental stewardship.

- **Fostering Education and Public Awareness :** ESS fosters education and public awareness by raising awareness about environmental issues and promoting scientific literacy. By communicating research findings and engaging with the public, educators and scientists can inspire curiosity about the natural world and encourage informed decision-making and action. This includes developing educational programs, outreach activities, and media campaigns to promote environmental awareness, sustainability, and stewardship among individuals, communities, and decision-makers.

Earth System Science is a multidisciplinary field that studies the interconnected processes and interactions within the Earth's atmosphere, hydrosphere, lithosphere, biosphere, and cryosphere. It embraces a holistic approach to understanding the Earth as a complex system undergoing continuous change. By integrating knowledge from various scientific disciplines, ESS contributes to addressing pressing global challenges such as climate change, natural hazards, resource management, biodiversity conservation, and sustainable development. Its significance lies in its ability to inform policies and strategies, predict and mitigate environmental risks, foster public awareness, and promote stewardship of the Earth's natural systems.

1.5 THE EARTH - THE ORIGIN AND THE EVOLUTION OF THE EARTH

The planet Earth is a dynamic and ever-changing celestial body. Understanding its origin and evolution is crucial in understanding the mysteries of its formation and development over billions of years.

1.6 THE ORIGIN OF EARTH

a. Nebular Hypothesis:

- Proposed by Immanuel Kant and further developed by Pierre-Simon Laplace in the 18th century.
- States that the solar system formed from the gravitational collapse of a giant molecular cloud composed mostly of hydrogen and helium, called the solar nebula.
- The collapse resulted in the formation of a rotating disk of gas and dust, with the densest material accumulating at the center to form the Sun, while the lighter material coalesced to form planets, including Earth.

b. Accretion and Differentiation:

- Over millions of years, small dust particles in the solar nebula collided and stuck together through a process called accretion.

- The growing planetesimals (small celestial bodies evolved in early stage of development of solar system) underwent further collisions and gravitational attraction, leading to the formation of protoplanets, one of which was Earth.
- Through differentiation, Earth's interior became layered, with heavier materials sinking to the core and lighter materials rising to the surface.

1.7 EARLY EARTH

a. Hadean Eon (4.6 to 4 billion years ago):

- Earth was a hostile world bombarded by asteroids and comets, undergoing intense volcanic activity.
- The atmosphere was primarily composed of gases released from volcanic eruptions, including water vapor, carbon dioxide, and nitrogen.

b. Archean Eon (4 to 2.5 billion years ago):

- The cooling of Earth's surface allowed for the formation of oceans through the condensation of water vapor.
- Primitive life forms, such as prokaryotic microorganisms like bacteria and archaea, emerged in the oceans, marking the beginning of life on Earth.

Earth's Evolution: a. Proterozoic Eon (2.5 billion to 541 million years ago):

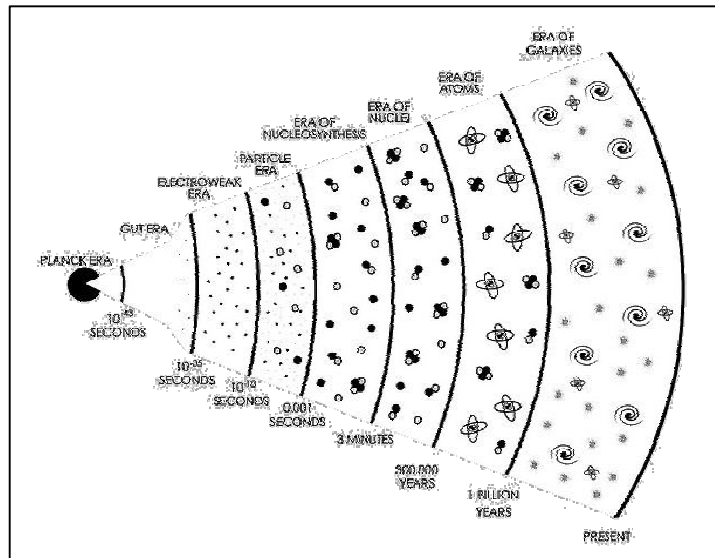
- Oxygen began to accumulate in the atmosphere due to photosynthetic activity by cyanobacteria, leading to the Great Oxygenation Event.
- Complex multicellular life forms, including algae and early animals, appeared in the oceans.

Phanerozoic Eon (541 million years ago to present):

- The Cambrian Explosion witnessed a rapid diversification of life forms, including the emergence of most major animal phyla.
- Continents formed and drifted over time due to plate tectonics, leading to changes in climate, ocean currents, and biodiversity.

1.8 BIG BANG THEORY

The Big Bang Theory is a cosmological model that describes the earliest known stages of the universe's evolution. It proposes that the universe began as a hot, dense point roughly 13.8 billion years ago and has been expanding and cooling ever since. Here's a breakdown of the key components and concepts associated with the Big Bang Theory:



1. **Singularity:** The universe is thought to have started as a singularity, an infinitely small, dense point of energy. The laws of physics as we know them break down at this point, making it difficult to describe what happened in the earliest moments of the universe.
2. **Expansion:** Around 13.8 billion years ago, the singularity underwent a rapid expansion known as the Big Bang. This expansion caused the universe to cool and allowed matter and energy to spread out.
3. **Cosmic Microwave Background (CMB):** As the universe expanded and cooled, it left behind a faint remnant of radiation known as the Cosmic Microwave Background (CMB). This radiation, discovered in 1965, provides crucial evidence supporting the Big Bang Theory.
4. **Formation of Matter:** As the universe cooled, elementary particles such as protons, neutrons, and electrons began to form. These particles eventually combined to form atoms, the building blocks of matter.
5. **Formation of Structure:** Over time, gravity caused matter to clump together, forming structures like galaxies, stars, and planets. This process of structure formation is still ongoing today.
6. **Inflation:** Some versions of the Big Bang Theory incorporate the concept of cosmic inflation, a brief period of extremely rapid expansion that occurred shortly after the Big Bang. Inflation helps explain certain observed properties of the universe, such as its large-scale uniformity.
7. **Expansion of the Universe:** Observations of distant galaxies show that the universe is still expanding today. The rate of expansion, known as the Hubble constant, provides valuable information about the universe's age and composition.
8. **Open, Closed, or Flat Universe:** The overall geometry of the universe can be described as open, closed, or flat, depending on factors such as its density and expansion rate. Current evidence suggests that

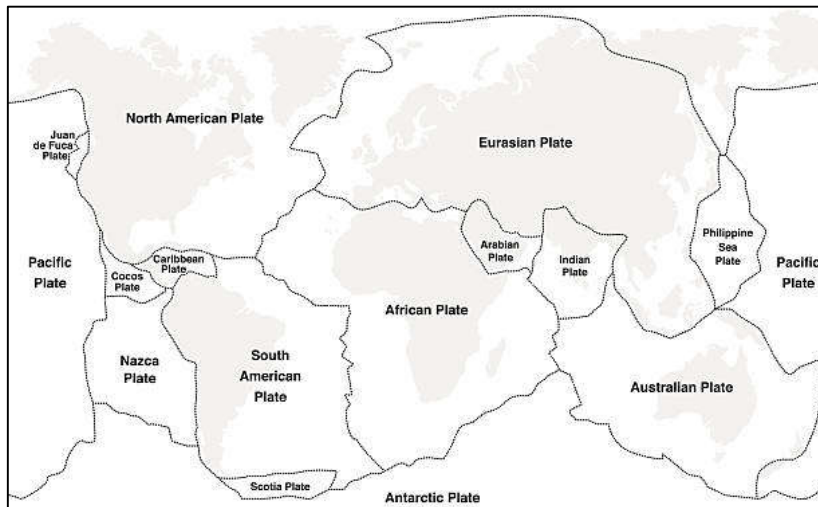
the universe is very close to flat, which has implications for its ultimate fate.

The Big Bang Theory is one of the most successful and widely accepted models for explaining the origin and evolution of the universe. It has been supported by a wealth of observational evidence from fields such as astronomy, cosmology, and particle physics. However, there are still unanswered questions and areas of ongoing research, such as the nature of dark matter and dark energy, which are thought to make up the majority of the universe's mass-energy content.

1.9 FORMATION OF LITHOSPHERE OF THE EARTH

The lithosphere is the rigid outer layer of the Earth, comprising the crust and the uppermost portion of the mantle. It is crucial for supporting life and geological processes on our planet. The formation of the lithosphere is a complex process influenced by various factors, including the Earth's composition, heat flow, and tectonic activity. Here's an overview of how the lithosphere of the Earth formed:

1. **Accretion and Differentiation:** The early Earth was a molten mass formed from the accretion of dust and gas in the solar nebula. As it cooled, heavier elements like iron and nickel sank to the center due to their higher density, forming the Earth's core. Lighter elements, such as silicon and oxygen, rose to the surface, laying the groundwork for the formation of the lithosphere.
2. **Crust Formation:** The Earth's crust formed through a process called differentiation, where lighter materials migrated towards the surface to form the crust, while denser materials sank deeper. Initially, the crust was likely composed of mafic rocks (rich in magnesium and iron), similar to basalt. Over time, as the Earth's surface cooled further, these rocks solidified to form the early crust.
3. **Plate Tectonics:** Plate tectonics play a significant role in shaping and reworking the Earth's lithosphere. The lithosphere is divided into several rigid plates that float on the semi-fluid asthenosphere beneath them. These plates are in constant motion due to processes like seafloor spreading, subduction, and continental drift. This movement leads to the formation of various geological features, including mountains, oceanic trenches, and volcanic arcs.
4. **Heat Flow and Mantle Convection:** Heat from the Earth's interior continuously drives mantle convection, which influences the movement of tectonic plates. Heat flow from the mantle to the lithosphere affects its temperature and physical properties, contributing to the formation and deformation of the lithosphere.



- 5. Continual Evolution:** The lithosphere is not static but continually undergoes changes over geological timescales. Processes like erosion, deposition, and metamorphism reshape the Earth's surface and alter the composition and structure of the lithosphere.

The formation of the Earth's lithosphere is a dynamic process shaped by geological forces such as differentiation, plate tectonics, mantle convection, and heat flow. These processes have been ongoing throughout Earth's history, leading to the diverse and complex lithospheric features we observe today.

1.10 THEORY OF PLATE TECTONICS

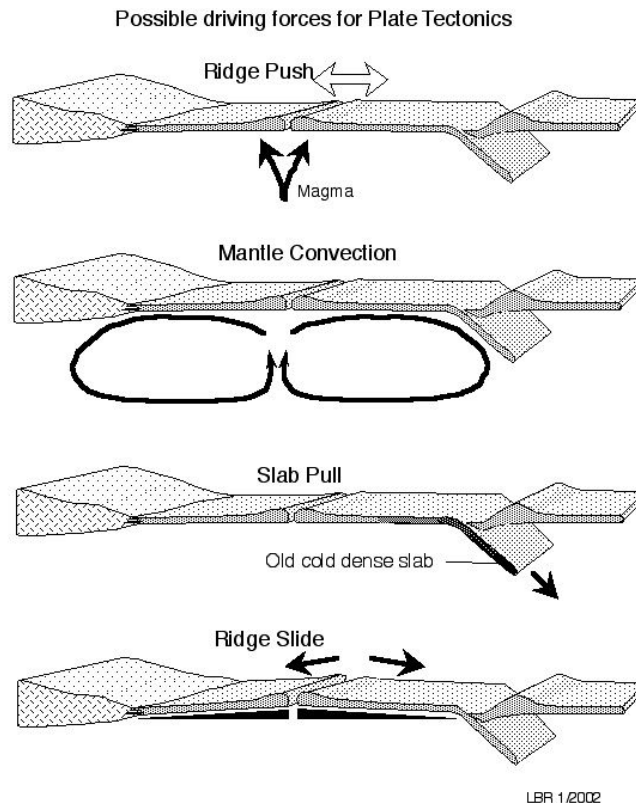
Plate tectonics is a comprehensive theory in geology that describes the movement and interaction of the lithospheric plates that form the Earth's outer shell. It is one of the fundamental concepts in Earth science and provides a framework for understanding various geological phenomena such as earthquakes, volcanoes, mountain formation, and the distribution of continents and oceans.

The theory of plate tectonics emerged in the mid-20th century, revolutionizing our understanding of the Earth's dynamics. It builds upon earlier ideas of continental drift proposed by Alfred Wegener in the early 20th century. According to plate tectonics, the Earth's lithosphere is divided into several large and small rigid plates that float on the semi-fluid asthenosphere beneath them.

Key components of plate tectonics theory include:

- 1. Plate Boundaries:** These are the zones where the edges of lithospheric plates interact. There are three main types of plate boundaries:
 - **Divergent Boundaries:** Where plates move apart, typically associated with the formation of new oceanic crust through seafloor spreading.
 - **Convergent Boundaries:** Where plates move toward each other, resulting in subduction zones (one plate descending beneath another) or continental collision zones.

- **Transform Boundaries:** Where plates slide past each other horizontally, often leading to earthquakes along faults like the San Andreas Fault in California.
2. **Driving Forces:** Plate tectonics is primarily driven by mantle convection currents, which are caused by the heat released from the Earth's core. This convective motion in the asthenosphere drives the movement of the lithospheric plates.



3. **Seafloor Spreading:** This process occurs at divergent boundaries where new oceanic crust is formed through volcanic activity along mid-ocean ridges. As magma rises from the mantle and solidifies, it creates new crust, pushing the existing plates apart.
4. **Subduction:** At convergent boundaries, denser oceanic crust sinks beneath less dense continental crust or another oceanic plate. This process leads to the formation of deep oceanic trenches and is associated with volcanic activity and earthquakes.
5. **Continental Drift:** Continental Drift theory was proposed by Alfred Wagner. The movement of continents over geological time scales is an integral part of plate tectonics. Continents are not fixed but rather drift slowly over the Earth's surface, carried by the movement of the underlying lithospheric plates.

Plate tectonics theory provides a unified explanation for various geological phenomena observed on Earth's surface, including the distribution of mountains, earthquakes, and the formation of geological features such as ocean basins and mountain ranges. It is a dynamic and

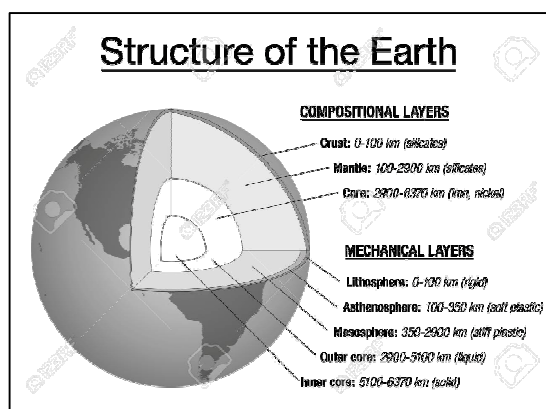
ongoing field of study, with ongoing research aimed at refining our understanding of the Earth's tectonic processes and their implications for geological hazards and the evolution of the planet.

1.11 THE EARTH'S INTERIOR

Three centuries ago, the English scientist Isaac Newton calculated, from his studies of planets and the force of gravity, that the average density of the Earth is twice that of surface rocks and therefore that the Earth's interior must be composed of much denser material. Our knowledge of what's inside the Earth has improved immensely since Newton's time, but his estimate of the density remains essentially unchanged. Our current information comes from studies of the paths and characteristics of earthquake waves traveling through the Earth, as well as from laboratory experiments on surface minerals and rocks at high pressure and temperature. Other important data on the Earth's interior come from geological observation of surface rocks and studies of the Earth's motions in the Solar System, its gravity and magnetic fields, and the flow of heat from inside the Earth.

1.12 STRUCTURE AND COMPOSITION OF THE EARTH

The planet Earth is made up of three main shells: the very thin, brittle crust, the mantle, and the core; the mantle and core are each divided into two parts. All parts are drawn to scale on the cover of this publication, and a table at the end lists the thicknesses of the parts. Although the core and mantle are about equal in thickness, the core forms only 15 percent of the Earth's volume, whereas the mantle occupies 84 percent. The crust makes up the remaining 1 percent. Our knowledge of the layering and chemical composition of the Earth is steadily being improved by earth scientists doing laboratory experiments on rocks at high pressure and analyzing earthquake records on computers.



A. The Crust

Because the crust is accessible to us, its geology has been extensively studied, and therefore much more information is known about its structure

and composition than about the structure and composition of the mantle and core. Within the crust, intricate patterns are created when rocks are redistributed and deposited in layers through the geologic processes of eruption and intrusion of lava, erosion, consolidation of rock particles, and solidification and recrystallization of porous rock.

By the large-scale process of plate tectonics, about twelve plates, which contain combinations of continents and ocean basins, have moved around on the Earth's surface through much of geologic time. The edges of the plates are marked by concentrations of earthquakes and volcanoes. Collisions of plates can produce mountains like the Himalayas, the tallest range in the world. The plates include the crust and part of the upper mantle, and they move over a hot, yielding upper mantle zone at very slow rates of a few centimeters per year, slower than the rate at which fingernails grow. The crust is much thinner under the oceans than under continents (see figure above).

The boundary between the crust and mantle is called the Mohorovicic discontinuity (or Moho); it is named in honour of the man who discovered it, the Croatian scientist Andrija Mohorovicic. No one has ever seen this boundary, but it can be detected by a sharp increase downward in the speed of earthquake waves there. The explanation for the increase at the Moho is presumed to be a change in rock types. Drill holes to penetrate the Moho have been proposed, and a Soviet hole on the Kola Peninsula has been drilled to a depth of 12 kilometers, but drilling expense increases enormously with depth, and Moho penetration is not likely very soon.

B. The Mantle

Our knowledge of the upper mantle, including the tectonic plates, is derived from analyses of earthquake waves (see figure for paths); heat flow, magnetic, and gravity studies; and laboratory experiments on rocks and minerals. Between 100 and 200 kilometers below the Earth's surface, the temperature of the rock is near the melting point; molten rock erupted by some volcanoes originates in this region of the mantle. This zone of extremely yielding rock has a slightly lower velocity of earthquake waves and is presumed to be the layer on which the tectonic plates ride. Below this low-velocity zone is a transition zone in the upper mantle; it contains two discontinuities caused by changes from less dense to more dense minerals. The chemical composition and crystal forms of these minerals have been identified by laboratory experiments at high pressure and temperature. The lower mantle, below the transition zone, is made up of relatively simple iron and magnesium silicate minerals, which change gradually with depth to very dense forms. Going from mantle to core, there is a marked decrease (about 30 percent) in earthquake wave velocity and a marked increase (about 30 percent) in density.

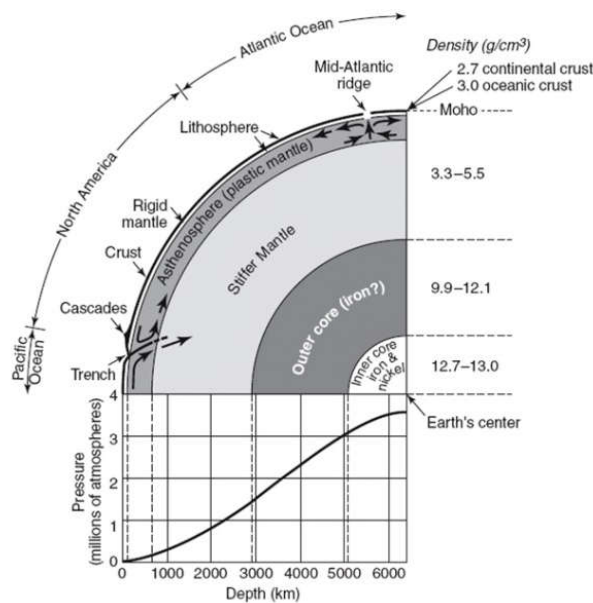
C. The Core

The core was the first internal structural element to be identified. It was discovered in 1906 by R.D. Oldham, from his study of earthquake records, and it helped to explain Newton's calculation of the Earth's density. The

outer core is presumed to be liquid because it does not transmit shear (S) waves and because the velocity of compressional (P) waves that pass through it is sharply reduced. The inner core is considered to be solid because of the behavior of P and S waves passing through it.

Cross-section of the whole Earth, showing the complexity of paths of earthquake waves. The paths curve because the different rock types found at different depths change the speed at which the waves travel. Solid lines marked P are compressional waves; dashed lines marked S are shear waves. S waves do not travel through the core but may be converted to compressional waves (marked K) on entering the core (PKP, SKS). Waves may be reflected at the surface (PP, PPP, SS).

Data from earthquake waves, rotations and inertia of the whole Earth, magnetic-field dynamo theory, and laboratory experiments on melting and alloying of iron all contribute to the identification of the composition of the inner and outer core. The core is presumed to be composed principally of iron, with about 10 percent alloy of oxygen or sulfur or nickel, or perhaps some combination of these three elements.



1.13 SEISMIC WAVES AND EXPLORATION FOR THE EARTH'S INTERIOR

Seismic waves are vibrations that propagate through the Earth's interior as a result of various geologic processes, such as earthquakes, volcanic eruptions, and human-induced activities like underground explosions. These waves provide valuable information about the composition, structure, and properties of the Earth's interior.

There are two main types of seismic waves: body waves and surface waves. Body waves travel through the Earth's interior, while surface waves travel along its surface.

1. **Body Waves:** a. **Primary Waves (P-Waves):** These are the fastest seismic waves and can travel through solids, liquids, and gases. P-waves cause particles in the material they pass through to move back and forth in the direction of wave propagation. They are the first waves detected by seismographs during an earthquake.
2. **Secondary Waves (S-Waves):** These waves are slower than P-waves and can only travel through solids. S-waves cause particles to move perpendicular to the direction of wave propagation. They are detected after P-waves during an earthquake.
3. **Surface Waves:**
 - a. **Love Waves:** These waves are named after A.E.H. Love, who mathematically described them in 1911. Love waves travel horizontally and cause the ground to move from side to side. They are typically the most damaging waves during an earthquake.
 - b. **Rayleigh Waves:** Named after Lord Rayleigh, who mathematically described them in 1885, Rayleigh waves travel both vertically and horizontally, causing elliptical motion in the ground surface. They are responsible for much of the shaking felt during an earthquake.

Exploration of Earth's Interior using Seismic Waves:

1. **Seismic Reflection:** This method involves sending seismic waves from the surface and recording their reflections off of underground rock layers. By analyzing the time it takes for the waves to return and their characteristics, geologists can determine the depth and properties of various subsurface layers.
2. **Seismic Refraction:** In this method, seismic waves are sent into the ground at an angle, and their change in velocity as they encounter different rock layers is measured. By analyzing the bending of these waves, geologists can infer the composition and structure of subsurface layers.
3. **Seismic Tomography:** This technique involves using seismic waves from earthquakes recorded at multiple seismograph stations around the world to create detailed 3D images of the Earth's interior. By analyzing how seismic waves travel through different regions, scientists can infer variations in temperature, density, and composition within the Earth.
4. **Seismic Interferometry:** This is a relatively newer technique that involves using ambient seismic noise (background vibrations) to create detailed images of the subsurface without the need for active seismic sources. By analyzing the interference patterns of these ambient waves, scientists can extract information about subsurface structures.

Overall, seismic waves play a crucial role in our understanding of the Earth's interior, providing valuable insights into its composition, structure, and dynamics.

1.14 DEEP DRILLING EXPERIMENTS

Deep drilling involves the penetration of the Earth's crust to reach deeper layers, providing access to samples and data that are otherwise inaccessible. Various drilling techniques have been developed to tackle different geological environments and depths. These techniques include rotary drilling, which is commonly used for shallow depths, and more advanced methods like diamond drilling and rotary-percussive drilling, which are employed for deeper penetration into hard rock formations.

Scientific Objectives: Deep drilling experiments serve a multitude of scientific objectives aimed at understanding different aspects of the Earth's interior. These objectives may include:

1. **Core Composition:** By retrieving samples from the Earth's mantle and core, scientists can analyze their composition to gain insights into the elemental makeup and thermal properties of these layers.
2. **Tectonic Processes:** Deep drilling helps in studying tectonic processes by examining fault zones, earthquake mechanisms, and crustal deformation at depth, providing valuable information about plate tectonics and continental drift.
3. **Geothermal Gradient:** Measuring temperature gradients at different depths helps in understanding heat flow and geothermal energy potential, which is vital for energy exploration and harnessing renewable resources.
4. **Seismic Studies:** Deep drilling experiments contribute to seismic studies by deploying sensors and instruments in boreholes to monitor seismic activity and study wave propagation through different geological materials.
5. **Evolution of Earth:** By analyzing samples obtained from deep drilling, scientists can reconstruct the Earth's evolutionary history, including processes like differentiation, magma evolution, and mantle dynamics over geological timescales.

1.15 GEOLOGICAL TIME SCALE

The geological time scale is a framework used by scientists to organize and understand the vast history of Earth. It divides Earth's history into distinct intervals based on significant geological and biological events, providing a chronological timeline that spans billions of years. This scale is crucial for interpreting the rock record, correlating stratigraphic layers, and understanding the evolution of life on our planet.

At the largest scale, the geological time scale is divided into eons, which represent the broadest divisions of time. Earth's history is categorized into four eons: the Hadean, Archean, Proterozoic, and Phanerozoic.

The Phanerozoic Eon, spanning approximately the last 541 million years, is further divided into three eras: the Paleozoic, Mesozoic, and Cenozoic.

Each era is characterized by distinct geological and biological events. For instance, the Paleozoic Era witnessed the Cambrian Explosion, a rapid diversification of multicellular life forms, as well as the formation of significant coal deposits. The Mesozoic Era is renowned as the "Age of Dinosaurs," marked by the dominance of these reptiles and the eventual extinction event that ended their reign. The Cenozoic Era, the most recent era, saw the rise of mammals, including the evolution of humans.

Era	System & Period	Series & Epoch	Some Distinctive Features	Years Before Present
CENOZOIC	Quaternary	Recent	Modern man.	11,000
		Pleistocene	Early man; northern glaciation.	1/2 to 2 million
	Tertiary	Pliocene	Large carnivores.	13 ± 1 million
		Miocene	First abundant grazing mammals.	25 ± 1 million
		Oligocene	Large running mammals.	36 ± 2 million
		Eocene	Many modern types of mammals.	58 ± 2 million
		Paleocene	First placental mammals.	63 ± 2 million
MESOZOIC	Cretaceous		First flowering plants; climax of dinosaurs and ammonites, followed by Cretaceous-Tertiary extinction.	135 ± 5 million
	Jurassic		First birds, first mammals dinosaurs and ammonites abundant.	181 ± 5 million
	Triassic		First dinosaurs. Abundant cycads and conifers.	230 ± 10 million
PALEOZOIC	Permian		Extinction of most kinds of marine animals, including trilobites. Southern glaciation.	280 ± 10 million
	Carboniferous	Pennsylvanian	Great coal forests, conifers. First reptiles.	310 ± 10 million
		Mississippian	Sharks and amphibians abundant. Large and numerous scale trees and seed ferns.	345 ± 10 million
	Devonian		First amphibians; ammonites; fishes abundant.	405 ± 10 million
	Silurian		First terrestrial plants and animals.	425 ± 10 million
	Ordovician		First fishes; invertebrates dominant.	500 ± 10 million
	Cambrian		First abundant record of marine life; trilobites dominant.	600 ± 50 million
	Precambrian		Fossils extremely rare, consisting of primitive aquatic plants. Evidence of glaciation. Oldest dated algae, over 2,600 million years; oldest dated meteorites 4,500 million years.	

Within each era, there are further divisions known as periods. These periods are defined by specific geological and paleontological characteristics and are named after significant rock formations or fossil groups. For example, the Paleozoic Era is divided into periods such as the Cambrian, Ordovician, Silurian, Devonian, Carboniferous, and Permian. Each period is marked by distinctive fossil assemblages and geological events.

Periods are then subdivided into epochs, which represent shorter intervals of time characterized by specific geological or biological changes. For instance, the Cenozoic Era is divided into epochs such as the Paleogene and Neogene, each marked by significant shifts in climate, sea level, and the evolution of mammals.

The smallest divisions of time on the geological time scale are ages. Ages represent relatively short intervals of geological time defined by specific geological or paleontological events and are named after characteristic fossils or rock formations. Ages provide finer detail within epochs and help scientists correlate rock layers and interpret the fossil record more precisely.

1.16 GEOLOGIC PERIODS AND CLIMATE CHANGE

Geological periods, also known as geologic time scales, are divisions of Earth's history into distinct intervals based on significant events and changes in the planet's geological, biological, and climatic conditions. These periods provide a framework for understanding the evolution of Earth and its inhabitants over billions of years. Climate change, which refers to long-term shifts in temperature, precipitation patterns, and other climate parameters, has played a crucial role in shaping Earth's history and is intricately linked to geological periods.

The geological time scale is typically divided into eons, eras, periods, epochs, and ages, with each unit representing different scales of time and corresponding to specific geological and biological events. One of the most prominent divisions is between the Precambrian eon, which encompasses Earth's earliest history, and the Phanerozoic eon, which includes the period from roughly 541 million years ago to the present day and is characterized by the proliferation of complex life forms.

Throughout Earth's history, climate change has been driven by various factors, including changes in solar radiation, volcanic activity, continental drift, and atmospheric composition. These changes have led to fluctuations in global temperatures, sea levels, and atmospheric CO₂ levels, which have had profound impacts on Earth's environments and ecosystems.

During the Precambrian eon, Earth's climate was largely influenced by geological processes such as volcanic activity and the formation of continents. The atmosphere during this time was composed primarily of gases like carbon dioxide, methane, and water vapor, leading to a greenhouse effect that kept the planet warm. However, as Earth's surface evolved and continents began to form, the climate gradually cooled, leading to the development of glaciations known as "snowball Earth" episodes.

The Phanerozoic eon is divided into three major eras: the Paleozoic, Mesozoic, and Cenozoic eras. Each era is characterized by distinct geological and biological events, often accompanied by significant changes in climate. For example, during the Paleozoic era, Earth experienced multiple ice ages and warm periods, while the Mesozoic era was marked by warmer temperatures and higher sea levels, with widespread tropical forests and shallow seas.

The Cenozoic era, which began roughly 66 million years ago, is often referred to as the "Age of Mammals" and is characterized by the diversification of mammals and the rise of modern ecosystems. Throughout this era, Earth's climate has undergone significant fluctuations, including periods of cooling (such as the ice ages) and warming (such as the Paleocene-Eocene Thermal Maximum), often driven by changes in atmospheric CO₂ levels and tectonic activity.

In recent history, human activities have become significant drivers of climate change, primarily through the burning of fossil fuels, deforestation, and industrial processes that release greenhouse gases into the atmosphere. These activities have led to unprecedented increases in atmospheric CO₂ levels and global temperatures, resulting in phenomena such as global warming, sea level rise, and more frequent extreme weather events.

1.17 RECENTLY PROPOSED GEOLOGICAL EPOCH (ANTHROPOCENE)

The Anthropocene epoch is a term used to describe a proposed geological epoch marked by the significant impact of human activities on the Earth's ecosystems and geology. While the concept of geological epochs typically refers to long periods of time characterized by distinct geological and environmental changes, the idea of the Anthropocene suggests that human activities have become a dominant force shaping the Earth's systems to such an extent that they warrant recognition as a new epoch.

The term "Anthropocene" was popularized by atmospheric chemist Paul Crutzen and biologist Eugene Stoermer in the early 2000s, although the concept has gained increasing attention and debate within the scientific community since then. Proponents argue that human activities, such as industrialization, urbanization, agriculture, and the burning of fossil fuels, have caused significant and unprecedented changes to the Earth's atmosphere, biodiversity, and geological processes.

Key indicators of the Anthropocene include:

1. **Climate Change:** The burning of fossil fuels, deforestation, and other human activities have led to increased levels of greenhouse gases in the atmosphere, resulting in global warming and climate change.
2. **Biodiversity Loss:** Human activities, including habitat destruction, overexploitation of resources, and the introduction of invasive species, have led to a rapid decline in global biodiversity, with many species facing extinction.
3. **Land Use Changes:** Urbanization, agriculture, and infrastructure development have transformed vast areas of land, leading to habitat loss, fragmentation, and degradation.
4. **Pollution:** The release of pollutants, including plastics, heavy metals, and chemicals, into the environment has caused widespread pollution of air, water, and soil.
5. **Altered Geological Processes:** Human activities have led to changes in sedimentation patterns, soil composition, and even the distribution of minerals and elements in the Earth's crust.

While the concept of the Anthropocene remains controversial, with some scientists arguing for its formal recognition as a geological epoch and

others questioning its validity or suggesting alternative terms, it has nevertheless sparked important discussions about the relationship between human activities and the Earth's natural systems. Recognizing the Anthropocene as a distinct epoch highlights the need for humanity to address the environmental challenges it faces and to adopt more sustainable practices to mitigate further damage to the planet.

1.18 EARTH'S GRAVITATIONAL FIELD - EXTENT VARIATION IN MAGNITUDE - GRACE MISSION

Earth's gravitational field is a fundamental aspect of its physical nature, exerting a force that influences the motion of objects on or near its surface. This gravitational field is not uniform across the planet, varying in both magnitude and direction due to factors such as differences in mass distribution, elevation, and local geological features.

The extent of Earth's gravitational field can vary significantly from one location to another. In areas where there is a concentration of mass, such as mountain ranges or dense rock formations, the gravitational field is stronger, resulting in a higher acceleration due to gravity. Conversely, in regions with lower mass concentrations, such as ocean basins or areas with less dense crustal materials, the gravitational field is weaker.

One of the most notable missions that have provided valuable insights into Earth's gravitational field is the Gravity Recovery and Climate Experiment (GRACE). Launched in 2002 by NASA and the German Aerospace Center (DLR), GRACE consisted of two identical satellites orbiting the Earth in tandem. These satellites precisely measured the distance between them, which varied slightly in response to changes in Earth's gravitational field caused by variations in mass distribution beneath the Earth's surface.

GRACE data revealed significant variations in Earth's gravitational field, including anomalies related to changes in water distribution, such as ice melting in polar regions or changes in groundwater storage. These measurements not only improved our understanding of Earth's structure and dynamics but also provided crucial information for studying climate change, water resource management, and geophysical processes.

Earth's gravitational field is a dynamic and complex phenomenon, varying in magnitude across different regions due to geological, hydrological, and atmospheric factors. Missions like GRACE have been instrumental in advancing our knowledge of these variations and their implications for Earth's environment and climate.

1.19 GRAVITY AND ITS EFFECTS ON EARTH SYSTEMS

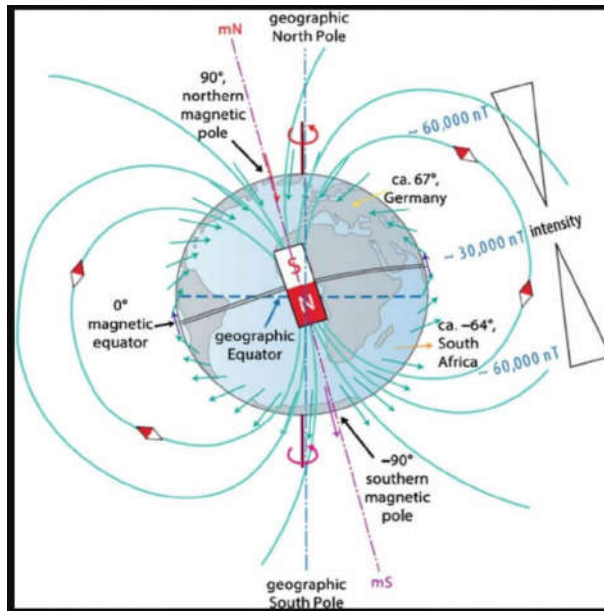
Gravity is one of the fundamental forces governing the universe, and its effects on Earth systems are profound and wide-ranging. Here's an overview of gravity and its impacts on various aspects of Earth:

1. **Orbital Dynamics:** Gravity is the force that keeps celestial bodies like Earth in orbit around the sun. The balance between the gravitational pull of the sun and the inertia of Earth's motion keeps our planet in a stable orbit. Similarly, the moon is held in orbit around Earth by gravity.
2. **Tides:** The gravitational pull of the moon and, to a lesser extent, the sun, creates tides in Earth's oceans. These tidal forces result in the rise and fall of sea levels, influencing coastal ecosystems, navigation, and erosion.
3. **Atmospheric Pressure:** Gravity pulls the atmosphere towards Earth's surface, creating atmospheric pressure. This pressure decreases with altitude, affecting weather patterns, atmospheric circulation, and the distribution of gases essential for life.
4. **Geological Processes:** Gravity plays a crucial role in shaping Earth's geology. It causes materials to settle, leading to processes like sedimentation, which is essential for the formation of sedimentary rocks. Gravity also influences the movement of tectonic plates, volcanic eruptions, and the formation of mountains.
5. **Hydrological Cycle:** Gravity is central to the hydrological cycle, which includes processes like evaporation, condensation, and precipitation. Gravity pulls water downhill, driving the flow of rivers and streams, and determines the shape and depth of bodies of water like lakes and oceans.
6. **Climate:** Gravity influences climate by affecting the distribution of heat and moisture around the globe. The uneven distribution of solar radiation due to Earth's spherical shape and its axial tilt, combined with gravitational effects on atmospheric circulation, result in diverse climates across different regions.
7. **Biological Effects:** Gravity shapes the evolution and behavior of organisms on Earth. It affects the growth of plants, the structure of organisms, and the behavior of animals. For example, organisms have evolved strategies to cope with gravitational forces, such as the development of bones and muscles in vertebrates to support their weight.
8. **Human Impact:** Gravity influences human activities and infrastructure, from construction and transportation to sports and recreation. Engineers and architects must consider gravitational forces when designing buildings and structures, while transportation systems rely on gravity for propulsion and navigation.

Overall, gravity is a fundamental force that profoundly influences Earth's systems, from the movement of celestial bodies to the dynamics of our atmosphere, geology, hydrology, climate, biology, and human activities. Understanding gravity's effects is essential for comprehending Earth's complex interconnected systems and for addressing various environmental and societal challenges.

1.20 GEOMAGNETISM – EXTENT MAGNITUDE AND VARIATIONS

Geomagnetism is a branch of science that studies the Earth's magnetic field, including its extent, magnitude, and variations. The Earth behaves as if it has a giant bar magnet at its core, with magnetic field lines stretching from the magnetic north to the magnetic south poles. This geomagnetic field plays a crucial role in various natural processes and has significant implications for human activities.



Extent and Magnitude: The Earth's magnetic field extends far beyond its surface, creating a protective shield known as the magnetosphere. This shield deflects harmful solar radiation and charged particles from the solar wind, safeguarding life on Earth from their detrimental effects. The magnetosphere extends tens of thousands of kilometers into space, forming a region where the Earth's magnetic influence dominates.

The magnitude of the Earth's magnetic field is measured in units of Gauss or Tesla. At the Earth's surface, the strength of the magnetic field typically ranges from approximately 25 to 65 microteslas (μT), with slight variations depending on location. Near the magnetic poles, where the field lines converge, the field strength is higher, while it is weaker at the equator.

Variations: Geomagnetic variations refer to changes in the Earth's magnetic field over time and space. These variations can occur on various timescales, from seconds to millennia, and are influenced by both internal and external factors.

1. Diurnal Variations: These are changes in the magnetic field that occur over the course of a day. They are primarily driven by the interaction between the Earth's rotating solid inner core and the surrounding fluid outer core, known as the dynamo effect.

2. **Secular Variations:** Secular variations are long-term changes in the Earth's magnetic field that occur over decades to millennia. These changes are attributed to processes within the Earth's core, such as convective motion and changes in the distribution of magnetic materials.
3. **Geomagnetic Storms:** Geomagnetic storms are short-term disturbances in the Earth's magnetic field caused by solar activity, particularly solar flares and coronal mass ejections (CMEs). These events can cause rapid fluctuations in the magnetic field, leading to phenomena such as auroras and disturbances in radio communications and power grids.
4. **Magnetic Anomalies:** Magnetic anomalies are localized deviations from the Earth's expected magnetic field strength and direction. They can result from geological features such as underground structures, mineral deposits, and variations in the composition of the Earth's crust.

Understanding geomagnetic extent, magnitude, and variations is essential for various scientific disciplines, including geology, geophysics, and space weather forecasting. Additionally, industries such as navigation, telecommunications, and oil exploration rely on accurate geomagnetic data for their operations. Ongoing research continues to enhance our understanding of geomagnetism and its implications for both natural and human-made systems.

1.21 DYNAMO EFFECT, MAGNETIC FIELD REVERSALS AND EFFECTS

1. **Dynamo Effect:** The Dynamo Effect is a phenomenon that describes the generation of a magnetic field by the movement of conducting fluids, such as molten iron in the Earth's outer core or plasma within stars. This effect is crucial in understanding the origin and maintenance of planetary magnetic fields, including Earth's magnetic field.
2. **Generation Mechanism:** The Dynamo Effect operates through the process of electromagnetic induction. When conducting fluids move within a planetary core, they generate electric currents due to their motion and the presence of an existing magnetic field. These electric currents, in turn, produce magnetic fields through the Ampère's law, creating a self-sustaining feedback loop known as the dynamo process.
3. **Earth's Magnetic Field Reversals:** Earth's magnetic field has undergone numerous reversals throughout its history, where the magnetic north and south poles exchange places. These reversals are documented in the geological record through magnetic signatures preserved in rocks. The process and timing of these reversals are not yet fully understood, but they are believed to be linked to changes in the Earth's core dynamics driven by the Dynamo Effect.

4. Effects of Magnetic Field Reversals:

- a. **Navigation and Migration:** Magnetic field reversals can affect navigation systems that rely on compasses, as the direction indicated by a compass would change during a reversal. Additionally, certain migratory animals, such as birds and sea turtles, use Earth's magnetic field for navigation, and reversals may influence their behavior.
- b. **Cosmic Radiation:** Earth's magnetic field acts as a shield against cosmic radiation, deflecting charged particles from the Sun and deep space. During a reversal, the magnetic field weakens, potentially allowing more cosmic radiation to reach the Earth's surface. This increased radiation could have implications for technological systems, space exploration, and biological organisms.
- c. **Climate and Evolution:** Some research suggests a correlation between magnetic field reversals and climatic variations or evolutionary events. However, the exact nature of this relationship is still debated among scientists. It is hypothesized that changes in the magnetic field may influence atmospheric processes or cosmic ray interactions, which could indirectly impact climate and biological evolution.

The Dynamo Effect plays a crucial role in generating and maintaining planetary magnetic fields, such as Earth's, which undergo periodic reversals. Understanding these phenomena and their effects is essential for various fields of science, including geophysics, astronomy, and biology. Ongoing research continues to deepen our understanding of the complex interactions between magnetic fields, planetary dynamics, and their broader implications.

1.22 SUMMARY

The chapter begins by introducing Earth system science, highlighting its nature and scope. It then delves into the origin and evolution of Earth, discussing theories such as the Big Bang Theory and the formation of the lithosphere. The Theory of Plate Tectonics is explored in detail, alongside the Earth's interior structure, composition, and methods of exploration like seismic waves and deep drilling experiments.

Geological time scales and periods are examined, including their relation to climate change, and the concept of the Anthropocene epoch is introduced. Earth's gravitational field and its variations, as observed through missions like GRACE, are discussed, as well as the effects of gravity on Earth's systems.

Additionally, the chapter covers geomagnetism, including the dynamo effect, magnetic field reversals, and their impacts. Overall, the chapter provides a comprehensive overview of Earth system science, from the formation of the planet to its dynamic systems and processes.

1.23 SAMPLE QUESTIONS

Q.1. Fill in the blanks.

- 1 The study of the interrelated processes and interactions that occur in the Earth's atmosphere, hydrosphere, lithosphere, biosphere, and cryosphere (frozen ecosystems / environment) is known as -----
---- (Earth System Science).
- 2 The -----is a cosmological model that describes the earliest known stages of the universe's evolution (Big Bang Theory).
- 3 -----is a comprehensive theory in geology that describes the movement and interaction of the lithospheric plates that form the Earth's outer shell.(Plate tectonics)
- 4 -----is the oldest geological period (Quaternary).
- 5 -----is a branch of science that studies the Earth's magnetic field, including its extent, magnitude, and variations (Geomagnetism).

Q. 2. Write short notes on the following.

- 1 Origin of the earth.
- 2 Plate tectonic theory
- 3 GRACE mission
- 4 Geomagnetism

Q. 3. Answer the following questions.

- 1 Elaborate the nature and scope of earth system science.
- 2 Explain structure and composition of the earth's interior.
- 3 Explain the importance of geological timescale in climate change studies.
- 4 Elaborate dynamo effect, magnetic field reversals and effects of geomagnetism.

1.24 REFERENCES FOR FURTHER READING

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ATMOSPHERE AND CLIMATE

After going through this chapter, you will be able to understand the following features.

Unit Structure :

- 2.1 Objectives
- 2.2 Introduction
- 2.3 Composition and Structure of the Atmosphere
- 2.4 Composition of the Atmosphere
- 2.5 Structure of the Atmosphere
- 2.6 Functions of the Atmosphere
- 2.7 Relationship of Climatology with Meteorology, Weather Elements and Climatic Controls
- 2.8 Climatology with meteorology
- 2.9 Weather Elements and Climatic Controls
- 2.10 Insolation and Heat Budget of The Earth, Temperature - Vertical, Horizontal and Seasonal Variations
- 2.11 Insolation
- 2.12 Heat Budget of the Earth
- 2.13 Temperature of the Atmosphere: Factors Affecting Temperature of The Atmosphere
- 2.14 Distribution of Temperature
- 2.15 Vertical Distribution of Temperature
- 2.16 Normal Lapse Rate
- 2.17 Inversion of the Temperature
- 2.18 Horizontal Distribution of the Temperature
- 2.19 Heat Energy Transfer
- 2.20 Summary
- 2.21 Sample Questions
- 2.22 References for Further Reading

2.1 OBJECTIVES

After learning this module, learners will be able to;

1. Evaluate theories of origin of earth's atmosphere.
2. Understand composition and structure of the atmosphere.
3. Compare climate and weather.
4. Establish relationship between climatology and meteorology.
5. Understand weather elements and climatic control.
6. Understand insolation and its equilibrium and distribution of global temperature.
7. Understand process of heat transfer and inversion of temperature.

2.2 INTRODUCTION

The Earth's atmosphere, a dynamic envelope of gases surrounding the planet, has undergone significant evolutionary changes throughout its long history. These changes have been influenced by a myriad of factors, including geological processes, biological activity, and interactions with space. Understanding the evolution of Earth's atmosphere provides crucial insights into the planet's past climates, the development of life, and its potential for habitability. In this essay, we will explore the evolution of Earth's atmosphere, starting from its formation to the present day.

1. **Formation of Earth's Atmosphere :** The Earth formed approximately 4.5 billion years ago through the accretion of dust and gas in the early solar system. Initially, the Earth's atmosphere was likely composed of volatile elements such as hydrogen and helium, similar to the composition of the primordial solar nebula. However, due to the Earth's relatively low gravity and the intense heat from its formation, these light gases would have escaped into space, leading to the loss of the primordial atmosphere.
2. **The Era of Volcanism :** During the Hadean eon, approximately 4.5 to 4 billion years ago, the Earth was subject to intense volcanic activity. Volcanic eruptions released gases such as water vapor (H₂O), carbon dioxide (CO₂), methane (CH₄), and ammonia (NH₃) from the Earth's interior into the atmosphere. This process, known as outgassing, gradually built up a secondary atmosphere dominated by these gases.
3. **The Great Oxygenation Event :** One of the most significant milestones in the evolution of Earth's atmosphere occurred around 2.4 billion years ago during the Proterozoic eon. This event, known as the Great Oxygenation Event (GOE) or the Oxygen Catastrophe, marked the widespread accumulation of oxygen (O₂) in the atmosphere. The primary source of this oxygen was the emergence of oxygenic

photosynthesis in cyanobacteria, which converted carbon dioxide and water into organic matter and released oxygen as a byproduct.

The increase in atmospheric oxygen had profound consequences for life on Earth. It paved the way for the evolution of aerobic respiration, a more efficient metabolic process that utilizes oxygen to extract energy from organic molecules. Additionally, the accumulation of oxygen in the atmosphere led to the formation of the ozone (O₃) layer in the stratosphere, providing protection against harmful ultraviolet (UV) radiation from the Sun.

4. **Variations in Atmospheric Composition:** Throughout Earth's history, the composition of the atmosphere has undergone significant variations due to various geological and biological processes. For example, fluctuations in volcanic activity, weathering of rocks, and the emergence of different forms of life have all influenced the levels of greenhouse gases such as carbon dioxide and methane.

During periods of extensive volcanic activity, such as the Permian-Triassic extinction event around 252 million years ago, large quantities of carbon dioxide were released into the atmosphere, leading to global warming and significant changes in climate. Conversely, periods of increased biological productivity, such as the Carboniferous period approximately 350 million years ago, saw the removal of carbon dioxide from the atmosphere through processes like photosynthesis and the burial of organic matter, leading to cooling and the formation of coal deposits.

5. **Impact of Life on the Atmosphere:** The evolution of life on Earth has played a crucial role in shaping the composition and dynamics of the atmosphere. Cyanobacteria were instrumental in oxygenating the atmosphere during the Great Oxygenation Event, while the proliferation of land plants contributed to the removal of carbon dioxide through photosynthesis and the stabilization of atmospheric oxygen levels.

Furthermore, the emergence of complex organisms with shells and skeletons, such as corals and mollusks, has influenced the carbon cycle and the deposition of carbonate minerals, affecting the long-term carbon storage capacity of the Earth's crust. Human activities, particularly since the Industrial Revolution, have also had a significant impact on the atmosphere through the burning of fossil fuels, deforestation, and the release of greenhouse gases.

6. **The Modern Atmosphere:** Today, Earth's atmosphere is predominantly composed of nitrogen (N₂) (~78%) and oxygen (O₂) (~21%), with trace amounts of other gases such as argon (Ar), carbon dioxide (CO₂), and methane (CH₄). The composition of the atmosphere is regulated by complex feedback mechanisms involving geological processes, biological activity, and atmospheric chemistry.

The Earth's atmosphere is divided into several layers based on temperature and composition, including the troposphere (where weather occurs), the stratosphere (containing the ozone layer), the mesosphere, and the thermosphere. Each layer plays a unique role in regulating the Earth's climate and supporting life.

7. **Anthropogenic Influence:** In recent centuries, human activities have had a profound impact on Earth's atmosphere, leading to environmental challenges such as climate change and air pollution. The burning of fossil fuels, deforestation, industrial processes, and agriculture have significantly increased the concentrations of greenhouse gases such as carbon dioxide, methane, and nitrous oxide in the atmosphere, leading to global warming and altered weather patterns.

Furthermore, emissions of air pollutants such as sulfur dioxide, nitrogen oxides, and particulate matter have detrimental effects on human health, ecosystems, and the environment. Addressing these anthropogenic impacts requires concerted efforts to reduce greenhouse gas emissions, transition to renewable energy sources, improve energy efficiency, and promote sustainable land use practices.

The evolution of Earth's atmosphere is a complex and dynamic process that has been shaped by geological, biological, and anthropogenic factors over billions of years. From its formation through volcanic outgassing to the oxygenation of the atmosphere by early life forms, and the subsequent influence of human activities, the atmosphere has undergone significant changes that have profound implications for the planet's climate, ecosystems, and habitability.

Understanding the evolution of Earth's atmosphere is essential for predicting future changes, mitigating anthropogenic impacts, and ensuring the long-term sustainability of our planet. By studying the past, we can gain valuable insights into how the Earth's atmosphere may continue to evolve and how we can better manage and protect this vital resource for future generations.

2.3 COMPOSITION AND STRUCTURE OF THE ATMOSPHERE

The atmosphere is considered as “a blanket of air” surrounding the earth surface. The Earth's atmosphere is a complex system of gases, particles, and other components that envelops our planet, playing a crucial role in sustaining life and shaping our climate. Comprising various layers with distinct characteristics, the atmosphere acts as a shield against harmful solar radiation, regulates temperature, and facilitates weather patterns. In this detailed composition, we will explore the composition, structure, and functions of the Earth's atmosphere in depth.

2.4 COMPOSITION OF THE ATMOSPHERE

The atmosphere is composed of different gases, water vapour and suspended particulate matter.

a) Gases:

The Earth's atmosphere is primarily composed of nitrogen (78%) and oxygen (21%), with trace amounts of other gases such as argon, carbon dioxide, neon, helium, and methane making up the remaining 1%. Water vapor, although a variable component, is also a significant constituent, contributing to the dynamics of weather and climate. These gases are crucial for sustaining life and maintaining the delicate balance of the Earth's ecosystem.

Table. 2.1 Important gases in the dry air of the lower atmosphere

Constituent	Per cent by volume	Constituent	Per cent by volume
Nitrogen (N ₂)	78.08	Ozone (O ₃)	0.00006
Oxygen (O ₂)	20.94	Hydrogen (H ₂)	0.00005
Argon (Ar ₂)	0.93	Krypton (Kr)	Trace
Carbon dioxide (CO ₂)	0.03	Xenon (X ₂)	Trace
Neon (Ne)	0.0018	Methane (Me)	Trace
Helium (He)	0.00005		

Nitrogen, the most abundant gas in the atmosphere, is essential for life as it is a key component of proteins and nucleic acids. Nitrogen composed of about 78% of the total atmosphere's volume. Nitrogen does not actively participate in chemical processes with other atmospheric substances, it is relatively inactive chemically. However, nitrogen is an important element in many organic compounds.

Oxygen, the second most abundant gas, is vital for respiration and combustion processes. Life is not possible without oxygen. Oxygen is capable of combining with all other elements. Oxygen is an essential in combustion process.

Carbon dioxide, despite being a minor element of the atmosphere (about 0.03%), plays significant role in the Earth's climate system as a greenhouse gas, trapping heat and contributing to global warming.

Trace gases such as argon, helium, and neon are inert and do not participate in chemical reactions. However, they contribute to the atmospheric pressure and density. Methane, another trace gas, is a potent greenhouse gas with a significant impact on climate change. Water vapor, though variable, plays a crucial role in the Earth's energy balance through its involvement in the formation of clouds, precipitation, and the greenhouse effect.

Apart from gases, the atmosphere also contains aerosols, which are tiny solid or liquid particles suspended in the air. These aerosols include dust, pollen, sea salt, and pollutants emitted from human activities. Aerosols play a significant role in cloud formation, precipitation processes, and scattering of solar radiation, influencing both weather and climate.

b) Water vapor:

Water vapour is an important element of the atmosphere which greatly varies from place to place. Although, the atmospheric water vapour is present in a small amount, it plays significant role in various atmospheric processes. The percentage of atmospheric water vapour in the atmosphere varies from 0.02% in dry air to about 4% in the moist air. The concentration of atmospheric water vapour is found up to 5 kilometres above the earth surface. Water vapour play important role in atmospheric processes like vertical movement of the air parcel, condensation, saturation, precipitation, transpiration and evaporation.

Table. 2.2 Amount of water vapour in one cubic meter of air parcel at different temperatures

Temperature (°C)	Grams	Temperature (°C)	Grams
-5	3.261	20	17.300
0	4.847	25	23.049
5	6.797	30	39.371
10	9.401	35	39.599
15	12.832	40	51.117

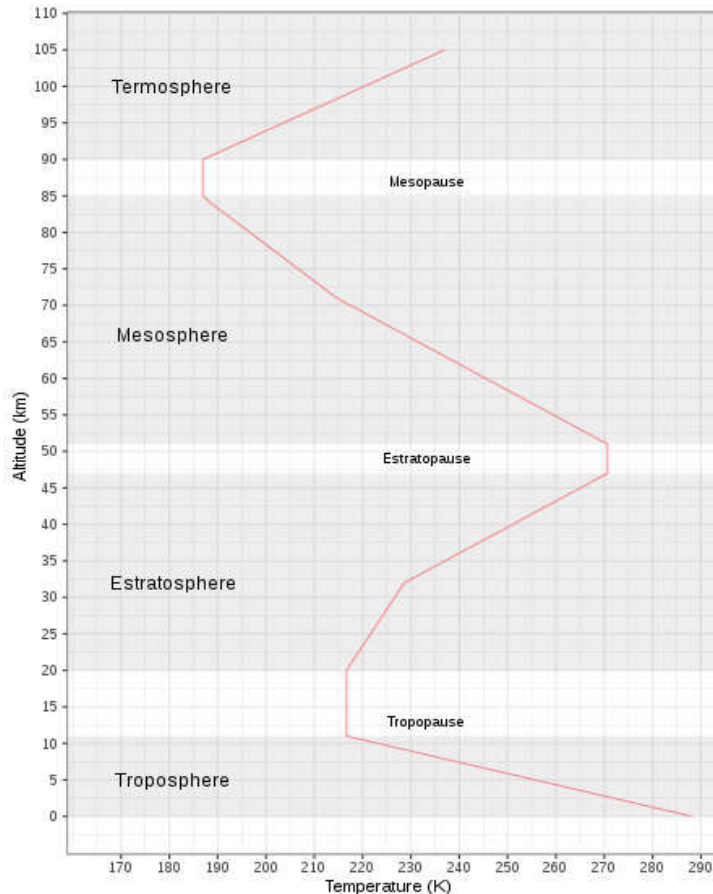
The amount of atmospheric water vapour significantly increases with increase in the temperature of the lower atmosphere. The increase temperature leads to increase in the rate of evapotranspiration, thereby increasing the concentration of water vapour in the lower atmosphere.

c) Dust particles:

Dust particles are also called as aerosols or suspended particulate matters (SPM) which exist in the lower atmosphere in suspension. Dust particles are present in the lower atmosphere up to the elevation of 1000 meters from the earth surface. Most of the time dust particles are microscopic in size and hence cannot be seen with the open eyes. Aerosols contains dust particles of different sizes produced from both natural processes (such as storms, cyclones, forest fire, pollens, sea salts from breaking sea waves, volcanoes etc.) and manmade activities (such as mining dust, construction work, farming operations, industrial smoke, blasting equipment, transportation dust etc.). Dust particles play important role in various atmospheric phenomena such as absorption of short wave solar radiation, selective scattering etc. Dust particles are also responsible for production dense fog, sometimes get combined with smoke (often refer to as smog).

2.5 STRUCTURE OF THE ATMOSPHERE

The earth's atmosphere has different spherical zones of distinct characteristics according to the altitude above the earth surface. Although, these layers are of distinct characteristics, boundaries between these layers cannot be sharply defined. The Earth's atmosphere can be divided into several layers based on their temperature profiles and characteristics: the troposphere, stratosphere, mesosphere, thermosphere, and exosphere.



- 1. Troposphere:** Troposphere forms the lowermost layer of the atmosphere in which the earth's life exist and interact. The troposphere is the lowest layer of the atmosphere, extending from the Earth's surface up to about 8-15 kilometers, depending on latitude and season. The vertical extent of the troposphere ranges from 5-6 km at the poles whereas it extends up to 16 km altitude at equator. This layer of the atmosphere is characterized by a decrease in temperature with altitude, known as the lapse rate. The troposphere contains the majority of the Earth's atmospheric mass and is where weather phenomena such as clouds, precipitation, and storms occur. Troposphere is also called as friction layer of the atmosphere where friction of air masses takes place with the land surface. Therefore, maximum interaction between land and the atmosphere takes place in the troposphere. Almost all kinds of atmospheric circulations and phenomena take place in the tropospheric layer of the atmosphere. At the top of the troposphere, there is a thin layer of the atmosphere separating it from next thermal

layer i.e. stratosphere. This thin (about 1 to 2 km extend from upper limit of the troposphere) layer is called tropopause. The temperature of the atmosphere in tropopause is found to be constant.

2. **Stratosphere:** The stratosphere begins at tropopause. Above the troposphere lies the stratosphere, extending from the tropopause (the boundary between the troposphere and stratosphere) to about 50 kilometers above the Earth's surface. Unlike the troposphere, the temperature in the stratosphere increases with altitude due to the presence of the ozone layer, which absorbs and re-emits solar radiation, warming the surrounding air. There is a persistent increase in the atmospheric temperature in upper stratosphere up to the elevation of 30 km. High velocity of winds at this layer form cirrus clouds occasionally in the lower stratosphere. Stratosphere is warmest between 50° - 60°.
3. **Mesosphere:** The mesosphere is the third layer of the atmosphere, extending from the stratopause (the boundary between the stratosphere and mesosphere) to about 85 kilometers above the Earth's surface. In this layer, temperatures decrease with altitude, reaching their lowest point in the mesopause region. There is a high concentration of ozone gas in the mesosphere, hence it is also called 'ozonosphere'. Ozone is important gas in this layer. It is made up of three atoms of oxygen (O₃). The formation of ozone at upper layer of the stratosphere is due to breaking of oxygen molecule into two atoms by intense ultraviolet radiation and free unstable atoms of oxygen combines with other oxygen molecules to form ozone. Ozone layer is warmer because it selectively absorb the solar radiation by total absorption of intense ultra-violet radiation. Hence, this layer is also acts as filter of ultra-violet rays from the sun and protects the life on the earth surface from intense UV radiation. The mesosphere is where most meteoroids burn up upon entering the Earth's atmosphere, creating shooting stars.
4. **Thermosphere:** Above the mesosphere lies the thermosphere, extending from about 85 kilometers to 600 kilometers above the Earth's surface. Despite its high altitude, the thermosphere experiences extremely high temperatures due to the absorption of solar radiation by oxygen and nitrogen molecules. This layer is also where the International Space Station orbits. The density of the atmosphere is very low in this layer. Temperature keep on increasing with altitude in this layer.
5. **Exosphere:** The exosphere is the outermost layer of the atmosphere, gradually transitioning into outer space. It extends from the thermopause (the boundary between the thermosphere and exosphere) to thousands of kilometers above the Earth's surface. The exosphere is characterized by extremely low densities of gases, and particles can escape into space due to their high kinetic energy. This layer has minimum density of the atmospheric layer and also the earth's gravitational force in this layer is minimum as compared to other layers of the atmosphere.

The Earth's atmosphere performs several crucial functions that are essential for sustaining life and maintaining the planet's climate system:

- 1. Protection from Solar Radiation:** The atmosphere acts as a shield against harmful solar radiation, particularly intense ultraviolet (UV) radiation, which can cause skin cancer and other health issues. The ozone layer in the stratosphere absorbs much of the incoming UV radiation, protecting life on Earth.
- 2. Regulation of Temperature:** Through processes such as absorption, emission, and reflection of solar radiation, as well as the greenhouse effect, the atmosphere regulates the Earth's temperature. Greenhouse gases such as carbon dioxide, water vapor, and methane trap heat in the atmosphere, preventing it from escaping into space and thereby maintaining a habitable temperature range on Earth.
- 3. Facilitation of Weather Patterns:** The atmosphere plays a central role in the formation of weather patterns such as clouds, precipitation, winds, and storms. These weather phenomena are driven by the uneven heating of the Earth's surface by the Sun, as well as interactions between air masses of different temperatures and humidity levels.
- 4. Distribution of Water:** Water vapor in the atmosphere facilitates the hydrological cycle, which involves the continuous movement of water between the Earth's surface, atmosphere, and oceans. Processes such as evaporation, condensation, and precipitation are essential for replenishing freshwater sources and sustaining ecosystems.
- 5. Support of Life:** The composition of the atmosphere, particularly the presence of oxygen and nitrogen, is essential for supporting life on Earth. Oxygen is necessary for aerobic respiration in organisms, while nitrogen is a crucial component of proteins and nucleic acids. The atmosphere also provides carbon dioxide for photosynthesis, the process by which plants and algae produce oxygen and organic compounds.

The Earth's atmosphere is a dynamic and complex system that plays a fundamental role in sustaining life and shaping the planet's climate. Comprising various gases, aerosols, and layers with distinct characteristics, the atmosphere regulates temperature, facilitates weather patterns, and protects against harmful solar radiation. Understanding the composition, structure, and functions of the atmosphere is crucial for addressing environmental challenges such as climate change and air pollution, as well as for promoting the sustainable management of Earth's resources.

2.7 RELATIONSHIP OF CLIMATOLOGY WITH METEOROLOGY, WEATHER ELEMENTS AND CLIMATIC CONTROLS

The atmospheric phenomena that took place in the lower atmosphere is of immense importance for all life forms on the earth surface. The study of weather conditions at given place in short time duration is meteorology whereas climatology is the study of spatio-temporal patterns of average weather conditions (generally more than 30 years). This section aims at describing the difference between climatology and meteorology. The role of different weather elements such as temperature, rainfall, wind velocity, humidity, cloud formation, atmospheric pressure etc., is significant in shaping the natural as well as manmade landscape. Following sub-section aims at discussing many of these climatic controls in detail.

2.8 CLIMATOLOGY WITH METEOROLOGY

The atmosphere is a complex of several atmospheric phenomena as well as elements. Insolation (solar radiation), heat budget, related atmospheric changes, dynamic nature of atmosphere needs to be studied scientifically to understand association between various atmospheric processes which impacts the life forms on the earth. Atmospheric science is the study of atmosphere and its dynamism. Aerology, meteorology and climatology are significant branches of atmospheric science. Aerology is the science of atmospheric compositions which scientifically studies the elements of the atmosphere and their atmospheric composition.

Weather refers to the sum total of all atmospheric conditions in a given place at a given time. Meteorology is science of weather. Meteorology is a science that deals with the atmospheric conditions and processes in the lower atmosphere. Meteorology studies different atmospheric processes (temperature, atmospheric pressure, humidity, evaporation, transpiration, wind direction, wind velocity, cyclones, anticyclones, atmosphere-earth surface interactions etc. Meteorology evaluates different atmospheric phenomena using various weather instruments that records weather phenomena at weather observatories and weather stations (in recent times automatic weather stations are being used). Meteorology deals largely with estimation (forecasting) of weather phenomena over a short period of time. Meteorology attempts to explain characteristics and changing behaviour of the atmosphere in a given place over a short period of time based on empirical information obtained using weather instruments.

Climate refers to the average (aggregate) weather conditions in a given region for long period of time (generally, the average weather conditions of 30 years or more). Climatology is science of studying the nature of climate and its spatial variations. Climatology studies the general atmospheric conditions in a given region for longer period of time and also variations within. It also emphasise variations in climatic conditions in different parts of the world. Hence, climatology is also considered as geography of climate. Climatology focuses on understanding the atmospheric circulations, seasonal variations in atmospheric conditions,

delineation of characteristic climatic regions, identification and classification of climate regions (zones), understanding the impact of climatic conditions of socio-economic conditions such as agriculture, industries, morphology of settlements, fishing, mining operations, aviation transport, land and water transportation, trade patterns and many more. Climatology is divided into many branches;

- 1) Physical climatology,
- 2) Regional climatology and
- 3) Applied climatology

1. Physical climatology:

Physical climatology is the most dynamic branch of climatology. It is closely associated with various weather elements and their characteristics. Physical climatology deals with weather elements such as insolation, heat budget, vertical and lateral distribution of temperature, atmospheric pressure and their distribution, wind belts and their diurnal as well as seasonal movements, humidity, precipitation, fog etc. The characteristics of these atmospheric elements have regional variations. Physical climatology deals with basic atmospheric principles of weather elements that explains physics and chemistry of weather elements.

2) Regional climatology:

Composition of weather elements differ from place to place. In fact, combination of different weather elements forms characteristic features of climate of a given region. The regional climatology tries to explain regional variations in climates and delineate climatic regions. Climatic regions can be of different spatial scales based on which climates are classified into three types; micro-climate, local climate, meso-climate and macro-climate.

Types of Climates based on spatial scales

Micro-climate	Horizontal extend up to 100 m and 1 m to 100 m vertical extent	Single crop-field, single household, area around a single tree
Local climate	Horizontal extend from 100 m to 1 km and 100 m to 1000 m vertical extent	Village, city
Meso-climate	Horizontal 100m to 20 km and up to 6000 m vertical extent	River plains, delta, Konkan coast
Macro-climate	Horizontal more than 20 km and vertical extent more than 6 km up to several hundred km	Countries, continents and global climatic conditions

3) Applied climatology

To put it simply, applied climatology is the study of how the climate affects social and natural systems. Let's also look at a few definitions provided by eminent academics. Applied climatology, as defined by H. Landsberg and W.C. Jacobs (1951), is the scientific examination of climatic data with an eye on practical applications for operational goals.

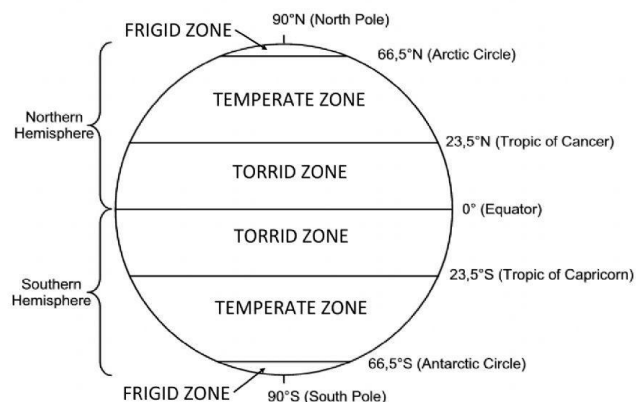
K. Smith (1987) defined applied climatology as the application of real-time and achieved meteorological data to address a range of social, economic, and environmental issues for clients and management in industries like agriculture, energy, and industry.

Climatologists are working on a significant amount of research these days, taking into account its practical elements. That being said, the discipline of applied climatology is quite new, having most likely developed between 1940 and 1950. When the effects of climate change were examined in connection to human activity, the field of applied climatology expanded even more by 1951–1960. It's also true that the climate has a big impact on how we live. It chooses the kinds of food we consume, the clothes we wear, and the homes we reside in. Humans need these three things in order to survive. Consider the snow-houses or igloos that the Eskimos of the Tundra region constructed. The extremely low temperatures there prevent the structure from melting and also keep the inside warm due to insulating property of snow.

The study of how the climate affects social and natural systems is known as applied climatology. Primary and secondary sources are the two main categories into which climate data sources can be separated. We have investigated how the five realms of natural systems are affected by climate. These spheres are always interacting, and the climate has a significant impact on the various processes that take place inside these systems. Other domains are inevitably impacted by atmospheric processes. Our social systems, including those related to agriculture, tourism, transportation, energy needs, and insurance, are all greatly impacted by the climate. Human health is significantly influenced by climate as well because the human body can only thrive in specific climate ranges.

2.9 WEATHER ELEMENTS AND CLIMATIC CONTROLS

Different weather elements such as temperature, air pressure, humidity, wind, condensation, precipitation etc. characterize the climate. In fact, climatic conditions are controlled by these elements. However, these elements of weather and climate are influenced by many factors. Following are important factors that control weather and climate.

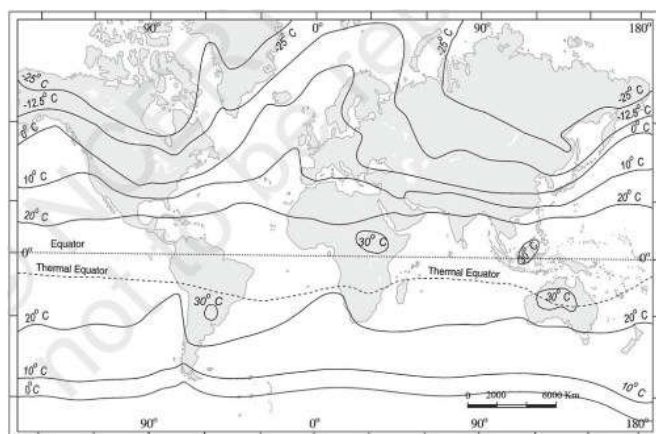


1. Longitude

Global temperatures are determined by multiple governing forces. Latitude is the first and most important. Temperatures are highest near the equator and lowest nearer the poles due to the shape of the Earth and the angle at which the sun strikes the globe. In actuality, more energy from the sun is absorbed at the equator than is emitted back into space. More energy is reflected back into space at the poles than is taken in by the sun. These two extremes are meant to be balanced by the weather and ocean currents.

2. Distribution of Land and Water

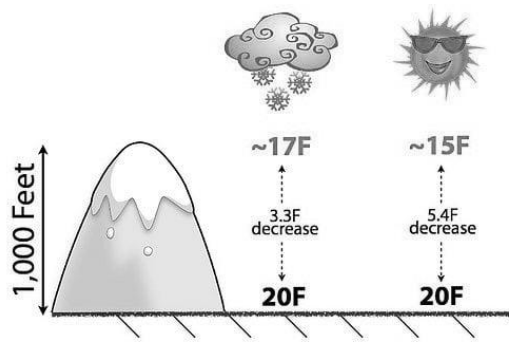
The planet's land-water distribution has an impact on temperature next. Compared to areas encircled by land, locations close to the water typically get milder year-round temperatures. This is due to the fact that the planet has a greater capacity for rapid temperature changes than the ocean. The explanation is that because light can travel across water, sunlight needs to heat a greater area in the ocean. Specific heat, the amount of energy needed to raise one degree Celsius in water, is five times more than that of landmasses. As a result, compared to land, the temperature in the area around big quantities of water changes more slowly. Another important factor regulating the planet's heat transport is ocean currents. Ocean currents circulate clockwise in the Northern Hemisphere and anti-clockwise direction in the Southern Hemisphere. Isotherms are straight over oceans whereas they are indented over land surfaces (fig.)



Distribution of surface air temperature in the month of January

3. Elevation

Elevation is the final method of temperature control. For every 1,000 feet of elevation gain, the air temperature drops by 3.6 degrees Fahrenheit (6.5 Degree Celsius) on average. This is referred to as the temperature lapse rate or the typical lapse rate. The temperature decreases with increasing elevation from mean sea level. Therefore, most of the peaks of the mountains are snow covered.



4. Moisture and Humidity:

Water molecules must take in enough energy to break their bonds with one another in order for liquid water to evaporate. The liquid water needs to take up heat and energy from its surroundings in order to accomplish this. We refer to this energy release as latent heat. The water vapor will start to vibrate quickly enough to break their molecular connections and transform into individual water molecules or gas if it absorbs enough energy. Since evaporation absorbs heat from its surroundings, it is a cooling process. Understanding latent heat is crucial, and it will be covered again later when talking about cloud formation and extreme weather.

The opposite must occur for water vapour to condense into liquid water. For fast vibrating water molecules to condense into liquid, it must release latent heat to the surrounding environment. Releasing energy allows the water molecules to slow down their vibration and attach to other water molecules to become liquid. However, one step is missing. For water vapour to become liquid, it needs something to condense onto condensation nuclei. Condensation nuclei consist of microscopic dust, smoke, salt particles, or even bacteria that float in the air. It is believed that bacteria make up nearly half of all condensation nuclei. To summarize, for water vapour to condense into small liquid or ice cloud droplets, condensation nuclei must be present.

Humidity is defined as the amount of water vapor in the atmosphere. There are several ways to classify humidity, but we will focus on relative humidity for this course. Relative humidity is the ratio of the atmosphere's actual water vapor content divided by the amount of water vapor required for atmospheric saturation at that temperature; it is usually expressed as a percentage. If the relative humidity is 25 percent, the atmosphere is only holding a quarter of what it could hold. If the relative humidity is at 100 percent, the atmosphere is saturated. There are two ways to change relative humidity: moisture content and temperature.

5. Atmospheric Pressure and Wind:

Atmospheric pressure is a force created by the weight of the atmosphere. Because of gravity, air pressure is highest at sea level and decreases with height. There is also high pressure and low pressure. High pressure, also called an anticyclone, occurs when descending air molecules "pile-up" at the surface and spread outward in a clockwise rotation in the Northern Hemisphere. In the Southern Hemisphere, the air within high pressure flows counterclockwise. In either case, the descending air will warm,

which prevents water vapour from cooling and condensing into clouds to produce storms. Instead, regions under high pressure tend to experience clear skies. Low pressure, also called a cyclone, occurs when converging air is forced upward (in a counter clock wise manner).

When atmospheric high pressure is near atmospheric pressure, there is an imbalance between the atmospheric pressure. The force to balance these two pressure imbalances is called the pressure gradient force, which creates wind. Wind is the horizontal movement of air from high pressure to low pressure to balance atmospheric pressure.

6. Atmospheric Stability:

To have cloud formation, the air must be unstable. Stable air means air does not want to rise, cool, and condense. Thus, weather conditions tend to be clear skies with stable air. Unstable air means the air wants to rise, cool, and condense into clouds and potential storms. The forces that cause air to rise are convection, orographic uplift, convergence, and weather fronts. Convection occurs when air rises, much like a hot air balloon. Because of albedo, some areas on the ground can get heated more than other areas. Where the land heats up more, the air above also warms, becomes less dense, and rises. If the air rises high enough, it may cool and condense to create clouds and possibly thunderstorms.

Orographic uplift is when mountains help destabilize air and occur when air must rise over a mountain range. As the air rises over the mountain, the moisture within it may begin to cool and condense to form thunderstorms. Often with orographic uplift, one side of the mountain will be very moist from the storms, while the other side is arid. The dry side of the mountain is called the rain-shadow effect. Later we will discuss how this process can generate what is called dry thunderstorms and wildfires.

2.10 INSOLATION AND HEAT BUDGET OF THE EARTH, TEMPERATURE - VERTICAL, HORIZONTAL AND SEASONAL VARIATIONS

Heat is a form of energy that is received by the earth from the sun. The concept of Heat Budget deals with the amount of heat energy received from the sun and its utilization in the atmosphere and the surface of the earth. This explains why the earth neither warms up nor cools down despite the huge transfer of heat that takes place.

2.11 INSOLATION

If the total insolation received at the top of the atmosphere is considered to be 100%, a certain amount of energy is reflected, scattered and absorbed while passing through Earth's atmosphere and only the remaining amount of radiation reaches the earth's surface.

- Approximately 35 units are reflected to space even before reaching the earth's surface.

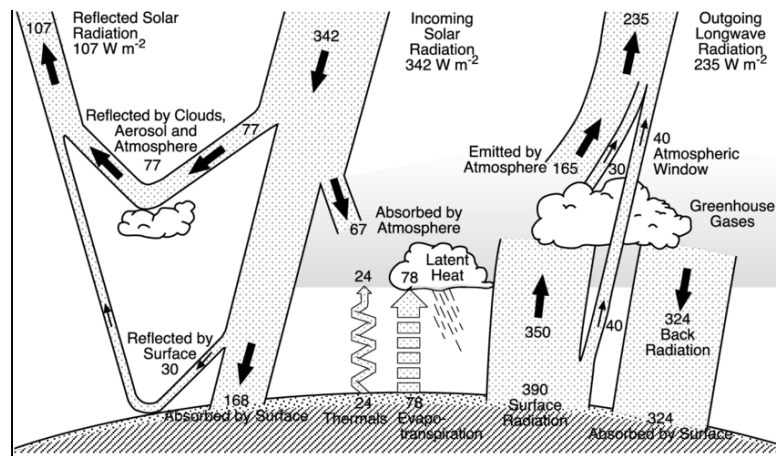
- Of these, 27 units are reflected from the top of the clouds and 2 units from the snow and ice-covered areas of the earth. The reflected amount of radiation is called the **albedo of the earth**.

The remaining **65 units** are absorbed, 14 units within the atmosphere and 51 units by the earth's surface. The earth radiates back 51 units in the form of **terrestrial radiation**.

Of these, 17 units are radiated to space directly and the remaining 34 units are absorbed by the atmosphere

The 48 units absorbed by the atmosphere (14 units from insolation + 34 units from terrestrial radiation) are also radiated back into space.

Thus, the total radiation returning from the earth and the atmosphere respectively is $17+48=65$ units which balance the total of **65 units** received from the sun.



Insolation – Insolation refers to the incoming shortwave solar radiation to the earth's surface. The processes involved with insolation in maintaining heat balance include:

- **Reflection** – Reflection occurs when incoming solar waves bounce back from a surface that it strikes in the atmosphere, on land, or water, and are not transformed into heat.
- **Absorption** – Absorption of radiation involves the conversion of electromagnetic radiation into heat energy.
- **Scattering** – Scattering of solar waves takes place when the radiation strikes small objects in Earth's atmosphere, such as air molecules or water droplets or aerosols which disperse the solar waves in all directions.

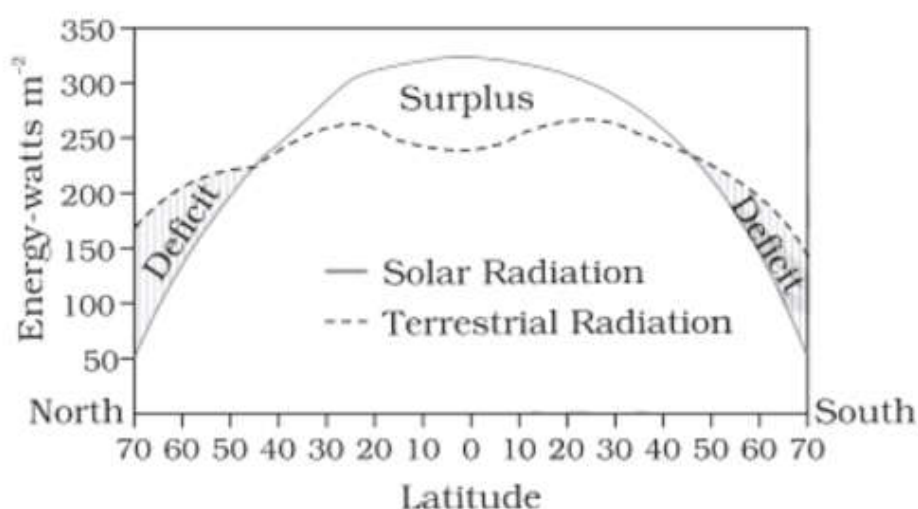
Terrestrial Radiation – Terrestrial Radiation refers to longwave radiation that is emitted by the Earth's surface or by the atmosphere. The processes involved with Terrestrial Radiation in maintaining heat balance include

- **Latent heat transfer** – It is the amount of heat transferred during the point where one substance is ready to change its state.

- Example: From solid to liquid or from liquid to gas,
- Sensible heat transfer – It is the energy that is transferred as heat to an object, without any change in the state
- Emission by vapour and clouds – Huge amounts of terrestrial radiation are also released by the water vapour and clouds.

2.12 HEAT BUDGET OF THE EARTH

A heat budget is a perfect balance between incoming heat (insolation) absorbed by the earth and outgoing heat (terrestrial radiation) escaping it in the form of radiation. If the incoming heat and the outgoing heat are not balanced, then Earth would be getting either too warmer or cooler. Since these are perfectly balanced the earth is neither too warm nor too cold. The



equilibrium that exists between the insolation (short waves) and the terrestrial radiation (long waves) is called the heat budget of the earth.

The incoming solar radiation at the surface of the Earth varies from place to place, i.e. some parts of the earth receive surplus radiation while some parts receive deficient radiation.

- There is a surplus of net radiation balance between 40°N and 40°S and the regions near the poles are in deficit.
- The surplus heat energy from the tropics gets redistributed towards the poles.
- This balance is extremely crucial as this ensures that the tropics don't get extremely heated up because of the accumulation of excess heat and the areas in high altitudes do not get permanently frozen because of deficit radiation .
- The factors that cause these variations in insolation are :
- The rotation of the earth on its axis

- The angle of inclination of the sun's rays
- The length of the day
- The transparency of the atmosphere
- The configuration of land in terms of its aspect.

2.13 TEMPERATURE OF THE ATMOSPHERE: FACTORS AFFECTING TEMPERATURE OF THE ATMOSPHERE

A substance's average heat or thermal energy is expressed as its temperature. The quantity of sunlight that the Earth's surface absorbs and the amount of heat that greenhouse gases reradiate into space influence the temperatures of the air and oceans. Regional temperature trends are shaped by the redistribution of heat across the Earth's surface via atmospheric and oceanic circulation.

Factors that Affecting Controlling Temperature Control

- The latitude of the place
- The altitude of the place
- Distance from the sea
- The air- mass circulation
- The presence of warm and cold ocean currents
- Local aspects

1. The latitude of the place

The amount of insolation received at a location determines its temperature. The temperature varies as a result of the variation in insolation according to latitude.

2. The altitude of the place

Terrestrial radiation heats the atmosphere indirectly. As a result, locations close to sea level experience warmer temperatures than those at higher altitudes. Generally speaking, the temperature drops with height. The term "normal lapse rate" refers to the pace at which temperature drops with height.

3. Distance from the sea

The location of a place in relation to the sea is the primary factor influencing its temperature. In comparison to land, the sea heats up and cool down more slowly. Rapid warming and cooling occurs on land. Thus, the water surface has a lower temperature differential than the land surface. The sea and land breezes that moderate the temperature have an impact on areas that are close to the water.

4. The air- mass circulation

The temperature is also influenced by the movement of air masses, such as sea and land winds. Locations that are affected by warm air masses have higher temperatures, whereas those that are affected by cold air masses have lower temperatures. Similarly, locations along the coast that experience warm ocean currents record greater temperatures than locations along the coast that experience cold currents.

5. The presence of warm and cold ocean currents

Warm and cold ocean currents moving in different parts of the world interact with the lower atmosphere. Warm ocean currents increases the temperature of the lower atmosphere whereas the areas dominated by cold ocean currents leads to decline in the atmospheric temperature.

6. Local aspects

Local land use, soil colour and texture, soil brightness, vegetation cover, physiographic settings etc. affects the temperature of lower atmosphere.

2.14 DISTRIBUTION OF TEMPERATURE

The temperature distribution globally can be explained in two ways:

1. Horizontal Temperature Distribution
2. Vertical Temperature Distribution

2.15 VERTICAL DISTRIBUTION OF TEMPERATURE

The atmospheric temperature changes vertically due to various factors controlling distribution of temperature. Generally, temperature decreases with increase in the altitude. However, in certain circumstances the decline in temperature with increasing altitude shows inverse trends. This sub-section attempts to discuss different form of vertical distribution of temperature.

2.16 NORMAL LAPSE RATE

Generally speaking, temperature drops as height rises. We refer to it as the typical lapse rate. Upward temperature change in the troposphere is typically roughly 6.5 °C per km, all the way to the tropopause. The term "vertical temperature gradient" is another name for this. The normal lapse rate varies based on many geographical characteristics such as latitude, height, and season. It is not constant.

2.17 INVERSION OF THE TEMPERATURE

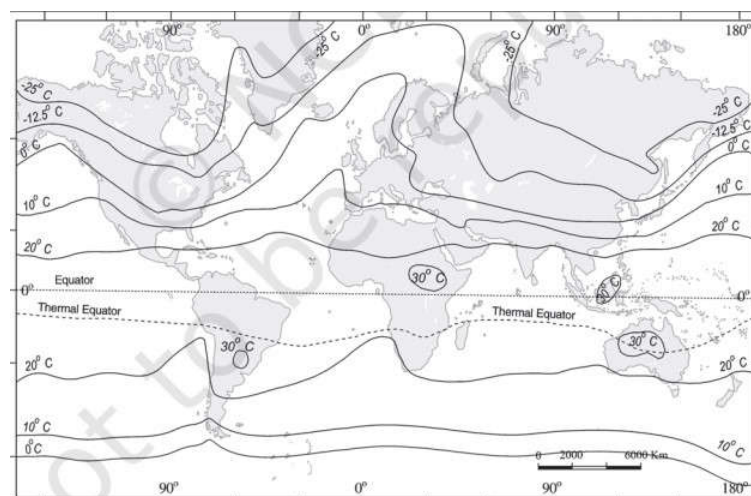
Temperature inversion is the reverse of the troposphere's typical temperature behaviour i.e. normal lapse rate. The lowest part of the atmosphere, the troposphere, rises between 6 and 10 kilometers above the

surface of the earth. The formation of clouds, precipitation, and visibility are all significantly influenced by inversions. The spread of smoke, dust, and other air pollutants will be minimal. The land surface is heated by solar radiation during the day, and air is mostly heated when it comes into contact with the heated land surface. Additionally, inversion is impacted by daily changes in air temperature. In areas with a strong low-level inversion, convective clouds are unable to reach high enough altitudes to cause showers. The accumulation of smoke and dust particles causes this. Even in the absence of clouds, visibility may be significantly reduced below the inversion. Since the air near the base of an inversion tends to be cool, fog is frequently present there. The topography has a significant impact on the magnitude of ground inversions. Temperature inversion is quite common, but it only lasts a short while. Perfect conditions for inversion include still air, long winter nights with clear skies, and inversion.

2.18 HORIZONTAL DISTRIBUTION OF THE TEMPERATURE

The term "horizontal distribution" refers to how temperatures vary across latitudes on Earth's surface. "Isotherms," or lines linking sites with equal temperatures, are a typical way for cartographers to depict the horizontal temperature distribution. The equatorial region experiences year-round high temperatures and is generally hot. In general, the temperature continues to drop from the equator toward the poles. The poles and their environs have the coldest temperatures. Since the seasonal extremes of high and low temperature are most noticeable in both the northern and southern hemispheres during these months, it is easy to study the horizontal distribution of temperature around the globe from the maps of the January and July months.

Horizontal Distribution of Temperature – January



By the end of the third week in December, the sun is above at the Tropic of Capricorn (December 21st). However, January records the highest average monthly temperature, while December does not. The whole Southern Hemisphere experiences high temperatures due to intense sun

and increased insolation. The two main continents, Africa and South America, dwindle out in the south. In contrast to the northern hemisphere, the southern hemisphere lacks a broad, substantial continent. In January, the highest average temperature in a limited region of the Western Australian desert is approximately 32 °C. At 80° N and 50° N latitudes, the average January temperature along 60° E longitude is minus 20° C. January's average monthly temperature has passed. The mean monthly temperature for January is over 27° C, in equatorial oceans over 24° C in the tropics and 2° C – 0° C in the middle latitudes and –18° C to –48° C in the Eurasian continental interior.

Horizontal Distribution of Temperature – July

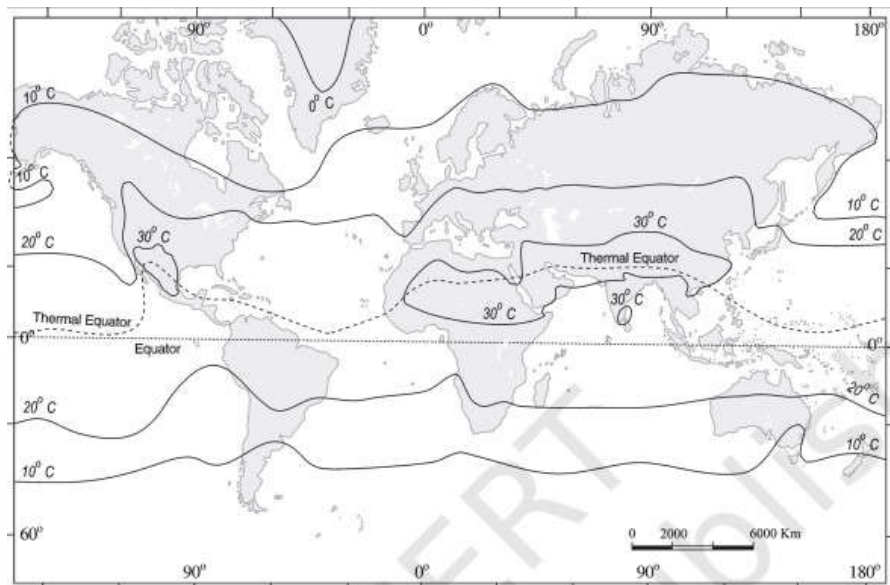
By the end of the third week of June, or June 21st, the sun is overhead at 23.5 °N, the Tropic of Cancer. However, June does not record the maximum average monthly temperature; however, July does. Bright sun and higher insolation cause high temperatures across the whole Northern Hemisphere. The 30 °C isotherm travels between latitudes 10° N and 40° N. Generally speaking, in July, the isotherms run parallel to the latitude. Higher temperatures—more than 27 °C—are recorded in the equatorial waters. South Western USA, the Sahara, Arabia, Iraq, Iran, Afghanistan, and the desert regions of India and China are among the places with this temperature. Nonetheless, summertime in the Northern Hemisphere also records the lowest temperature of 0 °C.

When a cold air mass undercuts a warm air mass and lifts it aloft, a frontal inversion occurs. When other inversions are horizontal, this kind of inversion has a considerable slope. Clouds may be present immediately above it, in addition, humidity may be high. Subtropical oceans and northern continents are the areas where subsidence inversions are common. As these areas are under large high-pressure centres, subsiding air is generally found in these regions. Inversion – Subsidence Inversion. When a widespread layer of air starts descending, it leads to subsidence inversion. The resulting increase in atmospheric pressure leads to heating and compression of atmospheric pressure. This leads to a reduction in the lapse rate of temperature. Temperature inversion is produced when the air at higher altitudes becomes warmer than lower altitudes, this happens when the air mass sinks low enough.

2.19 HEAT ENERGY TRANSFER

The heat source for our planet is the sun. Energy from the sun is transferred through space and through the earth's atmosphere to the earth's surface. Since this energy warms the earth's surface and atmosphere, some of it is or becomes heat energy. There are three ways heat is transferred into and through the atmosphere:

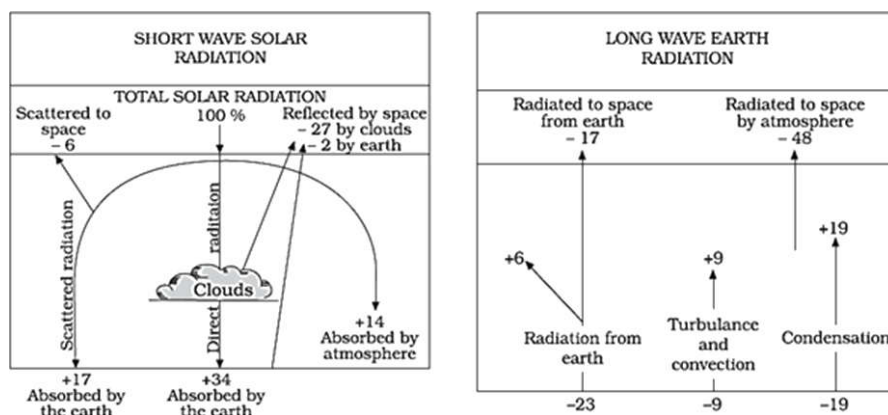
- radiation
- conduction
- convection



Radiation

If you have stood in front of a fireplace or near a campfire, you have felt the heat transfer known as radiation. The side of you nearest the fire warms, while your other side remains unaffected by the heat. Although you are surrounded by air, the air has nothing to do with this transfer of heat. Heat lamps, that keep food warm, work in the same way. Radiation is the transfer of heat energy through space by electromagnetic radiation.

Most of the electromagnetic radiation that comes to the earth from the sun is in the form of visible light. Light is made of waves of different frequencies. The frequency is the number of instances that a repeated event occurs, over a set time. In electromagnetic radiation, the frequency is the number of times an electromagnetic wave moves past a point each second.



Our brains interpret these different frequencies into colors, including red, orange, yellow, green, blue, indigo, and violet. When the eye views all these different colors at the same time, it is interpreted as white. Waves from the sun which we cannot see are infrared, which have lower frequencies than red, and ultraviolet, which have higher frequencies than violet light.

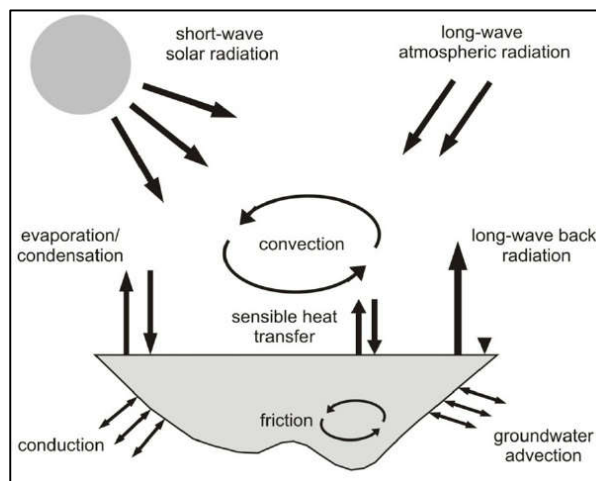
Most of the solar radiation is absorbed by the atmosphere and much of what reaches the earth's surface is radiated back into the atmosphere to become heat energy. Dark colored objects such as asphalt absorb more of the radiant energy and warm faster than light colored objects. Dark objects also radiate their energy faster than lighter colored objects.

Convection

Convection is the transfer of heat energy in a fluid. This type of heating is most commonly seen in the kitchen when you see liquid boiling.

Air in the atmosphere acts as a fluid. The sun's radiation strikes the ground, thus warming the rocks. As the rock's temperature rises due to conduction, heat energy is released into the atmosphere, forming a bubble of air which is warmer than the surrounding air. This bubble of air rises into the atmosphere. As it rises, the bubble cools with the heat contained in the bubble moving into the atmosphere.

As the hot air mass rises, the air is replaced by the surrounding cooler, more dense air, what we feel as wind. These movements of air masses can be small in a certain region, such as local cumulus clouds, or large cycles in the troposphere, covering large sections of the earth. Convection currents are responsible for many weather patterns in the troposphere.



Conduction

Conduction is the transfer of heat energy from one substance to another or within a substance. Have you ever left a metal spoon in a pot of soup being heated on a stove? After a short time the handle of the spoon will become hot.

This is due to transfer of heat energy from molecule to molecule or from atom to atom. Also, when objects are welded together, the metal becomes hot (the orange-red glow) by the transfer of heat from an arc. This is called conduction and is a very effective method of heat transfer in metals. However, air conducts heat poorly.

2.20 SUMMARY

The chapter on "Atmosphere and Climate" begins by introducing the Earth's atmosphere, explaining its composition, structure, and importance for sustaining life on the planet. It may delve into the different layers of the atmosphere, such as the troposphere, stratosphere, mesosphere, thermosphere, and exosphere, detailing their characteristics and functions. The chapter also explores the factors influencing climate, including solar radiation, the Earth's tilt and orbit, atmospheric circulation patterns, ocean currents, and greenhouse gases. It discusses the greenhouse effect and its role in regulating Earth's temperature, as well as the impact of human activities on increasing greenhouse gas concentrations and contributing to global warming and climate change. The chapter also cover various climate zones, such as polar, temperate, and tropical regions, explaining the differences in temperature, precipitation, and weather patterns between these zones.

The chapter attempted to address climate change impacts, including rising temperatures, sea-level rise, extreme weather events, biodiversity loss, and disruptions to ecosystems and human societies. Overall, the chapter provides a comprehensive overview of the Earth's atmosphere, its role in shaping climate patterns, and the current challenges and opportunities associated with climate change.

2.21 SAMPLE QUESTIONS

Q.1. Fill in the blanks.

- 1 The Earth formed approximately ----- billion years ago through the accretion of dust and gas in the early solar system (4.5).
- 2 Ozone (O₃) layer in the stratosphere, providing protection against harmful -----radiation from the Sun (ultraviolet - UV).
- 3 Nitrogen composed of about -----% of the total atmosphere's volume (78).
- 4 Elevation is the final method of temperature control. For every 1,000 feet of elevation gain, the air temperature drops by ----- Degree Celsius on average (6.5).

Q. 2. Write short notes on the following.

- 1 Origin of the atmosphere.
- 2 Inversion of the temperature
- 3 Terrestrial heat budget
- 4 Importance of Ozone layer
- 5 Heat energy transfer

Q. 3. Answer the following questions.

- 1 Discuss important theories of evolution of the earth's atmosphere.
- 2 Elaborate composition and structure of the atmosphere.
- 3 Explain lateral / horizonatal distribution of the temperature in detail.
- 4 Discuss importance of suspended particulate matter (SPM) and atmospheric vapor in atmospheric circulations.

2.22 SAMPLE QUESTIONS

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- Lal, D. (2009). CLimatology and oceanography. Allahabd: Sharda Pustak Bhavan.
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OCEANOGRAPHY

After going through this chapter, you will be able to understand the following features.

Unit Structure :

- 3.1 Objectives
- 3.2 Introduction
- 3.3 History of Oceanography
- 3.4 Classical Period: Contribution of Greeks
- 3.5 The Dark Age
- 3.6 The Golden Age of Discovery
- 3.7 Nineteenth Century – The Golden Age of Oceanography
- 3.8 Development of Oceanography on 20th Century
- 3.9 Satellite Oceanography
- 3.10 Ocean Water
- 3.11 Thermal Properties of Ocean Water
- 3.12 Major Dissolved Nutrients and Gases
- 3.13 Dissolved Gases
- 3.14 Dissolved Nutrients
- 3.15 Light and Sound Propagation in Sea Water
- 3.16 Sea Water and Ocean Water Salinity
- 3.17 Sea Water and Ocean Water Density
- 3.18 Oceanic Waves
- 3.19 Tsunami
- 3.20 World Occurrence of Tsunami
- 3.21 Types of Oceanic Waves
- 3.22 Wave Transformation
- 3.23 Tides
- 3.24 Equilibrium Theory of Tides
- 3.25 Ocean Currents – Meaning
- 3.26 Global Distribution of Ocean Currents
- 3.27 Ocean Currents in Pacific Oceans

3.1 OBJECTIVES

After learning this module, learners will be able to;

1. Understand history of oceanography.
2. Understand explorations of oceans through sea voyages and developments in oceanography.
3. Understand thermal properties of oceanic water.
4. Establish relationship between ocean water temperature and depth of the water.
5. Understand dynamics of oceanic wave generation.
6. Classify waves based on different criteria.
7. Examine equilibrium theory of tides.

3.2 INTRODUCTION

Oceanography, often referred to as marine science or oceanology, is the interdisciplinary study of the world's oceans. It encompasses a broad range of scientific disciplines, including biology, chemistry, physics, geology, and meteorology, all focused on understanding the complex interactions within Earth's oceans. From the depths of the abyssal plains to the dynamic surface currents, oceanography explores the vast and diverse marine environment that covers more than 70% of our planet's surface.

The oceans play a crucial role in regulating Earth's climate, supporting marine life, shaping coastlines, and influencing weather patterns. As such, the study of oceanography is essential for addressing pressing global challenges, including climate change, biodiversity conservation, sustainable resource management, and natural hazard mitigation.

Oceanographers utilize various tools and technologies to explore and investigate the oceans, including remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), satellite remote sensing, oceanographic buoys, and sophisticated computer models. These tools allow scientists to collect data on ocean currents, temperature, salinity, marine life, seabed topography, and other important oceanographic parameters.

Key areas of study within oceanography include:

- 1. Physical Oceanography:** Focuses on the study of ocean currents, waves, tides, and the physical properties of seawater such as temperature, salinity, and density. Physical oceanographers seek to understand the forces driving ocean circulation and their influence on climate and weather patterns.
- 2. Biological Oceanography:** Examines marine life and ecosystems, including the distribution, abundance, behavior, and physiology of organisms ranging from microscopic plankton to large marine mammals. Biological oceanographers study how marine organisms interact with their environment and respond to environmental changes.
- 3. Chemical Oceanography:** Investigates the chemical composition of seawater, including the distribution of elements, nutrients, pollutants, and gases. Chemical oceanographers study processes such as ocean acidification, nutrient cycling, and the impact of human activities on marine chemistry.
- 4. Geological Oceanography:** Focuses on the study of the ocean floor, including its composition, structure, and geological processes such as plate tectonics, seafloor spreading, and sedimentation. Geological oceanographers also investigate marine geological features such as seamounts, trenches, and hydrothermal vents.
- 5. Marine Meteorology:** Examines the interactions between the ocean and the atmosphere, including the formation of weather systems, ocean-atmosphere heat exchange, and the influence of oceanic conditions on weather patterns and climate variability.

Oceanography plays a critical role in advancing our understanding of the oceans and their interconnectedness with other Earth systems. By studying the complexities of the marine environment, oceanographers contribute valuable insights that inform policies, management strategies, and conservation efforts aimed at preserving and sustainably managing Earth's oceans for future generations.

3.3 HISTORY OF OCEANOGRAPHY

Oceans have been curiously studied since the time immemorial. Different processes and dynamics of oceans and seas have always been at the center of human curiosity. Although oceanography has been studied as an independent branch of physical geography since past few decades, various observations related to ocean floor morphology, sea waves, tides, coastal dynamics, tsunami, ocean deposits etc. have been dealt by many scholars during last many centuries now.

According to Swerdrup, an eminent geophysicist, “Our knowledge of the oceans is still fragmentary and inadequate”. There are large regions in world oceans about which we do not have detailed knowledge. Although, today with the help of improved technology, particularly geospatial

technologies, lots of information about oceans and their characteristics can be obtained and studied empirically, it is true that ancient sea voyagers like Columbus, Magellan, Vasco de Gama and many others have made significant contribution to the study of oceanography despite of having limited resources and technology. Therefore, it is important to discuss the development of oceanography since historical times. Let us have a brief look into the historical perspective of development of oceanography over the period.

3.4 CLASSICAL PERIOD – CONTRIBUTION OF THE GREEKS

Greeks and Romans have contributed to the study of oceanography during classical period. Aristotle was one of the early contributors of oceanography. He has elaborated the interactions between ocean and the atmosphere. He also explained the atmospheric phenomena like evaporation, condensation and precipitation as important processes involved in hydrological cycle. Eratosthenes, Pytheas, Strabo, Seneca, Ptolemy were among the early contributors.

3.5 THE DARK AGE

This period was dominated by Arab invaders after the fall of Roman Empire in Mediterranean region. Huge amount of knowledge generated by Greeks and Roman philosophers has been degenerated to a large extent. During this period, some explorations for new world were organized in Scandinavian region. Many sea voyages took place in Atlantic Ocean. Vikings explored Iceland. The development of Oceanography had slowed down during the medieval period.

3.6 THE GOLDEN AGE OF DISCOVERY

This period includes the age of discoveries from A.D. 1492 to 1522. Several adventurous sea voyages have been organized in different parts of the world in search of new lands. Conducting sea voyages were difficult during those times as ships were small and ships had to depend largely upon the direction and velocity of winds. No compass or other equipments were available. Europeans went across the Pacific and Atlantic oceans. There was a great contribution of Spanish and Portuguese sea voyagers. Bartholomeu Diaz successfully sailed around Cape of Good Hope in 1486. Columbus undertook his voyage to east India and crossed Atlantic Ocean when he discovered America. Vasco de Gama continued his voyage to India in 1498. F. Magellan carried out his adventurous voyage in Pacific Ocean in 1519.

The search for scientific knowledge about the oceans has started in early sixteenth century. Captain Cook was the first who took voyage for studying physical nature of the ocean. He was the first to navigate across Antarctic Ocean. He circled the entire globe twice by sailing through oceans.

3.7 NINETEENTH CENTURY – THE GOLDEN AGE OF OCEANOGRAPHY

Oceanography started as developing as a scientific subject in 19th century different voyages where Undertaker to investigate physical biological and chemical properties of the ocean. The morphology of sleep floor, ocean currents, tides and other properties of the ocean have been explore and analysed by different eminent Oceanographers across the world. Hence, oceanography has started as a separate branch of science. US exploring expeditions by Charles Wilkies, Charles Darwin, Matthew Maury and Wivillie Thomson have contributed a lot in development of scientific Oceanography. Charles Wilkes started his expedition in 1838 in different parts of Atlantic Ocean. Matthew Maury was the first to write a book on the physical geography of the sea in 1855 which is considered as milestone in the development of Oceanography. Charles Darwin was an eminent scientist who took part in many sea wvoyages. A major contribution of Charles Darwin is in the observation of Aquatic flora and fauna in the oceans. Based on his observations, Charles Darwin has wrote or popular book titled “The origin of Species” where he propounded theory of “natural selection”. John Ross started his voyage to Antarctica from 1839 to 1843 and measured the ocean depth of 7Km. He found the similarity in the animals of cold waters of Antarctic and Arctic oceans. Under the leadership of Wyville Thompson, the director of expedition, left England in Challenger ship in December 1872. This is one of the most important sea voyages in 19th century. Challenger expedition covered the sea distance of 127,500 km. This expedition identified the deepest trench in the Pacific Ocean Popularly known as ‘Mariana Trench’.

3.8 DEVELOPMENT OF OCEANOGRAPHY IN 20TH CENTURY

There has been a significant developments in the field of Oceanography in 20th century. The scientific study of oceans including accurate knowledge of ocean floor morphology, structure, ocean deposits, ocean water dynamics, etc. were studied in detail through various expeditions of 20th century. This century has improved Technology and developed modern equipments for exploring Ocean characteristics. Meteor, a popular German explorer, practically did expeditions from 1925 to 1927. He gathered the data about different depths in the oceans by using eco sounder. US based NOAA has done pioneering work on discovering oceanic resources. Under the umbrella of The World Meteorological Organizations, several scientific organisations were developed to study oceans in detailed through various instruments and equipments. Developments in equipments such as winches, water samplers, bottom samplers, fathometers led to understanding of oceans with more details.

3.9 SATELLITE OCEANOGRAPHY

Remote Sensing technology has made significant developments in almost every field of spatial sciences. After establishment of NASA in 1958, different satellite missions including SeaSat, OceanSat and many more have made revolutionary developments in the field of oceanography. NASA, ISRO and other leading Space Research Organizations in the world have made significant contribution to the development of scientific oceanography particularly related to the spatio-temporal patterns of ocean dynamics.

3.10 OCEAN WATER

Ocean water occupies over 97 percent of the total water on the earth. Ocean water provides habitat for billions of flora and fauna in world's largest aquatic ecosystem. Ocean waters are used for navigation purpose, production of salts, fishing etc. The detailed information about different characteristics such as Ocean water temperature, Salinity, density, dissolved nutrients and gases etc. is given in subsequent sections.

3.11 THERMAL PROPERTIES OF OCEAN WATER

Understanding patterns of ocean water temperature is of great importance from geographical point of view because three fourth of the total earth surface is covered with ocean surface. All physical, chemical and biological properties of ocean water are influenced by temperature of ocean water.

The temperature of ocean water has significant impact on formation and movement of ocean currents. Therefore, temperature of the ocean water play significant role in maintaining equilibrium in heat budget of the earth. Ocean water has a characteristic feature that it get worms slowly and cool down slowly. This unique property of the ocean water also called atmospheric circulation in the lower atmosphere. There are two sources of heat in the ocean water. Firstly, absorption of solar radiation and secondly conventional current produced in the ocean due to internal heat of the earth. Besides, ocean water heated due to conversion of kinetic energy into heat energy (due to sea waves), heat in the ocean water is also produced by chemical and biological processes, condensation of water vapour on the sea surface also lead to change in the temperature of the ocean water and radioactive disintegration in the sea water also radiates significant heat in the ocean water.

The patterns of distribution of ocean water temperature are complex. Generally, temperature of the ocean water decreases from equatorial region to polar belts gradually. In equatorial region, the average ocean water temperature is about 27 Degrees Celsius whereas it is - 1.8 Degrees Celsius in Polar Regions. The sea surface temperature in Southern Hemisphere is relatively less than that of Northern Hemisphere mainly due to vast and thick snow cover in Antarctic had cooling effect on ocean

waters. There is a noticeable difference in the ocean water temperature in different oceans at different latitudinal regions.

Table – Average Sea Surface Temperature in different latitudes

Lat. (degrees)	Northern Hemisphere			Southern Hemisphere		
	Atlantic ocean	Indian ocean	Pacific ocean	Atlantic ocean	Indian ocean	Pacific ocean
0-10	26.66	27.88	27.20	25.18	27.41	26.01
10-20	25.81	27.23	26.42	23.16	25.85	25.11
20-30	24.16	26.14	23.38	21.20	22.53	21.53
30-40	20.40	--	18.62	16.90	17.00	16.98
40-50	13.16	--	9.99	8.68	8.67	11.16
50-60	8.66	--	5.74	1.76	1.63	5.00
60-70	5.66	--	--	-1.30	-1.50	-1.30

Global patterns of sea surface temperature clearly depicts that maximum temperature is recorded along the equatorial regions with the range of 25.18 Degree Celsius (Atlantic Ocean) to 27.88 Degree Celsius (Indian Ocean). However in polar latitudes, the sea surface temperatures are found to be near freezing point except in the North Atlantic Ocean (5.66 Degree Celsius). Spatial patterns of sea surface temperature are controlled by solar radiation, latitudes, wind motions, planetary wind circulations, atmospheric pressure belts, local conditions, land and water masses etc.

Table – Annual sea surface temperature in Northern Hemisphere
(Degree Celsius)

Latitude	Equator	10°	20°	30°	40°	50°
Oceans	2.3	2.4	3.6	5.9	7.5	5.6
Continents	1.3	3.3	7.2	10.2	14.0	24.4

The variation in average annual sea surface temperature increases from equatorial regions to polar belts. Interestingly, variation in sea surface temperature is found to be less over oceans as compared to continents. Diurnal and seasonal range of sea surface temperature is largely influenced by incoming solar radiation, nature of ocean currents and prevailing winds.

Vertical Distribution of the sea water temperature

Generally, the boundary starts at 100 to 400 meters below the surface and goes up to hundreds of meters below. Thermocline is that region of the boundary where the rapid reduction in the temperature begins. Usually, approximately 90% of the ocean water lies beneath the thermocline. As we move towards this zone, the temperature reaches closer to 0-degree Celsius. Across the low and middle latitudes, the ocean's temperature

structure can be categorized into 3 layers. These layers start at the surface and end at the bottom of the ocean.

1st layer: It showcases the topmost layer of ocean water that is warm and about 500 meters thick. The temperature of this layer can vary between 20 to 25-degree Celsius. Tropical oceans have this layer all year. However, this layer is evident only in the summer in the oceans that lie in the middle **latitude**.

2nd layer: This layer falls below the top layer and is known as the thermocline layer. A quick fall in temperature is noted with increasing depth here. The thermocline layer is generally 500 to 1000 meters thick.

3rd layer: This layer falls below the 2nd layer and is usually quite cold. In the Antarctic and Arctic region, the temperatures are usually close to 0-degree Celsius even at the surface. Therefore, the temperature varies slightly with the increase in the depth. In these areas, only one cold layer is formed from the top (surface water) to the bottom (ocean floor).

There is a steady decrease in the ocean water temperature with increasing depth. However, below certain depth, sea water temperature remains constant.

3.12 MAJOR DISSOLVED NUTRIENTS AND GASSES

Seawater is composed of different gasses and nutrients in dissolved forms. Different gases are found in the atmosphere, and can enter the ocean by dissolving into the water at the ocean's surface. But the amount of each gas in air is very different from the amount found in the ocean. For instance, the percentage of Nitrogen in the atmosphere is 78% whereas on the ocean surface it is merely 48%. The composition of Carbon dioxide and Oxygen in the ocean water are 6% and 83% respectively. Dissolved nutrients are probably the most important property of seawater in terms of its effect on life in the oceans. The most critical of these nutrients are nitrogen and phosphorus because they play a major role in stimulating primary production by plankton in the oceans. Let us discuss the importance of these elements in the ocean water in detail.

3.13 DISSOLVED GASSES

Seawater has many different gases dissolved in it, especially nitrogen, oxygen and carbon dioxide. It exchanges these gases with the atmosphere to keep a balance between the ocean and the atmosphere. This exchange is helped by the mixing of the surface by wind and waves. Dissolved oxygen and carbon dioxide are vital for marine life. Marine plants use dissolved carbon dioxide, sunlight and water to make carbohydrates through the process of photosynthesis. This process releases oxygen into the water. All marine organisms use oxygen for respiration, which releases energy from carbohydrates and has carbon dioxide and water as byproducts. Marine animals with gills, such as fish, use these organs to extract oxygen from the seawater.

Variation in dissolved gases

Some of the properties of seawater affect how much gas can be dissolved in it:

- Cold water holds more gas than warm water. You will have seen this with bottles of fizzy drink, which are basically carbon dioxide in water. A warm fizzy drink cannot hold its gas, so as soon as you open a bottle of it, the carbon dioxide leaves the water in a big spray of bubbles. It is less messy to open a cold bottle of fizzy drink.
- Seawater with low salinity holds more gas than high salinity water.
- Deep water, which has a high pressure, holds more gas than shallow water.

The use and creation of dissolved gases by living things can over-ride the effect of these properties. For example, warm water with lots of plankton in it can hold more carbon dioxide than cold water with few living things in it.

3.14 DISSOLVED NUTRIENTS

Probably the most important property of seawater in terms of its effect on life in the oceans is the concentration of **dissolved nutrients**. The most critical of these nutrients are nitrogen and phosphorus because they play a major role in stimulating primary production by plankton in the oceans. These elements are known as limiting because plants cannot grow without them. However, there are a number of other nutrients that also play a role, including silicon, iron, and zinc. Nutrients in the ocean are cycled by a process known as biological pumping, whereby plankton extract the nutrients out of the surface water and combine them in their organic matrix. Then, when the plants die, sink and decay, the nutrients are returned to their dissolved state at deeper levels of the ocean. The abundance of nutrients determines how fertile the oceans are. A measure of this fertility is the primary production, which is the rate of fixation of carbon per unit of water per unit time. Primary production is often mapped by satellites using the distribution of chlorophyll, which is a pigment produced by plants that absorbs energy during photosynthesis. The distribution of chlorophyll is shown in the figure above. You can see the highest abundance close to the coastlines, where nutrients from the land are fed in by rivers. The other location where chlorophyll levels are high is in upwelling zones, where nutrients are brought to the surface ocean from depth by the upwelling process.

Another critical element for the health of the oceans is the **dissolved oxygen** content. Oxygen in the surface ocean is continuously added across the air-sea interface as well as by photosynthesis; it is used up in respiration by marine organisms and during the decay or oxidation of organic material that rains down in the ocean and is deposited on the ocean bottom. Most organisms require oxygen, thus its depletion has adverse effects for marine populations. Temperature also affects oxygen levels, as warm waters can hold less dissolved oxygen than cold waters.

This relationship will have major implications for future oceans, as we will see.

The final seawater property we will consider is the content of **dissolved CO²**. CO² is nearly opposite to oxygen in many chemical and biological processes; it is used up by plankton during photosynthesis and replenished during respiration as well as during the oxidation of organic matter. As we will see later, CO² content has importance for the study of deep-water aging.

3.15 LIGHT AND SOUND PROPAGATION IN SEA WATER

Sound travels well through water, and this makes possible the remote sensing of objects and the transmission of information. Light travels only relatively short distances through water, and the greater part of the oceans is almost completely dark. When light propagates through water, its intensity decreases exponentially with distance from the source. The exponential loss of intensity is called attenuation and it is caused by absorption and scattering. Underwater visibility depends on contrast, which is a function partly of object brightness or reflectivity and partly of attenuation with distance. Water preferentially absorbs longer wavelengths of the electromagnetic spectrum, which is why water appears blue. Sound travels much more slowly than light through water but can travel much further, and so is used for remote sensing and communication in the oceans. The speed of sound in seawater increases as the axial modulus of seawater increases, and decreases as the density increases. Sound intensities decrease with distance from the source because of two processes: spreading loss and attenuation. Acoustic oceanography experiments make use of the effect of temperature and other properties on the speed and attenuation of sound in seawater, to detect and monitor relatively short-term changes within and between water masses on scales ranging from microstructure to whole ocean basins.

3.16 SEA WATER AND OCEAN WATER SALINITY

Salinity means the total content of dissolved salts in Sea or Ocean. Salinity is calculated as the amount of salt dissolved in 1,000 gm of seawater. It is generally expressed as 'parts per thousand' (ppt). A salinity of 24.7 ‰ has been regarded as the upper limit to fix 'brackish water'. It is a significant factor in deciding several characteristics of the chemistry of natural waters and biological processes.

Dissolved Salts in Sea water (gm of salts per Kg of sea water)

Chlorine	Sodium	Sulphate	Magnesium	Calcium
18.97	10.47	2.65	1.28	0.41
Potassium	Bicarbonate	Bromine	Borate	Strontium
0.38	0.14	0.06	0.02	0.01

Important Salts in the sea water:

- Sodium chloride — 77.7%
- Magnesium chloride—10.9%
- Magnesium sulphate — 4.7%
- Calcium sulphate — 3.6%
- Potassium sulphate — 2.5%

Factors affecting salinity of sea water:

- Salinity, temperature, and density of water are interconnected. The salinity of water in the surface layer of oceans is influenced by:
- Evaporation
- Precipitation

In the coastal regions, the surface salinity is influenced by the freshwater flow from rivers.

In the Polar region, the surface salinity is influenced by the processes of freezing and melting of ice.

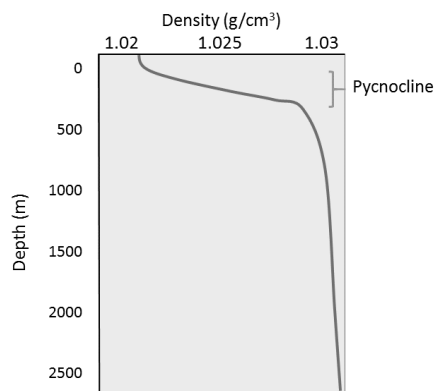
The wind also influences the salinity of an area by moving water to other areas.

The ocean currents contribute to the salinity variations.

The change in the density or temperature influences the salinity of water in an area.

3.17 SEA WATER AND OCEAN WATER DENSITY

The density of pure water is 1000 kg/m^3 . Ocean water is more dense because of the salt in it. Density of ocean water at the sea surface is about 1027 kg/m^3 . There are two main factors that make ocean water more or less dense than about 1027 kg/m^3 : the temperature of the water and the salinity of the water. Ocean water gets more dense as temperature goes down. So, the colder the water, the more dense it is. Increasing salinity also increases the density of sea water.



Less dense water floats on top of more dense water. Given two layers of water with the same salinity, the warmer water will float on top of the colder water. There is one catch though! Temperature has a greater effect on the density of water than salinity does. So a layer of water with higher salinity can actually float on top of water with lower salinity if the layer with higher salinity is quite a bit warmer than the lower salinity layer.

The temperature of the ocean decreases and decreases as you go to the bottom of the ocean. So, the density of ocean water increases and increases as you go to the bottom of the ocean. The deep ocean is layered with the densest water on bottom and the lightest water on top. Circulation in the depths of the ocean is horizontal. That is, water moves along the layers with the same density.

The density of ocean water is rarely measured directly. If you wanted to measure the density of ocean water, you would have to collect a sample of sea water and bring it back to the laboratory to be measured. Density is usually calculated using an equation. You just need to measure the salinity, temperature and pressure to be able to find density. These measurements are often made with a CTD instrument, where the instrument is placed in the ocean water from a ship or a platform.

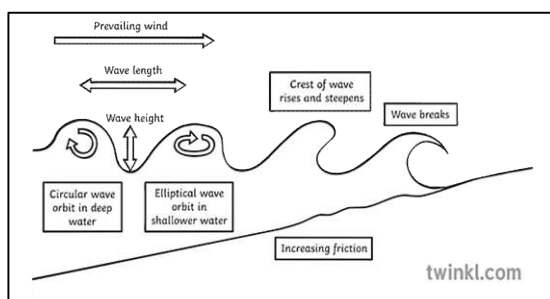
3.18 OCEANIC WAVES

Ocean waves (swell) are formed by transferring energy from the motion of atmospheric wind to the ocean surface and releasing a certain amount of energy to the shoreline, causing erosion and accretion of coastal landforms for long-term scale (Kaliraj et al., 2014).

Characteristics of oceanic waves

Wave characteristics

- Crest: the highest point of a wave
- Trough: the lowest point of a wave
- Height: the distance between a wave's crest and trough
- Amplitude: the distance between the crest or the trough to the still water line in between
- Period: the time between successive swell crests
- Frequency: the number of waves that cross a fixed point in a given amount of time



Causes of oceanic Wave formation

Waves are most commonly caused by wind. Wind-driven waves, or surface waves, are created by the friction between wind and surface water. As wind blows across the surface of the ocean or a lake, the continual disturbance creates a wave crest.

The ocean is never still. Whether observing from the beach or a boat, we expect to see waves on the horizon. Waves are created by energy passing through water, causing it to move in a circular motion. However, water does not actually travel in waves. Waves transmit energy, not water, across the ocean and if not obstructed by anything, they have the potential to travel across an entire ocean basin.

Waves are most commonly caused by wind. **Wind-driven waves**, or **surface waves**, are created by the friction between wind and surface water. As wind blows across the surface of the ocean or a lake, the continual disturbance creates a wave crest. These types of waves are found globally across the open ocean and along the coast.

More potentially hazardous waves can be caused by severe weather, like a hurricane. The strong winds and pressure from this type of severe storm causes storm surge, a series of long waves that are created far from shore in deeper water and intensify as they move closer to land. Other hazardous waves can be caused by underwater disturbances that displace large amounts of water quickly such as earthquakes, landslides, or volcanic eruptions. These very long waves are called tsunamis. Storm surge and tsunamis are not the types of waves you imagine crashing down on the shore. These waves roll upon the shore like a massive sea level rise and can reach far distances inland.

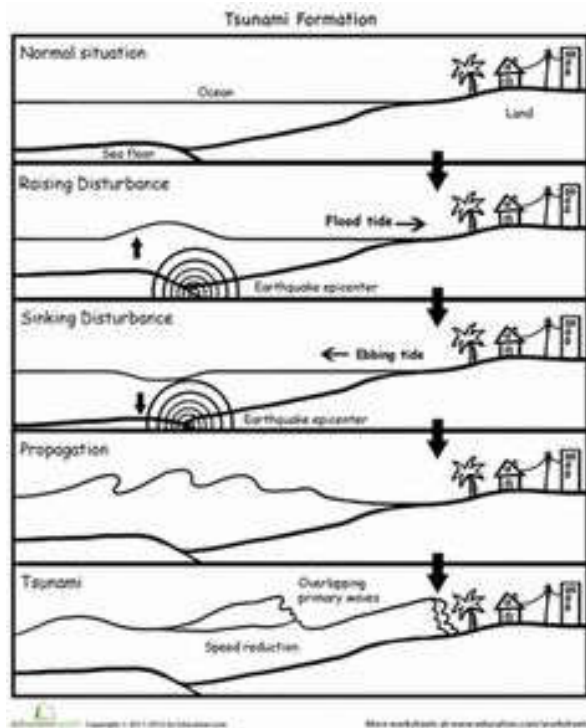
The gravitational pull of the sun and moon on the earth also causes waves. These waves are tides or, in other words, **tidal waves**. It is a common misconception that a tidal wave is also a tsunami. The cause of tsunamis are not related to tide information at all but can occur in any tidal state.

3.19 TSUNAMI

How tsunamis are formed. A tsunami is a wave that spreads in the sea and is caused by an underwater earthquake, a landslide, a volcanic eruption or the fall of a meteorite. As the first cause is the most frequent one, we will focus on unravelling underwater earthquakes. The vast majority of earthquakes occur in faults.

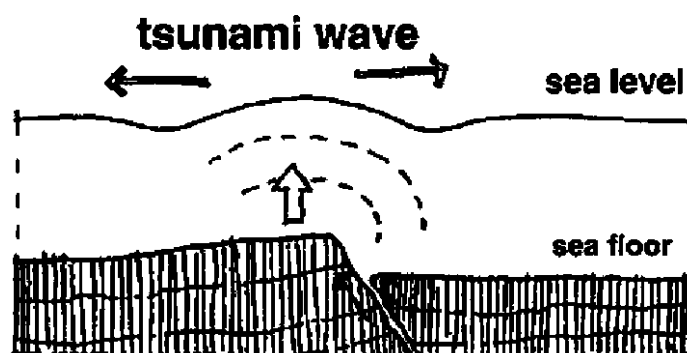
What happens is that the two portions of the earth's crust separate, where one side slips over to the other side. That slide can be completely vertical, which literally means the fall of one of the sides of the fault, totally horizontal or something intermediate. In order for an underwater earthquake to cause a tsunami, the movement must have a vertical component; if it is totally horizontal it will not occur.

The movement of the fault is so fast that the "step" that occurs on the ocean floor is instantly reflected on the surface of the sea, which deforms just like the bottom. We all know that a "step" in the water is not stable, the surface tends to recover horizontality. The higher water descends and vice versa, giving rise to a series of waves that propagate in all directions from the site of the earthquake: the tsunami.



Tsunami Characteristics

Most tsunamis are caused by a rapid vertical movement along a break in the Earth's crust (i.e., their origin is tectonic). A tsunami is generated when a large mass of earth on the bottom of the ocean drops or rises, thereby displacing the column of water directly above it. This type of displacement commonly occurs in large subduction zones, where the collision of two tectonic plates causes the oceanic plate to dip beneath the continental plate to form deep ocean trenches. Most subduction occurs along most of the island arcs and coastal areas of the Pacific, the notable exception being the west coast of the United States and Canada. Movement along the faults there is largely strike-slip, having little vertical displacement, and the movement produces few local tsunamis.



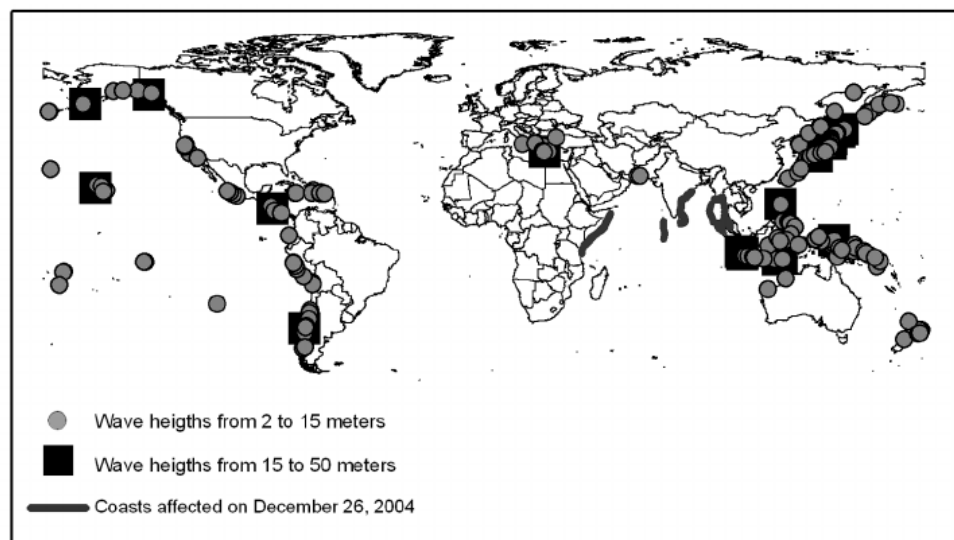
Volcanoes have generated significant tsunamis with death tolls as large as 30,000 people from a single event. Roughly one fourth of the deaths occurring during volcanic eruptions where tsunamis were generated, were the result of the tsunami rather than the volcano. A tsunami is an effective transmitter of energy to areas outside the reach of the volcanic eruption itself. The most efficient methods of tsunami generation by volcanoes include disruption of a body of water by the collapse of all or part of the volcanic edifice, subsidence, an accompanying or preceding the eruption. Roughly one-half of all volcanic tsunamis are generated at calderas or at cones within calderas. Submarine eruptions may also cause minor tsunamis.

Locally destructive tsunamis may be generated by subaerial and submarine landslides into bays or lakes. Lituya Bay, Alaska, has been the site of several landslide-generated tsunamis, including one in 1958 that produced a splash wave that removed trees to a height of 525 m. It also caused a tsunami of at least 50 m in the bay. The 1964 Prince William Sound earthquake triggered at least four submarine landslides, which accounted for 71 to 82 of the 106 fatalities in Alaska for the 1964 event. However, it is tectonic earthquake-generated tsunamis (those produced by a major deformation of Earth's crust) that may affect the entire Pacific Basin.

Other possible but less efficient methods of tsunami generation include: strong oscillations of the bottom of the ocean, or transmission of energy to a column of water from a seismic impulse (e.g., a deep-focus earthquake that has no surface rupture); transmission of energy from a horizontal seismic impulse to the water column through a vertical or inclined wall such as a bathymetric ridge; strong turbidity currents; underwater and above-water explosions. Several mechanisms commonly are involved in the generation of a tsunami (e.g., vertical movement of the crust by a seismic impulse or an earthquake, and a submarine landslide).

3.20 WORLDWIDE OCCURRENCE OF TSUNAMIS

Worldwide Occurrence of Tsunamis



Tsunamis have been reported since ancient times. They have been documented extensively, especially in Japan and the Mediterranean areas. The first recorded tsunami occurred off the coast of Syria in 2000 B.C. Since 1900 (the beginning of instrumentally located earthquakes), most tsunamis have been generated in Japan, Peru, Chile, New Guinea and the Solomon Islands. However, the only regions that have generated remote-source tsunamis affecting the entire Pacific Basin are the Kamchatka Peninsula, the Aleutian Pacific.

The Mediterranean and Caribbean Seas both have small subduction zones, and have histories of locally destructive tsunamis. Only a few tsunamis have been generated in the Atlantic Ocean. In the Atlantic Ocean, there are no subduction zones at the edges of plate boundaries to spawn such waves except small subduction zones under the Caribbean and Scotia arcs.

In the Indian Ocean, the Indo-Australian plate is being subducted beneath the Eurasian plate at its east margin. On December 26, 2004, an earthquake off the coast of northern Sumatra generated a tsunami that was recorded nearly world-wide and killed more people than any other tsunami in recorded history. More than 227,899 people were either killed or listed as missing and presumed dead and 1,126,900 were displaced by the earthquake and subsequent tsunami. The estimated economic losses exceed \$10 billion. The devastating megathrust earthquake of December 26th, 2004 occurred on the interface of the India and Burma plates and was caused by the release of stresses that develop as the India plate subducts beneath the overriding Burma plate. The India plate begins its descent into the mantle at the Sunda trench which lies to the west of the earthquake's epicenter. The trench is the surface expression of the plate interface between the Australia and India plates, situated to the southwest of the trench, and the Burma and Sunda plates, situated to the northeast.

3.21 TYPES OF OCEANIC WAVES

Water waves are formed by the interaction between the earth, moon and the sun. Also, the wind blowing across the surface of water bodies like rivers and oceans is the reason for the formation of water waves.

Wind waves: The most common type of waves are the wind waves, where the wind transfers a lot of energy when it comes in contact with the surface of the water, forming ripples in lakes and waves in oceans. The more substantial the wind causes, the larger the waves.

Tidal waves: Tidal waves are the wind waves that arise due to the gravitational force between the moon and the earth. The ocean water stays in its place because of the earth's gravity, but the moon's gravity pulls the ocean water on the planet, which causes the waves to sway up and down. This happens when the moon is closer to the side of the Earth. This is termed as high tide, and the other part of the earth where the moon is not comparable is termed low tide.

Underwater explosions: This is one more reason why waves are formed. Huge waves like tsunamis are produced due to underwater earthquakes in the oceans. Also, volcanoes, landslides, and meteors are other underwater explosions resulting in enormous destructive waves.

There are basically three types of water waves: sea waves of seismic origin (tsunamis), swell waves, and wind surges.

Ocean Wave Characteristics

- **Wave crest and trough:** The peak and bottom-most points of a wave are termed the crest and trough, respectively.
- **Wave amplitude:** One-half of the wave height is termed wave amplitude.
- **Wave height:** The vertical distance from the top of a crest to the bottom of a wave trough is called wave height.
- **Wave period** is simply the time break between two consecutive wave crests or troughs as they pass a fixed point.
- **Wavelength:** The horizontal distance between two successive crests.
- **Wave speed:** The rate at which a wave travels through the water; wave speed is measured in knots.
- **Wave frequency:** During the time interval of one second, the total number of waves passing through a given point.

3.22 WAVE TRANSFORMATION

When the waves approach the shoreline, they are affected by the seabed through processes such as refraction, shoaling, bottom friction and wave-breaking. However, wave-breaking also occurs in deep water when the waves are too steep. If the waves meet major structures or abrupt changes in the coastline, they will be transformed by diffraction. If waves meet a submerged reef or structure, they will overtop the reef. These phenomena will be further explained in the following. The following types of wave transformation occur mainly in connection with ports and the like. If the waves meet a steep structure, reflection will take place, and if the waves meet a permeable structure, partial transmission will take place.

The following is a summary of the transformation types to be found in nature.

Refraction

Depth-refraction is the turning of the direction of wave propagation when the wave fronts travel at an angle with the depth contours at shallow water. The refraction is caused by the fact that the waves propagate more slowly in shallow water than in deep water. A consequence of this is that the wave fronts tend to become aligned with the depth contours. Currents can also result in refraction and this is termed current refraction.

Diffraction can be seen when there are sheltering structures such as breakwaters. Diffraction is the process by which the waves propagate into the lee zone behind the structures by energy transmittance laterally along the wave crests.

Shoaling

Shoaling is the deformation of the waves, which starts when the water depth becomes less than about half the wavelength. The shoaling causes a reduction in the wave propagation velocity as well as shortening and steeping of the waves.

Bottom friction

Bottom friction causes energy dissipation and thereby wave height reduction as the water depth becomes more and more shallow. Friction is of special importance over large areas with shallow water.

Depth-induced wave-breaking

Depth-induced wave-breaking of individual waves starts when the wave height becomes greater than a certain fraction of the water depth. As a rule of thumb, the wave height of an individual wave at breaking is often said to be around 80% of the water depth, but this is a very approximate figure. Breaking waves are generally divided into three main types, depending on the steepness of the waves and the slope of the shoreface:

Spilling takes place when steep waves propagate over flat shorefaces. Spilling breaking is a gradual breaking which takes place as a foam bore on the front topside of the wave over a distance of 6–7 wavelengths.

Plunging is the form of breaking where the upper part of the wave breaks over its own lower part in one big splash whereby most of the energy is lost. This form of breaking takes place in cases of moderately steep waves on moderately sloping shorefaces.

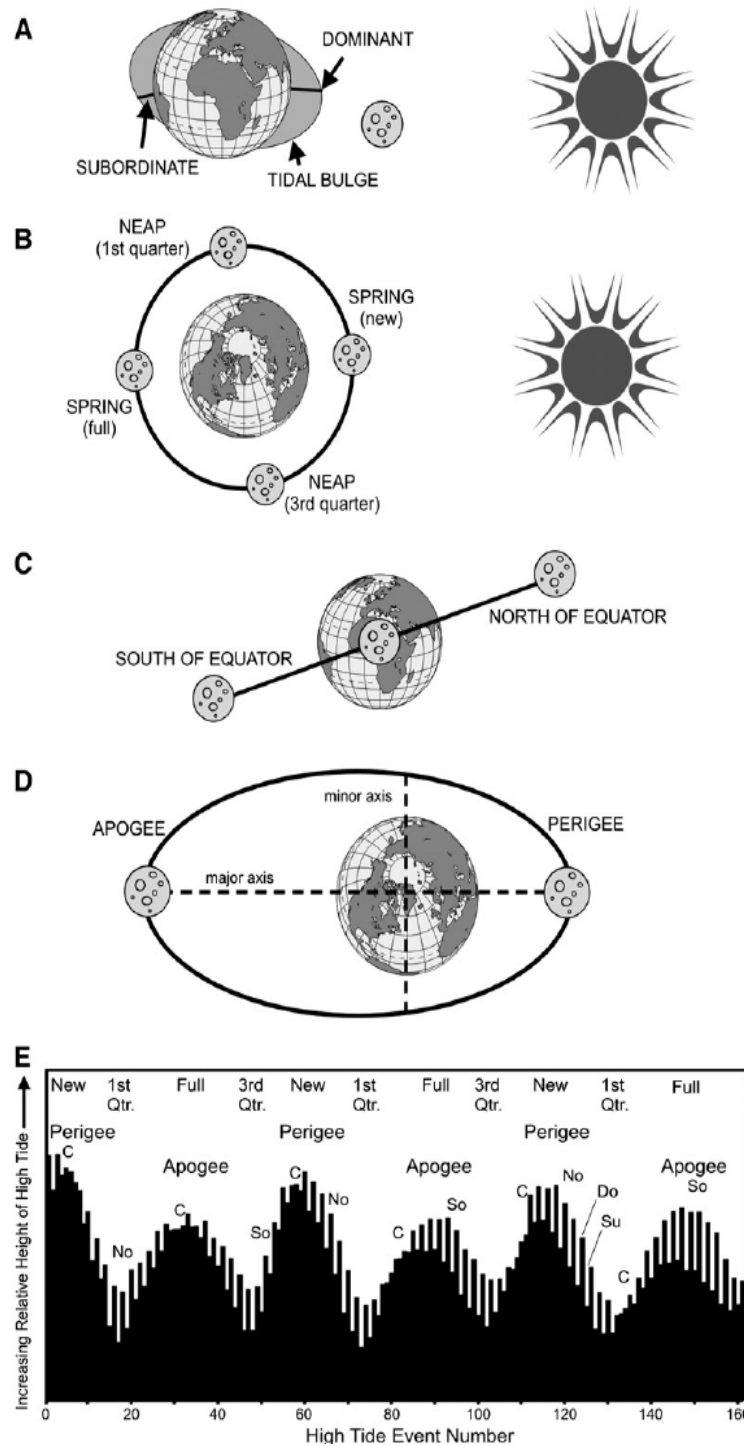
Surging is when the lower part of the wave surges up on the foreshore in which case there is hardly any surf-zone. This form of breaking takes place when relatively long waves (swell) meet steep shorefaces.

3.23 TIDES

Tide refer to as 'any of the cyclic deformations of one astronomical body caused by the gravitational forces exerted by others'. The most familiar are the periodic variations in sea level on Earth that correspond to changes in the relative positions of the Moon and the Sun. The tides may be regarded as forced waves, partially running waves and partially standing waves. They are manifested by vertical movements of the sea surface (the height maximum and minimum are called high water [HW] and low water [LW]) and alternating horizontal movements of the water, the tidal

currents. The words ebb and flow are used to designate the falling tide and the rising tide, respectively.

3.24 EQUILIBRIUM THEORY OF TIDES



Until now we have been referring to tides on an imaginary earth that is totally covered in water and has no land masses/ continents. This is the basis for the Equilibrium Tide theory. The Equilibrium tide theory is defined as the elevation of the sea surface that would be in equilibrium with the tide forces if the earth were covered with water to such a depth

that the response to these forces is instantaneous. In reality this has no resemblance to the real tides, and the rise and fall predicted by it are too small compared to observed tides. This is however an important reference system for tidal analysis.

The dynamic theory/ real tide on the other hand, represents the tide as a wave “forced” by the tide-producing forces, and the rise and fall on the coast as a result of flow convergence or divergence. In theory, it allows calculations of tidal flows in the ocean, and the rise and fall on the shores. However, the real ocean basins have very complicated coastal and bottom topography and it is not possible to obtain exact solutions, except in the open sea.

There are several important factors that modify the movement of water in real tide situations:

1. **The Sun/Moon:** The moon’s gravitational effect is greater than that of the suns due to it’s closer proximity to the Earth, but acting sometimes in conjunction with the sun and sometimes in opposition it varies the amplitude and timing of the tides.
2. **Geography:** Land masses obviously impede and deflect movement of water on the Earth’s surface.
3. **Friction:** Friction retards the movement of water particles across the Earth’s surface – (the movement of tides across it is gradually slowing down the rotational speed of the Earth.)
4. **Basin Oscillation:** All bodies of water have natural periods of oscillation determined by their size and shape. All oceans are made up of a number of oscillating basins. The resultant oscillations at any one place affect the tidal movement or wave form depending upon the degree of resonance with the astronomic tidal curve.
5. **Lunar and Terrestrial Orbits:** The shape and plane of both the Earth’s orbit around the Sun and the moon’s orbit around the Earth are such that the distance between these bodies, their gravitational effect, varies continuously in cycles of months, years and even longer periods.
6. **The Earth’s Orbit:** is in the form of an eccentric ellipse (eg or pear shaped). At perihelion the Earth is 91.3 million miles and at aphelion it is 94.5 million miles away from the sun respectively.
7. **The Earth’s Declination/ Tilt:** 23° 27’ off the vertical, hence the declination of the relative position of the sun and the moon as they appear to revolve around the Earth.
8. **The Moon’s Orbit:** Also an eccentric ellipse with a varying apogee and perogee.

The Equilibrium theory explained above describes two bulges moving around the Earth from east to west at a steady rate. Their range would be

0.5m at the equator. This is not exactly what happens with the observed tides. The theoretical explanation of diurnal tides does not agree with the observations either. So why not?

The main reason for this complicated response to the tidal forcings is the fact that the land divides the world's waters into oceans, seas, gulfs etc. of different size, shape and depth. The only latitudes for the unimpeded circumpolar movement are around Antarctica and in the Arctic.

In addition, the water movements are affected by the rotation of the Earth. The Coriolis effect (which we will come to later) causes the water to take a curved path rather than a straight one and Kelvin waves produce different tidal ranges across channels. The best example of this is that of the English Channel where the French coast experiences a much larger tidal range than the British side

Natural Resonance

The various bodies of water have their individual natural periods of oscillation. This influences their response to the tide-raising force. The Pacific Ocean has, in general, a natural period of oscillation of about 25 hours, making it resonant to the diurnal components of the tide raising forces, so the tides tend to be diurnal there. The natural period of oscillation of the Atlantic is about 12.5 hours making it resonant to the semi-diurnal components and so the tides in that ocean are mainly semi-diurnal. Pacific tides are observed to have much more diurnal characteristics in general than Atlantic tides. There are also seas that have a natural period of oscillation that makes them unresponsive to either diurnal or semi-diurnal forces, these are known as non-tidal waters. Good examples of non-tidal waters are: Eastern Mediterranean, Baltic, Black and Caspian Seas

Coriolis and Friction.

Coriolis and friction are linked an understanding of both is important to understanding water movement. Newton's law of motion applies only when all measurements are made with respect to an inertial coordinate system, that is, one that is neither accelerating nor rotating. However the Earth is rotating and so allowances need to be made for this. This is done by providing two "fictitious forces", the centrifugal force and the Coriolis force. The centrifugal force is conveniently combined with the Earth's gravitational force (G) in what we commonly refer to as "gravity" (g).

The Coriolis force is rarely noticeable in laboratory-scale measurements, but it is very significant in large-scale geophysical motions such as winds, ocean currents and tides. In the upper wind driven layers of water bodies a balance is achieved between wind-stress, Coriolis force and pressure gradient field. The Coriolis force arises through relative motion on the rotating Earth and is proportional to the relative velocity and the sine of the latitude. It acts at right angles to the velocity, to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. The

Coriolis force without pressure gradients arising may balance the wind-stress. Thus a strong wind-stress leads to a strong Coriolis force.

Coriolis force acts in both the vertical and horizontal plane, but we will consider only the horizontal component. Imagine the earth to be covered with a frictionless film, the surface of which conforms to that of a level surface, ie is everywhere normal to the direction of gravity. As a body (or surface layer of water) moves to a higher latitude, the easterly velocity of the earth's surface decreases and so the easterly velocity of the body relative to the Earth increases. This is seen as an acceleration to the left in the Southern Hemisphere and an acceleration to the right in the Northern Hemisphere.

Now we need to ask the question, how does water move? Another major component of water movement is friction. But first we need to look at wind-stress.

The major current systems of the ocean are driven by the wind acting on the surface. The direct effect of the wind-stress is transmitted only to limited depth by viscosity and turbulence. The main surface current systems of the Atlantic and Indian oceans are in the form of large gyres that occupies most of the width of the ocean and are clockwise in the Northern hemisphere and anti-clockwise in the southern hemisphere. The Coriolis force is responsible for these circular patterns, deflecting both the winds and the currents driven by the winds.

The frictional forces that affect a particle in the ocean are:

1. **internal friction**, due mainly to eddy viscosity, which in shallow seas is often negligible compared with
2. **external friction**, due to stresses at the surface and at the sea-bed.

In 1905 V.W. Ekman, a Swedish mathematician and oceanographer, observed that icebergs in the Arctic ice pack were drifting at an angle to the direction of the wind. Ekman showed theoretically that the effect of wind blowing steadily over an ocean of infinite depth, extent and uniform eddy viscosity is to drive the surface layer at an angle $\pm 45^\circ$ to the left of the wind direction in the Southern Hemisphere (to the right in the Northern Hemisphere) and to move the successive deeper layers of water more and more to the left until at a given depth the direction of the motion of water is opposite to that at the surface. In addition to the motion being directed more and more to the left (in the Southern Hemisphere), the speed of the motion decreases with depth, due to friction.

3.25 OCEAN CURRENTS: MEANING

Movement of ocean water is an important form ocean water dynamics. Oceans are never static. Different kinds of movements take place in ocean continuously. Sea waves, tides and ocean currents are important movements of sea water. Ocean currents refer to as the general movement of mass of surface water in a fairly defined direction. Ocean currents may

be defined as any persistent and dominantly horizontal flow of ocean water. Unlike oceanic waves, ocean currents comprise not only surface waters but also the movement of water up to the depth of 1000 meters. Hence ocean currents are considered to be the most extensive type of ocean water movements.

Ocean currents are the continuous, predictable, directional movement of seawater driven by gravity, wind (Coriolis Effect), and water density. Ocean water moves in two directions: horizontally and vertically. Horizontal movements are referred to as currents, while vertical changes are called upwellings or downwellings. This abiotic system is responsible for the transfer of heat, variations in biodiversity, and Earth's climate system (National Geographic). Ocean Current is a horizontal movement of seawater that is produced by gravity, wind, and water density. Ocean currents play an important role in the determination of climates of coastal regions. The streams of water that flow constantly on the ocean surface in definite directions are called ocean currents.

Ocean currents are one of the factors that affect the temperature of ocean water. The magnitude of the ocean currents ranges from a few centimeters per second to as much as 4 meters (about 13 feet) per second. The intensity of the ocean currents generally decreases with increasing depth. The speed of ocean currents is more than that of upwelling or downwelling which are the vertical movements of ocean water.

Dynamics of ocean currents:

Horizontal pressure-gradient forces, Coriolis forces, and frictional forces are important forces that cause and affect ocean currents.

Rise and fall of the tide

Tides give rise to tidal currents. Near the shore, tidal currents are the strongest. The change in tidal currents is periodical in nature and can be predicted for the near future. The speed of tidal currents at some places can be around 8 knots or more.

Wind

The ocean currents at or near the ocean surface are driven by wind forces. The process is called Thermohaline Circulation. 'Thermo' stands for temperature and 'Haline' stands for salinity. The variations in temperature and salinity at different parts of the oceans create density differences which in turn affect the ocean currents. The movement of water through the oceans is slowed by friction, with surrounding fluid moving at a different velocity. A faster-moving layer of water and a slower-moving layer of water would impact each other. This causes momentum transfer between both layers producing frictional forces. When the pressure gradient force on the ocean current is balanced by the Coriolis forces, it results in the geostrophic currents.

- The direction of geostrophic flow is parallel to an isobar.
- The high pressure is to the right of the flow in the Northern Hemisphere, and the high pressure to the left is found in the Southern Hemisphere.

North and South Equatorial Currents

1. North Equatorial Current

- North Equatorial Current flows from east to west in the Pacific and the Atlantic Ocean.
- North Equatorial Current flows between the latitudes of 10 degrees and 20 degrees north.
- It is not connected to the equator.
- Equatorial circulation separates this current between the Pacific and Atlantic oceans.

2. South Equatorial Current

- It flows in the Pacific, Atlantic, and Indian oceans.
- The direction of the south equatorial current is east to west.
- The latitudes in which the current flows are between the equator and 20 degrees south.
- It flows across the equator to 5 degrees north latitudes in the Pacific and Atlantic Oceans.

3.26 GLOBAL DISTRIBUTION OF OCEAN CURRENTS

The ocean currents flowing across the globe are distributed in Atlantic, Pacific and Indian oceans. Major ocean currents in the world are given below.

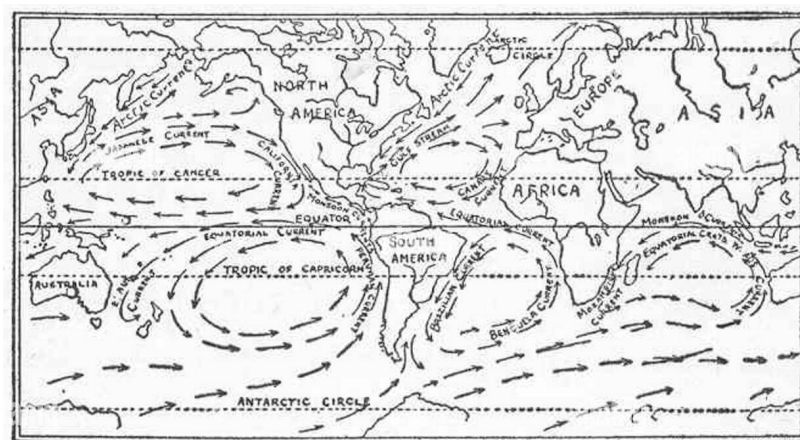
Ocean Currents in Atlantic Ocean	
Angola Current	Warm
Antilles Current	Warm
Benguela Current	Cold
Brazil Current	Cold
Cape Horn Current	Cold
Carribean Current	Warm
Falkland Current	Cold
Florida Current	Warm
North Atlantic Current	Warm

South Atlantic Current	Cold
Ocean Currents in Indian Ocean	
Agulhas Current	Warm
Leeuwin Current	Warm
Mozambique Current	Warm
West Australian Current	Cold
Ocean Currents in Pacific Ocean	
Alaska Current	Warm
Humboldt Current	Cold
Kamchatka Current	Cold
Kuroshio Current	Warm
North Pacific Current	Warm

3.27 OCEAN CURRENTS IN PACIFIC OCEAN

Pacific Ocean is the largest ocean on planet earth. The movement of ocean currents in Pacific Ocean is mostly along the coastal areas. The distribution of ocean currents in Pacific Ocean is divided into three sections;

1. Currents in Mid-Pacific Ocean
2. Currents in North Pacific Ocean
3. Currents in South Pacific Ocean



THE GREAT OCEAN CURRENTS

1. Currents in Mid-Pacific Ocean:

- a) **North Equatorial currents:** This current of the Pacific Ocean runs from west coast of Mexico and flows towards the east and continue up

to Philippines. The transportation of water in this current is more than other currents in Atlantic and Indian oceans in equatorial regions. Near Mexico, this current is added to California Current.

- b) South Equatorial current:** This current is present on both sides of the equator. The formation of this current is caused by south-east trade winds. This current covers a total distance of about 13600 kms in south Pacific Ocean. Numerous small ocean currents meet this current on its left margin.
- c) Equatorial counter current:** It flows between north and south equatorial currents. It continues to flow from west to east throughout the year. It is interesting to note that this current always flows in northern hemisphere. During north summer the current velocity reaches to 100 cm/sec.

2. Currents in North Pacific Ocean:

Kurioshio currents is in fact is the extension of north Equatorial Current. In the Western part of the Pacific ocean, the North Equatorial Current bifurcates one joins counter current and one flows to Philippines. The one which flows along the north coast of Philippines is called Kuroshio current. Tsushima is warm current which generate on the left side of Kurioshio current. Oyashio, North Pacific, Aleutian, California currents are important currents flowing in North Pacific Ocean.

3. Currents in South Pacific Ocean:

Peru current, East Australia current and West wind drift are important currents flowing in South Pacific Ocean. Peru current is cold current that flows along west coast of South America from South to North. It is also called as Humboldt current. This current originates near Antarctica. The cold waters in Antarctica is carried by westerlies toward east. It bends near west coast of South America and then flows towards north. In January-March, Equatorial counter current is displaced to south. Due to this warm waters flowing along the coast of Equador converges with Peru Current. This south flowing current is refer to as “El Nino current”.

3.28 OCEAN CURRENTS IN ATLANTIC OCEAN

Currents in North Atlantic Ocean include North Equatorial Current, The Equatorial Counter Current, Florida Current, Gulf stream, North Atlantic Drift The Canaries Current and the Labrador current. South Atlantic Ocean include South Equatorial current, Brazil current, Falkland current, South Atlantic current, Benguela current.

3.29 OCEAN CURRENTS IN INDIAN OCEAN

Because of peculiar geographical location the Indian ocean is entirely different from the Pacific and Atlantic ocean currents. Northern part of the Indian ocean is different from other parts of it. North India ocean is under

the influence of Indian monsoon. In southern part of Indian Ocean anti-cyclonic system of current is present.

The Winter Monsoon Drift, South Monsoon Drift are important ocean currents in North Indian Oceans whereas the South Equatorial Current, , Madagascar current, Mozambique current are dominant in South Indian Ocean.

3.30 SUMMARY

The study of oceanography aims at discussing mysteries and complexities of Earth's oceans. Throughout this chapter, we have discussed the vastness of the oceanic realm, exploring its dynamic processes, intricate ecosystems, and vital role in shaping our planet's climate and environment. From the ocean's role in regulating temperature and weather patterns to its significance in supporting biodiversity and sustaining life on Earth, it is clear that the oceans hold a crucial place in the intricate web of global systems.

Through the lens of oceanography, we have gained insights into the interconnectedness of Earth's geophysical, biological, and chemical processes, highlighting the importance of interdisciplinary approaches in understanding and managing our marine environments. Moreover, as we confront pressing environmental challenges such as climate change, pollution, and overexploitation of resources, the knowledge gained from oceanographic research becomes ever more pertinent in informing sustainable practices and policies to safeguard our oceans for future generations.

As we continue to explore the depths of our oceans and expand our understanding of this vast and mysterious realm, it is essential to recognize the inherent value of preserving and protecting these invaluable ecosystems. By fostering collaboration, innovation, and stewardship, we can strive towards a future where our oceans thrive in harmony with human activities, ensuring the well-being of both marine life and coastal communities. In essence, oceanography serves not only as a scientific discipline but also as a beacon guiding us towards a more sustainable and resilient relationship with the world's oceans.

3.31 SAMPLE QUESTIONS

Q.1. Fill in the blanks.

- 1 Sea surface temperature is minimum at ----- (poles).
- 2 Most of the oceanic waves are ----- driven (wind).
- 3 ----- waves are the wind waves that arise due to the gravitational force between the moon and the earth(Tidal).
- 4 Brazil ocean current is ----- type of ocean current (cold).

Q. 2. Write short notes on the following.

- 1 Salinity of ocean water.
- 2 Ocean water density
- 3 Types of tides
- 4 Ocean currents
- 5 Vertical distribution of ocean water temperature

Q. 3. Answer the following questions.

- 1 Discuss distribution of ocean water temperature.
- 2 Critically examine equilibrium theory of tides.
- 3 What is tsunami? Explain causes and effects of tsunami waves..
- 4 Elaborate types and characteristics of ocean currents.

3.32 REFERENCES FOR FURTHER READING

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HYDROLOGY

After going through this chapter, you will be able to understand the following features.

Unit Structure :

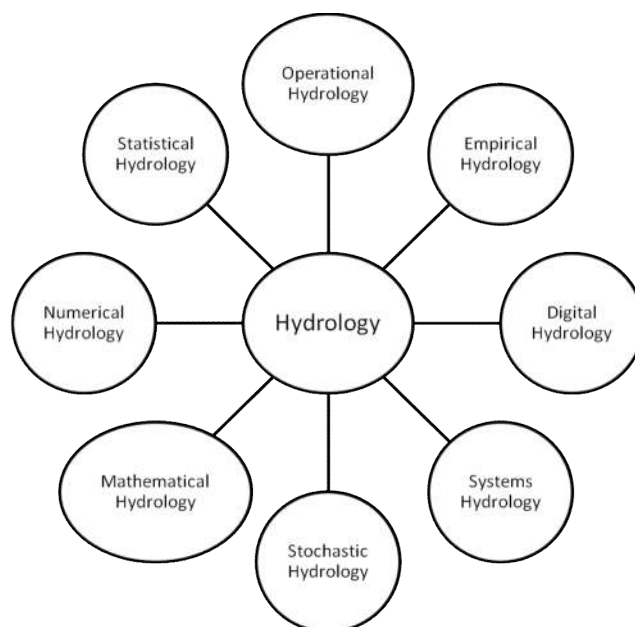
- 4.1 Objectives
- 4.2 Introduction
- 4.3 Hydrological Cycle
- 4.4 Earth's Water Balance
- 4.5 Scientific Approaches to Understand Dynamics of Water Balance
- 4.6 Concept of Watershed
- 4.7 Watershed Delineation
- 4.8 Energy Input and Output of Watershed
- 4.9 Watershed Characteristics
- 4.10 Precipitation
- 4.11 Mean Rainfall Over Drainage Basin
- 4.12 Precipitation Calculation Methods
- 4.13 Characteristics of Rain- Storms
- 4.14 Rainfall Run-Off Control
- 4.15 Forms of Sub Surface Water
- 4.16 Summary
- 4.17 Sample Questions
- 4.18 References For Further Reading

4.1 OBJECTIVES

After learning this module, learners will be able to;

1. Understand processes involved in hydrological cycle.
2. Compute precipitation using different methods.
3. Understand characteristics of rain-storm.
4. Establish relationship between rainfall runoff and infiltration.
5. Understand different forms of subsurface water.
6. Compare different branches of hydrology.
7. Compare between confined and un-confined aquifers.

The concept of hydrology is derived from two words; Logia means study, and hydro means water. Thus, the study of water can be broadly characterized as hydrology. The following is a definition that is more useful: The science of hydrology is the study of the space-time properties of the earth's water quantity and quality, including its occurrence, transport, distribution, circulation, storage, exploration, development, and management. The relationship between water and the earth determines these features. A wide range of academic fields, including agriculture, biology, chemistry, geography, geology, glaciology, meteorology, oceanography, physics, and volcanology, are included in the definition of hydrology. The intimate relationship that water has with the ground and atmosphere has allowed many disciplines of hydrology to stand forth.



1. Operational Hydrology:

Operational hydrology is a branch of hydrology that focuses on the practical aspects of managing water resources. It involves the monitoring, analysis, and prediction of various hydrological phenomena to support decision-making in water-related activities such as flood forecasting, reservoir management, irrigation scheduling, and water supply planning. Operational hydrology heavily relies on the collection of hydrological data from various sources such as stream gauges, weather stations, satellite imagery, and remote sensing technologies. This data includes information on precipitation, evaporation, streamflow, groundwater levels, soil moisture, and snowpack. Hydrological data undergoes rigorous analysis and modeling to understand the behavior of water systems. Mathematical models, including hydrological models and hydraulic models, are used to simulate the movement of water within watersheds, rivers, reservoirs, and other water bodies. These models help in predicting future water levels, flow rates, and other hydrological variables under different scenarios. Forecasting is a critical aspect of operational hydrology,

especially in mitigating the impacts of extreme weather events such as floods and droughts. Advanced forecasting techniques, including statistical methods, numerical weather prediction models, and ensemble forecasting, are employed to predict future hydrological conditions with increasing accuracy and lead time.

2. Empirical Hydrology:

Empirical hydrologic studies depend on monitoring the various water processes within selected drainage basins, which may often be designated either representative or experimental. Empirical approach to hydrology takes into consideration, the empirical observations and field investigations with the help of modern technologies and machineries.

3. Digital Hydrology

Digital hydrology is a burgeoning field that leverages advanced technologies and computational methods to understand, model, and manage water resources. It integrates hydrological principles with data-driven approaches, transforming the way we perceive, analyze, and respond to water-related challenges. This note delves into the significance of digital hydrology and its impact on water management. Digital hydrology relies heavily on data acquisition from various sources such as remote sensing, IoT sensors, satellite imagery, and ground-based monitoring stations. These data, often in large volumes and diverse formats, are processed using advanced algorithms and computational techniques to extract meaningful insights about water cycles, precipitation patterns, soil moisture, and river flow dynamics.

4. Systems Hydrology

Systems hydrology is an interdisciplinary field that focuses on understanding the movement, distribution, and quality of water within various interconnected natural and human-made systems. It integrates principles from hydrology, ecology, climatology, geology, geography, and engineering to analyze and manage water resources effectively. Systems hydrology studies the hydrological cycle, which describes the continuous movement of water on, above, and below the surface of the Earth. This cycle includes processes such as evaporation, condensation, precipitation, infiltration, runoff, and groundwater flow.

5. Mathematical hydrology

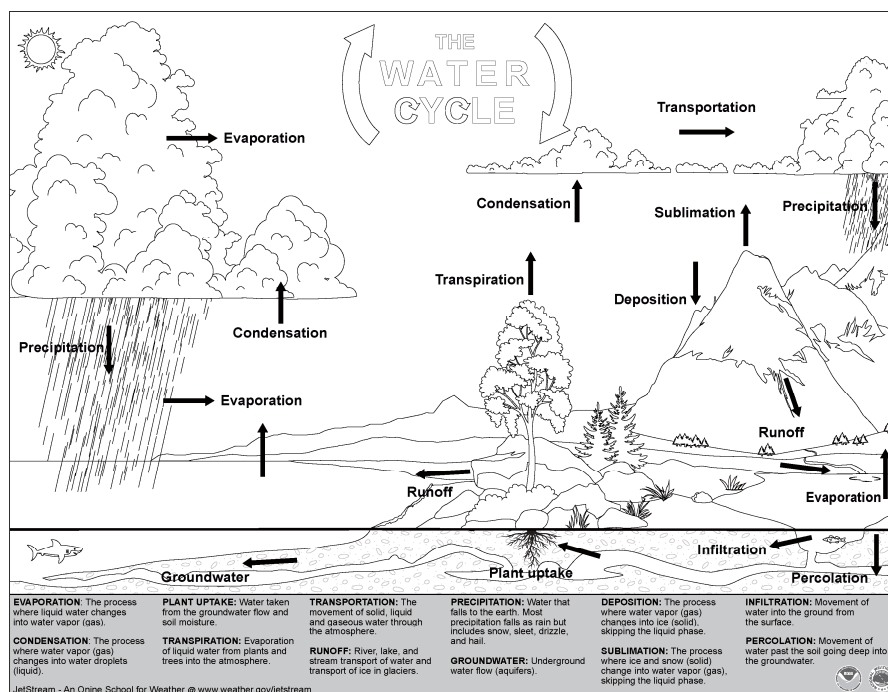
Mathematical modeling of hydrology is employed to address a wide spectrum of environmental and water resources problems. A historical perspective of hydrologic modeling is provided, and new developments and challenges in watershed models are discussed. These include data acquisition by remote sensing and space technology, digital terrain and elevation models, chemical tracers, geographic information and data management systems, topographic representation, upscaling of hydrologic conservation equations, spatial variability of hydraulic roughness, infiltration and precipitation, spatial and temporal scaling, model calibration, and linking with water quality models. Model construction,

calibration, and data processing have received a great deal of attention, while model validation, error propagation, and analyses of uncertainty, risk, and reliability have not been treated as thoroughly. Finally, some remarks are made regarding the future outlook for watershed hydrology modeling.

4.3 HYDROLOGICAL CYCLE

The hydrologic cycle involves the continuous circulation of water in the Earth-Atmosphere system. At its core, the water cycle is the motion of the water from the ground to the atmosphere and back again. Of the many processes involved in the hydrologic cycle, the most important are:

- Evaporation
- Transpiration
- Condensation
- Precipitation
- Runoff



1. Evaporation

Evaporation is the change of state in a substance from a liquid to a gas. In meteorology, the substance we are concerned about the most is water. For evaporation to take place, energy is required. The energy can come from any source: the sun, the atmosphere, the Earth, or objects on the Earth such as humans.

Everyone has experienced evaporation personally. When the body heats up due to the air temperature or through exercise, the body sweats,

secreting water onto the skin. The purpose is to cause the body to use its own heat to evaporate the liquid, thereby removing heat and cooling the body. The same effect can be seen when you step out of a shower or swimming pool. The coolness you feel is the removal of body heat through evaporation of the water on your skin.

2. Transpiration

Transpiration is the evaporation of water from plants through stomata. Stomata are small openings found on the underside of leaves that are connected to vascular plant tissues. In most plants, transpiration is a passive process largely controlled by the humidity of the atmosphere and the moisture content of the soil. Of the transpired water passing through a plant only 1% is used in the growth process of the plant. The remaining 99% is passed into the atmosphere.

3. Condensation

Condensation is the process whereby water vapor is changed into a liquid state. In the atmosphere, condensation may appear as clouds or dew. This is also the process whereby water appears on the side of an uninsulated cold drink can or bottle. Condensation is not a matter of one particular temperature but of a difference between two temperatures: the air temperature and the dewpoint temperature. The dew point is the temperature at which dew can form - it is the point at which air becomes saturated and can not hold any more water vapor. Any additional cooling causes water vapor to condense. Foggy conditions often occur when air temperature and dew point are equal.

4. Precipitation

Precipitation results when tiny condensation particles, through collision and coalescence, grow too large for the rising air to support, and thus fall to the Earth. Precipitation can be in the form of rain, hail, snow, or sleet. Precipitation is the primary way we receive fresh water on Earth. On average, the world receives about 38½" (980 mm) each year over both the oceans and land masses.

5. Runoff

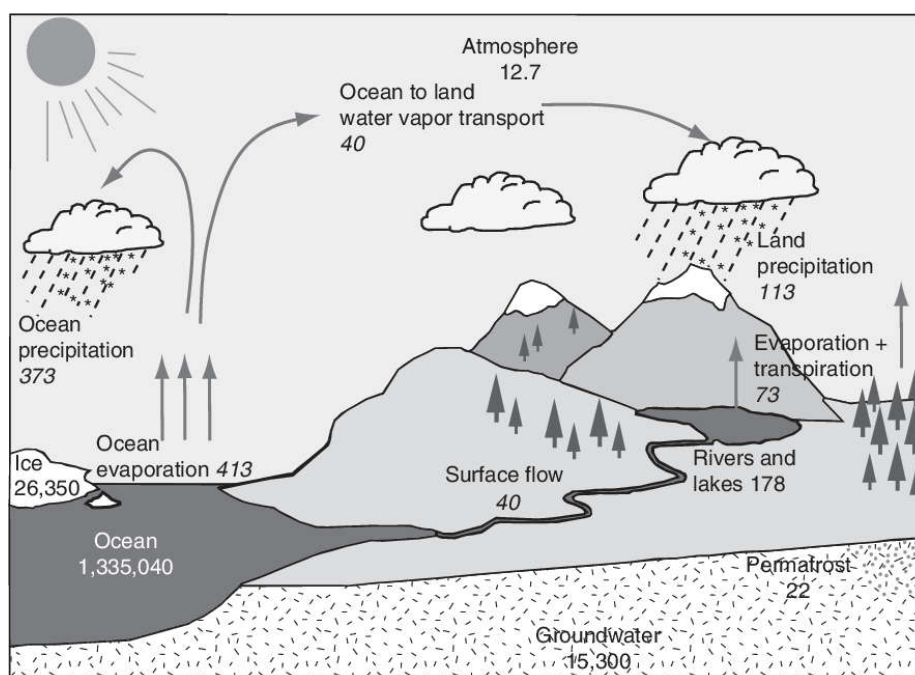
Runoff occurs when there is excessive precipitation and the ground is saturated (cannot absorb any more water). Rivers and lakes are results of runoff. Some runoff evaporates into the atmosphere, but most water in rivers and lakes returns to the oceans. If runoff water flows into a lake only with no outlet for water to flow out, then evaporation is the only means for water to return to the atmosphere. As water evaporates, impurities or salts are left behind. As a result, the lake becomes salty, as in the case of the Great Salt Lake in Utah or Dead Sea in Israel.

Evaporation of this runoff into the atmosphere begins the hydrologic cycle over again. Some of the water percolates into the soil and into the ground water only to be drawn into plants again for transpiration to take place.

Condensation is the opposite of evaporation. Since water vapor has a higher energy level than that of liquid water, when condensation occurs, the excess energy in the form of heat energy is released. This release of heat aids in the formation of hurricanes.

4.4 EARTH'S WATER BALANCE

Also referred to as the hydrologic cycle, the natural water balance represents the endless recirculatory transport process that constantly moves water between the earth's storage reservoirs – the land, the oceans and the atmosphere. Water moves constantly between the reservoirs through the following major processes.



Precipitation is all the moisture that reaches the earth's surface in the form of rain, snow, sleet and hail. The precipitation reaching the earth's surface is then dispersed by the three main processes of evapotranspiration, overland runoff, and groundwater infiltration.

Groundwater Infiltration describes the movement of rainwater that infiltrates into surficial soils and percolates down through pores and cracks in soil and rock. Water remaining in the shallow soil is taken up by plants while water that percolates deeper may ultimately contribute to groundwater aquifers. Depending on subsurface hydraulic gradients, water can also move upwards or horizontally towards the surface and discharge to a water body as baseflow.

Surface Runoff is made up of precipitation and snowmelt in excess of the absorptive capacity of surface soils and the depression storage capacity of the landscape. This excess water flows overland to receiving waterbodies at lower elevations. Surface runoff flows as sheet flow or as accumulated flow in swales, ditches and natural watercourses. The flow pathways of

surface runoff are determined largely by the physical geography and topography of the landscape.

Evapotranspiration is a term that describes the conversion of liquid water to water vapour through two pathways: evaporation and transpiration. Evaporation occurs when water on plant and soil surfaces absorbs energy and transforms into vapour. Transpiration, which occurs within plants, is the process by which plants release water vapour through their leaves.

4.5 SCIENTIFIC APPROACHES

Hydrology, the study of water and its movement, distribution, and properties on Earth, is a critical scientific discipline with profound implications for various aspects of human life and the environment. From managing water resources to understanding climate change impacts, adopting a rigorous scientific approach to hydrology is essential. This essay explores the significance of the scientific approach to hydrology, its methodologies, and its broader implications.

At the heart of hydrology lies a complex network of processes governing the movement and distribution of water. These processes include precipitation, evaporation, transpiration, infiltration, runoff, and groundwater flow. A scientific approach to hydrology involves studying these processes systematically, employing mathematical models, empirical data, and observational techniques to understand the intricate dynamics of water movement within the hydrological cycle.

Central to the scientific approach in hydrology is the collection and analysis of data. This includes gathering information on rainfall patterns, river flow rates, groundwater levels, soil moisture content, and other relevant variables. Advanced technologies such as remote sensing, Geographic Information Systems (GIS), and automated monitoring stations play a crucial role in data collection, enabling hydrologists to gather vast amounts of information with precision and efficiency.

Mathematical models serve as powerful tools in hydrological research, allowing scientists to simulate complex hydrological processes and make predictions about future scenarios. These models range from simple empirical equations to sophisticated numerical simulations based on physical principles. By calibrating models against observed data, hydrologists can assess the accuracy of their predictions and gain insights into the behavior of water systems under different conditions.

Hydrology is inherently interdisciplinary, drawing upon principles from fields such as meteorology, geology, biology, chemistry, and engineering. A scientific approach to hydrology integrates knowledge from these diverse disciplines, recognizing the interconnectedness of Earth's systems. For example, understanding the impacts of climate change on hydrological processes requires collaboration between climatologists, hydrologists, and

ecologists to assess both direct and indirect effects on water availability and quality.

One of the primary applications of hydrology is water resource management, which involves optimizing the use of water for various purposes while ensuring sustainability and resilience. By applying scientific principles, hydrologists can assess water availability, identify potential sources of contamination, evaluate infrastructure needs, and develop strategies for allocation and conservation. This is particularly crucial in regions facing water scarcity or experiencing increased variability due to climate change.

Hydrology plays a critical role in mitigating natural hazards such as floods, droughts, and landslides. By understanding the underlying processes driving these events, hydrologists can develop early warning systems, design flood control measures, implement sustainable land use practices, and enhance resilience in vulnerable communities. The scientific approach to hydrology provides the foundation for evidence-based decision-making in risk assessment and disaster management.

Embracing a scientific approach to hydrology is essential for understanding Earth's vital water systems and addressing the challenges posed by water-related issues. By studying hydrological processes, collecting and analyzing data, developing models, and collaborating across disciplines, scientists can advance our knowledge of water dynamics and contribute to more effective water resource management and hazard mitigation efforts. As we face increasing pressures on water resources and the growing impacts of climate change, the importance of a rigorous scientific approach to hydrology has never been more evident.

4.6 CONCEPT OF WATERSHED

The Watershed is a natural geomorphic unit. It may be defined as the area which contributes water to a particular stream or sets of streams. Defined by topographic divides, it is an area of land which drains the water, sediment and dissolved materials to a common outlet. Thus, the watershed is an area that drains surface water to a common outlet.

A Watershed provides the opportunity to estimate the amount of erosion because measurement of river flow, and by knowing the area of the watershed and by assuming a diversity of material, the rate of land erosion over the whole catchment may be deducted. Watershed is a limited, convenient and usually clearly defined and unambiguous topographic unit available in a nested hierarchy of sizes based on stream order. It provides the best way to measure precipitation and solar radiation inputs and outputs of discharge. Watershed is ecologically and geomorphologically a relevant management unit. Its analysis provides a practical analytical framework for spatially explicit, process-oriented scientific assessment that provides information useful for guiding management decisions. The boundary between two watersheds is referred to as a watershed boundary

or water divide. The watershed area is normally defined as the total area flowing to a given outlet or pour point, or mouth of the watershed.

The pour point is where water flows out of a watershed. This is the lowest point along the boundary of a watershed. The cell in the source raster is used on the pour point about which the contributing area is determined. The source cell may be a feature such as a stream gauging station, dam site or watershed mouth for which characteristics of the contributing area are determined. A Watershed has a stream or network of streams of different orders having specific flow directions. The confluence of two streams is known as a stream junction. Other dimensions of a watershed are length, width, perimeter and area.

4.7 WATERSHED DELINEATION

Delineation of watersheds is the first step to proceed further on integrated watershed modelling and management. There are two ways of watershed delineation. These are the traditional way through topographic sheets and automated watershed delineation using GIS technology. The traditional way of watershed delineation is delineating watershed boundaries through topographic sheets. This method draws the watershed boundary manually on a topographic map using a pattern of contours. Delineation of the watershed or the total runoff contributory area to a part depends on the watershed drainage pattern. The person who draws the boundary uses topographic features on the map to determine where a divide is located.

Today, GIS software is used to delineate watershed boundaries automatically through computers. One can generate watershed boundaries in a fraction of the time through this technique. Watershed boundary through a computer is determined by using the Digital elevation model (DEM) as data input. A stream network can be derived from the DEM. From DEM, there are two ways for watershed delineation. These are point-based and watershed area-wide.

4.8 ENERGY INPUTS AND OUTPUTS OF WATERSHED

The famous geomorphologist, W.M. Davis treated the river like the vein of a leaf; broadly viewed, it is like an entire leaf. Like a leaf, the watershed is an open system. Close systems are those which possess clearly defined boundaries across which no import or export of materials or energy takes place. The open system requires a continuing energy supply and is, the effect, maintained by constant supply and removal of energy. The watershed is an excellent example of a geomorphological system.

The watershed has energy inputs to regulate its system. Therefore, the watershed can be envisaged as receiving energy or input from the climate over the watershed surface, and it loses energy (or output) through the water discharge, sediment and mineral flow through the watershed mouth and evaporation and transpiration from its surface.

The endogenic forces below the watershed surface are the second source of energy input of the watershed. The endogenic forces are responsible for developing an initial form of a watershed. On the initial landform, various kinds of denudational processes originated from climatic energy, i.e., rainfall and temperature; and the landforms are developed in watersheds of different forms and characteristics.

4.9 WATERSHED CHARACTERISTICS

The energy provided by the climate is regularized within the watershed system, which is controlled by watershed characteristics, i.e., geology, soils, relief morphometry, drainage morphometry, morphology, vegetation etc. Geological variability in the watershed causes different rates of discharge and silt delivery.

Under identical rain inputs, the different rock units of the watershed may produce water discharge and silt delivery at different rates. Soil depth and texture directly influence rainwater infiltration, soil moisture storage and groundwater recharge. The relief morphometric parameters such as altitudinal zones, slope and aspect play an important role in controlling the hydrological and denudation processes. The aspect plays a very important role in the distribution of temperature.

The drainage morphometric parameters drainage density, stream frequency, bifurcation ratio, drainage texture, watershed shape, stream order and watershed size play a significant role in controlling various watershed processes.

Watersheds with high drainage density, stream frequency, bifurcation ratio and drainage texture are subject to high overland flow, low infiltration, low water balance and high denudation rates. The shape of the watershed influences the time taken for water from the remote part of the watershed to arrive at the outlet.

Thus, the occurrence of the peak and the shape of the hydrograph are affected by the watershed shape. Stream ordering, watershed size and hierarchy also play a significant role in the regularization of climatic energy inputs within the watershed.

Morphologically a watershed is constituted of three major zones, i.e., the crest zone, the mid-crest zone and the valley zone. These are also known as upland areas, midland areas and lowland areas. These morphological zones are characterized by different natural landforms of different genetics, i.e., pluvial, fluvial etc., depending upon the location of the watershed.

Vegetation directly controls hydrological processes such as interception loss, infiltration, overland flow, rain splash erosion, sheet wash erosion and mass wasting processes. Given the significant controlling roles, it is necessary to study in detail the watershed characteristics for wise management of watersheds.

Watershed Input and Output Balance

The environment and form of a watershed are a function of interactions of watershed input parameters (i.e., climate and tectonic processes) with watershed characteristics (i.e., geology, soils, morphometry, morphology and vegetation etc.). Balance or equilibrium between the input and output parameters of a watershed means no environmental deterioration, pollution or a healthy environment.

An equilibrium state is one in which the many parameters of a watershed system are dynamically balanced. When the entire watershed remains in physical balance, nutrients like water and soils are detained longer within the watershed. The soil builds and retains more moisture, further retaining water and simultaneously encouraging life. The built-up soils have increased nutrient storage sites, and the biogeochemical cycle looks more, keeping the chemicals a richer lingering life.

In a balance watershed system, a hill slope profile is a product of a balance between runoff, infiltration and erosion. All of these are modified by the degree of soil developed since that, in turn, controls what grows on the hillside and thus controls runoff, infiltration and erosion. In the disequilibrium state of the watershed, runoff intensity usually increases, thus, causing erosion on hill slopes. Simultaneously, flood waters reach watercourses faster due to the denser and more effective integration of ephemeral channels on the hill slopes, and flood heights increase coupled with increased sedimentation.

Increased sedimentation and increased flooding lead to increased lateral erosion of stream channels that must change their channel geometry to accommodate a greater percentage of sediment load to water discharge. Under such a disequilibrium state, a headwater anthropogenic change can affect a change in the shape of the whole watershed below it.

4.10 PRECIPITATION

Precipitation in a watershed refers to any form of moisture falling from the atmosphere to the Earth's surface within the boundary of that specific watershed area. This precipitation can take various forms, including rain, snow, sleet, or hail. The amount and type of precipitation within a watershed play a crucial role in determining its hydrology, influencing factors such as streamflow, groundwater recharge, soil moisture, and overall ecosystem health. Understanding precipitation patterns within a watershed is essential for effective water resource management, flood forecasting, and ecological conservation efforts. By monitoring precipitation levels and distribution over time, hydrologists and environmental scientists can assess the water balance within a watershed, identify trends, and predict potential impacts of climate change or land use changes on water availability and quality.

Most of the **precipitation** that falls within the drainage area is released in the form of stream flows through the watershed and collects precipitated

water in a common outlet point. However, precipitation (generally in different forms such as water droplets, snow particles etc.) in the basin area undergo several processes. Therefore, the amount of precipitated water collected at the common outlet point may not be equal to the total precipitation in the catchment area. Many factors determine how much of the streamflow will flow in the basin area and how much precipitated water is either lost in form of vapour or infiltrates into the subsurface. Imagine that the whole basin is covered with a big (and strong) plastic sheet. Then if it rained one inch, all of that rain would fall on the plastic, run downslope into gulleys and small creeks and then drain into main stream. Ignoring evaporation and any other losses, and using a 1-square mile example watershed, then all of the approximately 17,378,560 gallons of water that fell as rainfall would eventually flow by the watershed-outflow point.

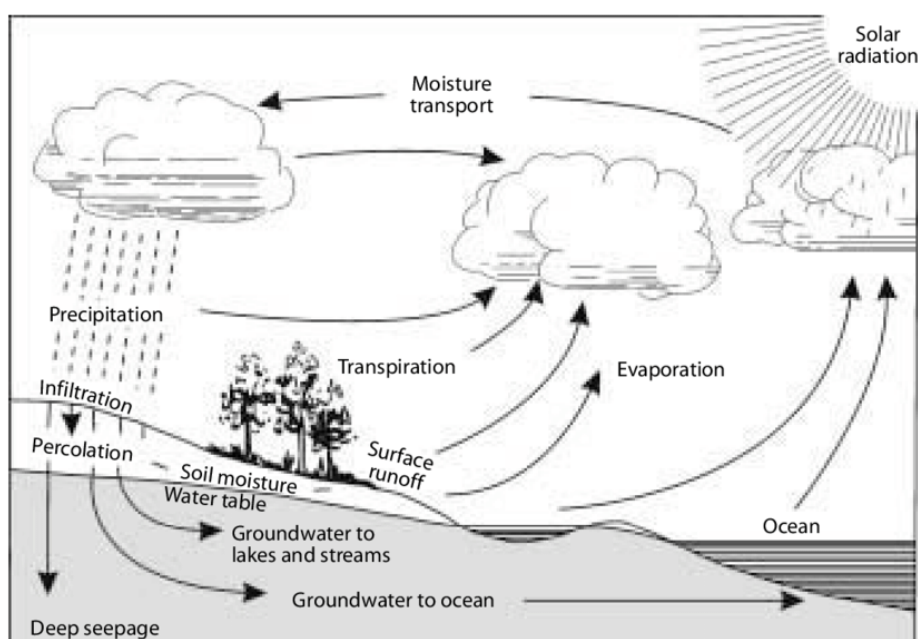


Figure: Precipitation dynamics in Watershed

To picture a watershed as a plastic-covered area of land that collects precipitation is overly simplistic and not at all like a real-world watershed. A career could be built on trying to model a watershed water budget (correlating water coming into a watershed to water leaving a watershed). There are many factors that determine how much water flows in a stream (these factors are universal in nature and not particular to a single stream):

1. **Precipitation:** The greatest factor controlling streamflow, by far, is the amount of precipitation that falls in the watershed as rain or snow. However, not all precipitation that falls in a watershed flows out, and a stream will often continue to flow where there is no direct runoff from recent precipitation.
2. **Infiltration:** When rain falls on dry ground, some of the water soaks in, or infiltrates the soil. Some water that infiltrates will remain in the shallow soil layer, where it will gradually move downhill, through the

soil, and eventually enters the stream by seepage into the stream bank. Some of the water may infiltrate much deeper, recharging groundwater aquifers. Water may travel long distances or remain in storage for long periods before returning to the surface. The amount of water that will soak in over time depends on several characteristics of the watershed:

3. **Soil characteristics:** In Georgia, clayey and rocky soils of the northern areas absorb less water at a slower rate than sandy soils, such as in Georgia's Coastal Plain. Soils absorbing less water results in more runoff overland into streams.
4. **Soil saturation:** Like a wet sponge, soil already saturated from previous rainfall can't absorb much more ... thus more rainfall will become surface runoff.
5. **Land cover:** Some land covers have a great impact on infiltration and rainfall runoff. Impervious surfaces, such as parking lots, roads, and developments, act as a "fast lane" for rainfall - right into storm drains that drain directly into streams. Flooding becomes more prevalent as the area of impervious surfaces increase.
6. **Slope of the land:** Water falling on steeply-sloped land runs off more quickly than water falling on flat land.
7. **Evaporation:** Water from rainfall returns to the atmosphere largely through evaporation. The amount of evaporation depends on temperature, solar radiation, wind, atmospheric pressure, and other factors.
8. **Transpiration/Evapotranspiration:** The root systems of plants absorb water from the surrounding soil in various amounts. Most of this water moves through the plant and escapes into the atmosphere through the leaves. Transpiration is controlled by the same factors as evaporation, and by the characteristics and density of the vegetation. Vegetation slows runoff and allows water to seep into the ground.
9. **Storage:** Reservoirs store water and increase the amount of water that evaporates and infiltrates. The storage and release of water in reservoirs can have a significant effect on the streamflow patterns of the river below the dam.
10. **Water use by people:** Uses of a stream might range from a few homeowners and businesses pumping small amounts of water to irrigate their lawns to large amounts of water withdrawals for irrigation, industries, mining, and to supply populations with drinking water.

4.11 MEAN RAINFALL OVER DRAINAGE BASIN

Rainfall is a fundamental component of the Earth's hydrological cycle, playing a crucial role in shaping the environment and sustaining life. Mean rainfall over a drainage basin refers to the average amount of precipitation

that falls within a specific area drained by a river and its tributaries. Understanding mean rainfall patterns is essential for various purposes, including water resource management, flood prediction, agricultural planning, and ecological conservation.

Mean rainfall over drainage basins is a fundamental aspect of hydrology with far-reaching implications for water resource management, flood prediction, agricultural planning, and ecological conservation. By understanding rainfall patterns and their influencing factors, societies can better adapt to and mitigate the impacts of climate variability and change. Continued research, monitoring, and collaboration are essential for improving our understanding of mean rainfall over drainage basins and enhancing resilience to future hydrological challenges.

Measuring mean rainfall over a drainage basin involves collecting data on precipitation within the basin's boundaries over a specific period. Rain gauges are commonly used for this purpose, positioned strategically across the basin to capture spatial variations in rainfall. These gauges collect precipitation data, which are then averaged to determine the mean rainfall over the entire drainage basin. Additionally, remote sensing technologies such as satellites provide valuable insights into rainfall patterns over large areas, complementing ground-based measurements.

Factors Influencing Mean Rainfall: Several factors influence mean rainfall over drainage basins, including geographical features, atmospheric conditions, and climatic patterns. Geographical factors such as elevation, slope, and land cover influence the distribution and intensity of rainfall within a basin. Mountains, for example, can induce orographic precipitation, leading to higher rainfall on windward slopes compared to leeward slopes. Atmospheric conditions such as temperature, humidity, and air pressure also play a significant role in determining rainfall patterns. Climatic phenomena like El Niño and La Niña can influence rainfall variability over large regions, affecting drainage basin hydrology.

Implications for Water Resource Management: Mean rainfall over drainage basins is a critical determinant of water availability within a region. Understanding rainfall patterns helps water resource managers assess the replenishment of surface water reservoirs, groundwater recharge rates, and overall water balance within the basin. Deviations from the mean rainfall can impact water availability for various sectors, including agriculture, industry, and domestic use. Additionally, knowledge of mean rainfall patterns enables the development of effective water management strategies, such as drought preparedness plans and flood control measures.

4.12 PRECIPITATION CALCULATION METHODS

To compute the average rainfall over a catchment area or basin, rainfall is measured at a number of gauges by suitable type of measuring devices. A rough idea of the number of the needed rain gauges to be installed in a practical area is depending on experience of the hydrologist although this was determined by the regulation of the World Meteorological

Organization (WMO). In areas where more than one rain gauge is established, following methods may be employed to compute the average rainfall:

1. Arithmetic average method
2. Weighing mean method or Thiessen polygon method
3. Isohyetal method.

1. Arithmetic Average Method:

This is the simplest method of computing the average rainfall over a basin. As the name suggests, the result is obtained by the division of the sum of rain depths recorded at different rain gauge stations of the basin by the number of the stations. If the rain gauges are uniformly distributed over the area and the rainfall varies in a very regular manner, the results obtained by this method will be quite satisfactory and will not differ much than those obtained by other methods. This method can be used for the storm rainfall, monthly or annual rainfall average computations. Example: During a storm the rainfall observations in a selected basin were found as follows:

Table 3

Computation of average precipitation over a basin using Arithmetic mean method

Station No.	Precipitation in [mm]	Average precipitation [mm]
1	15	$P_{avg} = 120.6/6 = 30.1 \text{ mm}$
2	19	
3	20	
4	16.6	
5	22	
6	28	
Total (mm)	120.6	

2. Thiessen Polygon Method

This is the weighted mean method. The rainfall is never uniform over the entire area of the basin or catchment, but varies in intensity and duration from place to place. Thus the rainfall recorded by each rain gauge station should be weighted according to the area, it represents. This method is more suitable under the following conditions: - - -

- For areas of moderate size.
- When rainfall stations are few compared to the size of the basin
- in moderate rugged areas.

For the construction of the polygon, the following procedure is to be followed:

Step 1: Draw the area concerned to a suitable scale, showing its boundary, locations of the raingauges in the area and outside but close to the boundary

Step 2: Join location of the raingauges to form a network of

Step 3: Draw perpendicular bisectors to the triangle sides.

Step 4: Delineate the formed polygons and measure their areas using a planimeter or by converting them into smaller regular geometric shapes (i.e. triangles, squares, rectangles, etc.)

Step 5: Compute the average rainfall using the following formula

$$P_{av} = (P_1 \times A_1 + P_2 \times A_2 + \dots + P_n \times A_n) / (A_1 + A_2 + \dots + A_n)$$

If the calculated or measured sectional areas of the polygon, and the measured precipitation are given by the values presented in the following table (3) below.

Table - Bi-sectional areas (A) of Thiessen polygon, and the measured precipitation (P) for stations

Station No.	Bi-sectional areas (A _i) [km ²]	Measured precipitation (P _i) [mm]	(Col. 2 * Col. 3) (A _i * P _i)
P1	25	10	250
P2	125	15	1875
P3	80	20	1600
P4	90	17	1530
P5	120	25	3000
P6	115	40	4600
P7	130	12	1560
Total	685		14415

Then the average precipitation over the catchment will be computed by the total of the column 4 to the total area in column 2. The result will be found as: 21.04 mm.

3. Isoyetal Method:

An isohyetal is a line joining places where the rainfall amounts are equal on a rainfall map of a basin. An isohyetal map showing contours of equal rainfall is more accurate picture of the rainfall over the basin. This method is more suited under the following conditions:

- For hilly and rugged areas.
- For large areas over 5000 km².
- For areas where the network of rainfall stations within the storm area is sufficiently dense, isohyetal method gives more accurate distribution of rainfall.

For explaining of drawing an isohyetal map for a basin, the following procedure is usually applied:

Step 1: Draw the area under study to scale and mark rain gauges on it. Put at each of the rain gauge location the recorded values of rainfall at the station, for the period within which the average is required to be determined.

Step 2: Draw the isohyets of various values by considering the point rainfall data as guidelines and interpolating between them. Also, incorporate the knowledge of orographic effects.

Step 3: Determine the area between each pair of the isohyet lines, either by a planimeter or by converting the areas into smaller regular geometric shapes.

Step 4: Calculate the average rainfall using the following formula:

$$P_{av} = \frac{\left(A_1 \frac{P_1 + P_2}{2} + A_2 \frac{P_2 + P_3}{2} + \dots + A_n \frac{P_{n-1} + P_n}{2} \right)}{(A_1 + A_2 + \dots + A_n)}$$

Where, P_i = Value of Isohyet lines

A_i = Area between pair of isohyet lines.

Comparison Between the Three Methods:

Arithmetic mean method:

- 1- This is the simplest and easiest method to compute average rainfall.
- 2- In this method every station has equal weight regardless its location.
- 3- If the recording stations and rainfall is uniformly distributed over the entire catchment, then this method is equally accurate.

Thiessen method

1. This method is also mechanical
2. In this method the rainfall stations located at a short distance beyond the boundary of drainage are also used to determine the mean rainfall of the basin, but their influence diminishes as the distance from the boundary increases.
3. It is commonly used for flat and low rugged areas.

Isohyetal method:

1. It is the best method for rugged areas and hilly regions.
2. It is the most accurate method if the contours are drawn correctly. However to obtain the best results good judgment in drawing the isohyets and in assigning the proper mean rainfall values to the area between them is required.
3. Other points are as for Thiessen method.

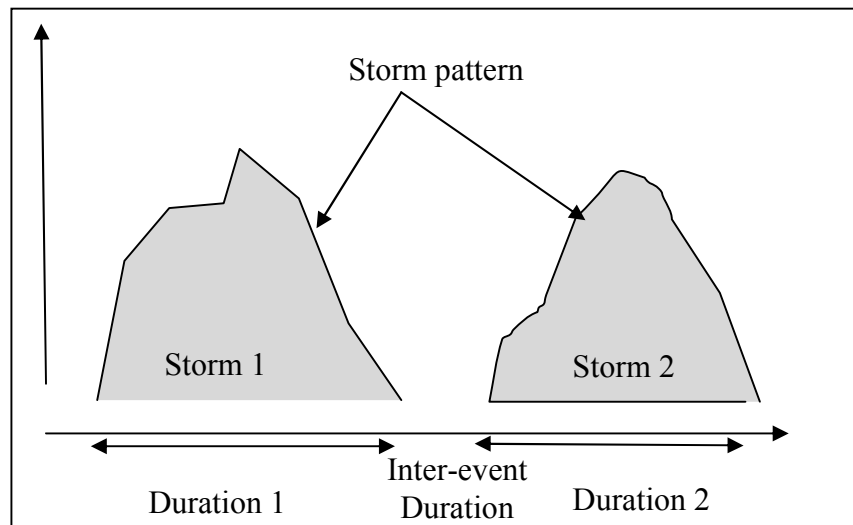
The Isohyetal method allows the use of judgment and experience in drawing the contour map. The accuracy is largely dependent on the skill of the person performing the analysis and the number of gauges. If simple linear interpolation between stations is used for drawing the contours, the results will be essentially the same as those obtained by the Thiessen method. The advantages of both the Thiessen and Isohyetal methods can be combined where the area closes to the gauge is defined by the polygons but the rainfall over that area is defined by the contours from the Isohyetal method. This combination also eliminates the disadvantage of having to draw different polygon patterns when analyzing several different storm events with a variety of reporting gauges. Regardless of the technique selected for analysis of basin average rainfall, a regional map of areal distribution for the total storm event is also produced.

4.13 CHARACTERISTICS OF RAIN-STORM

A rainstorm is a meteorological event characterized by heavy rainfall, often accompanied by strong winds, thunder, lightning, and sometimes hail. Here's a detailed note on the characteristics of a rainstorm:

1. **Heavy Rainfall:** Rainstorms are defined by their significant precipitation rates, often resulting in large amounts of rainfall over a relatively short period. The intensity of rainfall can vary, but during a rainstorm, it's typically enough to cause flooding, especially in urban areas with poor drainage systems.
2. **Strong Winds:** Rainstorms are often accompanied by strong winds, which can exacerbate the impact of the storm. These winds can cause damage to structures, uproot trees, and contribute to the spread of debris, further complicating the situation.
3. **Thunder and Lightning:** Thunder and lightning are common features of rainstorms, particularly in more severe instances known as thunderstorms. Lightning is a discharge of electricity caused by the buildup of charged particles in the atmosphere, often occurring alongside thunder, which is the sound produced by the rapid expansion and contraction of air heated by the lightning bolt.
4. **Low Visibility:** Due to the heavy rainfall and sometimes thick cloud cover, visibility during a rainstorm can be significantly reduced. This poses hazards for drivers and pedestrians alike, increasing the risk of accidents and making navigation difficult.

5. **Hail:** In some cases, rainstorms may also produce hail, which are small balls or lumps of ice that form within strong thunderstorm updrafts. Hailstones can vary in size from tiny pellets to large chunks, and their impact can cause damage to property and crops.
6. **Temperature Changes:** Rainstorms can lead to rapid changes in temperature, particularly as cooler air rushes in behind the storm front. This can result in a noticeable drop in temperature during or after the storm, which may contribute to other weather-related phenomena such as fog formation.
7. **Duration and Frequency:** Rainstorms can vary in duration, ranging from brief, intense downpours to prolonged periods of rainfall lasting several hours or even days. They can occur sporadically throughout the year but are often associated with specific seasons or weather patterns, such as the monsoon season in tropical regions or frontal systems in temperate climates.



8. **Impact on Environment:** Rainstorms play a crucial role in the Earth's water cycle, replenishing groundwater reserves, nourishing vegetation, and maintaining ecosystem balance. However, they can also have negative impacts, including erosion, landslides, and habitat destruction, particularly in areas prone to flooding or with fragile ecosystems.

Rainstorms are complex meteorological phenomena characterized by heavy rainfall, strong winds, thunder and lightning, and various other features that can have significant impacts on both natural and human environments. Understanding their characteristics is essential for effective preparedness, response, and mitigation efforts to minimize their adverse effects.

4.14 RAINFALL RUNOFF CONTROL: EVAPOTRANSPIRATION, INFILTRATION AND RUNOFF FLUXES

An important question in hydrology is how much stream flow occurs in a river in response to a given amount of rainfall. To answer this question we need to know where water goes when it rains, how long does water reside in a watershed, and what pathway does water take to the stream channel. These are the questions addressed in the study of rainfall – runoff processes, or more generally surface water input – runoff processes. The term, "surface water input" is used in preference to rainfall or precipitation to be inclusive of snowmelt as a driver for runoff.

The rainfall – runoff question is also at the heart of the interface linking meteorology and hydrology. Quantifying and forecasting precipitation falls into the realm of meteorology and is part of the mission of the National Weather Service. Meteorological forcing is also a driver of snowmelt surface water inputs. River forecasting involves the use of meteorological variables as driving inputs to the surface hydrology system to obtain streamflow. The temporal and spatial scales associated with surface water inputs, given as output from meteorological processes have profound effects on the hydrological processes that partition water inputs at the earth surface. High intensity short duration rainfall is much more likely to exceed the capacity of the soil to infiltrate water and result in overland flow than a longer less intense rainfall. In arid climates with deep water tables, spatially concentrated rainfall on a small area may generate local runoff that then infiltrates downriver, whereas a more humid area with shallow water tables is less likely to be subject to stream infiltration losses and even gentle rainfall when widespread and accumulated over large areas may lead to large stream flows. Following processes control stream flow in the watershed: Precipitation

1. Infiltration
2. Transpiration
3. Base flow
4. Interflow
5. Overland flow and Return flow
6. Through flow

7. Capillary action Precipitation may be in the form of rain or snow. Vegetation may intercept some fraction of precipitation. Precipitation that penetrates the vegetation is referred to as throughfall and may consist of both precipitation that does not contact the vegetation, or that drops or drains off the vegetation after being intercepted. A large fraction of intercepted water is commonly evaporated back to the atmosphere. There is also flux of water to the atmosphere through transpiration of the vegetation and evaporation from soil and water bodies. The surface water input available for the generation of runoff consists of throughfall and

snowmelt. This surface water input may accumulate on the surface in depression storage, or flow overland towards the streams as overland flow, or infiltrate into the soil, where it may flow laterally towards the stream contributing to interflow. Infiltrated water may also percolate through deeper soil and rock layers into the groundwater. The water table is the surface below which the soil and rock is saturated and at pressure greater than atmospheric. This serves as the boundary between the saturated zone containing groundwater and unsaturated zone. Water added to the groundwater is referred to as groundwater recharge. Immediately above the water table is a region of soil that is close to saturation, due to water being held by capillary forces. This is referred to as the capillary fringe. Lateral drainage of the groundwater into streams is referred to as baseflow, because it sustains streamflow during rainless periods. Subsurface water, either from interflow or from groundwater may flow back across the land surface to add to overland flow. This is referred to as return flow. Overland flow and shallower interflow processes that transport water to the stream within the time scale of approximately a day or so are classified as runoff. Water that percolates to the groundwater moves at much lower velocities and reaches the stream over longer periods of time such as weeks, months or even years. The terms quick flow and delayed flow are also used to describe and distinguish between runoff and baseflow. Runoff includes surface runoff (overland flow) and subsurface runoff or subsurface stormflow (interflow).

The general climatic regime controls the total volume of runoff in any region through its effect on the water balance. In a broad sense, over a time scale long enough that storage changes average out (are negligible), and over a region large enough or with boundary defined so that inflows (surface and subsurface) are negligible, the water balance may be stated as:

$$P = Q + E$$

Where,

P = precipitation rate,

Q = runoff rate, and

E = evapotranspiration rate.

This equation indicates that the precipitation input is disposed of either into runoff or evapotranspiration. In general the climatic regime controls the overall proportioning. Here groundwater recharge supplying baseflow is included in Q. Because the quantities in equation (1) must be positive, this equation places limits on the values of Q and E given any specific P. Both Q and E are constrained to be less than P.

Where soils are well-drained, deep and very permeable, and cover steep hillsides bordering a narrow valley floor, subsurface stormflow dominates the volume of storm runoff. The saturated zone is more or less confined to the valley floor, and saturation overland flow is limited, though even in

such situations, it frequently generates the peak rates of runoff from small catchments. Subsurface stormflow achieves its greatest importance in areas such as forested highlands; in deep permeable forested soils on volcanic tuffs and sandstones; and in deep, permeable volcanic ash deposits. In most other humid regions, where the saturated and near-saturated valley bottoms are more extensive, and where foot slopes are gentler and soils thinner, the saturated area is more extensive before and throughout a storm or snowmelt period. Although subsurface stormflow occurs in such regions, it is less important to the storm hydrograph than are return flow and direct precipitation onto saturated areas, which produce saturation overland flow from limited areas of the catchment.

Infiltration is the movement of water into the soil under the driving forces of gravity and capillarity, and limited by viscous forces involved in the flow into soil pores as quantified in terms of permeability or hydraulic conductivity.

The infiltration rate, f , is the rate at which this process occurs. The infiltration rate actually experienced in a given soil depends on the amount and distribution of soil moisture and on the availability of water at the surface. There is a maximum rate at which the soil in a given condition can absorb water. This upper limit is called the infiltration capacity, f_c . Note that this is a rate, not a depth quantity. It is a limitation on the rate at which water can move into the ground. If surface water input is less than infiltration capacity, the infiltration rate will be equal to the surface water input rate, w . If rainfall intensity exceeds the ability of the soil to absorb moisture, infiltration occurs at the infiltration capacity rate.

Therefore, to calculate the actual infiltration rate, f , is the lesser of f_c or w . Water that does not infiltrate collects on the ground surface and contributes to surface detention or runoff. The surface overland flow runoff rate, R , is the excess surface water input that does not infiltrate.

$$R = w - f$$

This is also often referred to as precipitation excess. The infiltration capacity declines rapidly during the early part of a storm and reaches an approximately constant steady state value after a few hours. The focus of this section on at a point infiltration models for calculating runoff is on how to calculate runoff accounting for the reduction of infiltration capacity. We use accumulated infiltration depth, F , as an independent variable and write infiltration capacity as a decreasing function $f_c(F)$, then as F increases with time f_c is reduced. f_c may be a gradually decreasing function, or a threshold function, as in the case of saturation excess runoff where there is a finite soil moisture deficit that can accommodate surface water input.

4.15 FORMS OF SUB-SURFACE WATER, SATURATED FORMATION

Aquifers are generally classified into four different categories: confined, unconfined, leaky and multiple aquifers. All the different categories of aquifers are discussed in details in below section.

Confined aquifers

Confined aquifers or artesian aquifers or pressure aquifers, are the water saturated geological formation, sandwiched between impervious or semi-pervious unsaturated zone at pressure greater than atmospheric pressure. This pressure may sometime results to rise in water level above Earth surface in wells. Generally, the existence of such aquifer systems take place in sedimentary rocks of low permeability in deep beneath the Earth surface where water get entrapped at the time of deposition. These aquifers are characterized with low groundwater circulation intensity, very large storage and inadequate replenishment. The average replenishment period for a confined aquifer could be extended up to 1000 years which is even less than 0.1% of the aquifer storage period. These aquifers may be recharged by rain or stream water infiltrating the pervious or semi-pervious rock at some considerable distance away from the aquifer. The water level in borehole or well installed in confined aquifers may sometimes rise above the level of the aquifer, especially in the condition when piezoelectric or potentiometric surface is above the ground surface. There may be possibility of having piezoelectric surface of confined aquifer, above the Earth surface, which resulted to the formation of flowing wells under natural pressure. The term artesian is used to depict the behavior of water rise above Earth surface in such flowing confined aquifers. The water received from these aquifers may be sometime older than thousands of years. Moreover, such aquifer systems are present in deeper layers and hence, less susceptible to natural hazards and human interferences.

The water balance in confined aquifers can be represented through the equation described below, considering negligible replenishment or recharge and loss through evaporation in one day period.

Unconfined aquifers

Unconfined aquifers or phreatic aquifers or water-table aquifers are water saturated geological formations, which is overlain by the free permeable unsaturated zone at the upper boundary of the aquifer. Unlike confined aquifers, saturated zone is open to the atmosphere through open pore spaces of the overlying permeable rock or sediments, which are interconnected vertically and laterally. The pressure of water in the unconfined aquifer is equal to the atmospheric pressure and upper groundwater surface is recognized as water-table, which is free to rise and fall. Typically, water does not rise above the water-table in such aquifers. However, depth to the water-table remain variable under various geological factors like topography, geology, season and tidal effects, and the quantities of groundwater being extracted from the saturated zone. Groundwater in such an aquifers is unconfined, therefore, these aquifers are recognised as unconfined aquifers. Unconfined aquifers are usually replenished with rain or stream water infiltrating directly through the overlying soil. Shallow unconsolidated aquifers are located in unconsolidated glacial or fluvial deposits overlain with permeable unsaturated zone of little thickness, resulting to interface of groundwater with surface water. While, in deep unconfined aquifers exists in

consolidated rocks (such as sandstones), overlaid with thick permeable unsaturated zone.

Perched aquifers are some special kind of unconfined aquifers where a small number of aquitard exists between Earth surface and water table. In such water saturated formations, groundwater accumulates above the impervious rocks or sediments like clay layer. In other sense, the occurrence of groundwater is separated from groundwater bodies with relatively impervious strata of aerial extent.

The water balance in unconfined aquifers can be demonstrated with the equation 5, described as under, considering short-term replenishment inputs and interaction of groundwater and surface water.

Leaky aquifers

Completely confined or unconfined aquifers are hard to find in nature, however, their existence is more frequently in form of leaky aquifers. These aquifers are overlain or underlain by a semi-confining layer or semi-pervious aquitards, therefore, such aquifers are also recognized as semi-confined aquifers. Generally, aquitards represents the lower permeability beds saturated or partial saturated zone which limit the movement of groundwater between the aquifers. Aquitard will be partially saturated when these extend to the land surface. On other hand, aquitard will be available in fully saturated form, when overlain with unconfined aquifers bounded above with the water table. These characteristics are reflected especially in alluvial valley plains or former lake basins. Groundwater exploration in wells or bore-wells installed in these aquifers make available water bounded in aquifers as well as in aquitards. Groundwater flows horizontally in aquifers, while movement of groundwater takes place in vertical direction in aquitards during extraction of water.

Multi-layered aquifers

Hydraulically, single aquifer exists infrequently in nature. Generally, aquifer is a part of multiple aquifers, which are arranged in a system. The movement of groundwater in such multi-layered aquifer system is much complex and depends upon the degree of hydraulic communication between the individual aquifers. A multi-layered aquifer system may be one of different types of aquifers available in the system. The aquifer may consists of a system containing two or more aquifers separated with aquicludes (Fig. 4e). The system of such aquifers may consist of confined aquifers or a mixture of unconfined aquifer overlain with a confined aquifer. In such an aquifer system, hydraulic characteristics like transmissivity and storativity of both the individual aquifers are maintained. This system helps to pump out the groundwater from more than one of the aquifer layer at a time, when a well fully penetrate the aquifer system. In another system of multi-layered aquifers, two or more aquifers with their own hydraulic characteristics, are separated by interfaces maintaining unrestricted crossflow of groundwater among the aquifers. The system mimics the similar response to that of a single layered aquifer, where their hydraulic characteristics including

transmissivity and storativity behave collectively for the system. This system's response to pumping will be analogous to that of a single-layered aquifer which is equal to the sum of the transmissivity and storativity of the individual layers. In third possibility for a multi-layered aquifer system, two or more aquifers are separated with aquitards, which strengthens the prospective of leaky aquifer system. This kind of aquifer system may have a measurable impact on other aquifer layer, when pumping of water is done from leaky single-layered aquifer system. However, the impacts may be negligible or measurable, depending upon pumping time.

4.16 SUMMARY

This chapter provides a foundational overview of hydrology, the scientific study of the movement, distribution, and quality of water on Earth. It begins by defining hydrology and explaining its importance in understanding various water-related processes and addressing global challenges such as water scarcity, flooding, and climate change.

The chapter details the continuous movement of water through the atmosphere, land, and oceans. It explains processes such as precipitation, evaporation, transpiration, infiltration, and runoff. Each process is described in terms of its role in the overall cycle and its impact on water distribution. The chapter identifies major components of the hydrologic system, including surface water (rivers, lakes, and reservoirs), groundwater (aquifers), and the atmosphere. It explains how these components interact and influence each other. It discusses methods for measuring and analyzing various hydrologic processes. This includes techniques for gauging precipitation, streamflow, and groundwater levels, as well as the use of hydrological models to simulate water movement and predict future trends.

The concept of water balance is introduced, emphasizing the importance of accounting for all water inputs and outputs in a given system to understand changes in water storage. The chapter outlines the water balance equation and its applications in hydrologic studies.

The chapter addresses the implications of climate change on hydrologic patterns. It examines how changes in temperature and precipitation patterns are expected to alter the hydrologic cycle, influencing water resources and posing new challenges for water management. The chapter concludes by highlighting the practical applications of hydrology in areas such as agriculture, urban planning, environmental conservation, and disaster management. It underscores the role of hydrologists in developing strategies to manage water resources effectively and mitigate the impacts of water-related hazards.

Overall, this chapter serves as an essential introduction to the principles and practices of hydrology, setting the stage for more advanced study in the field. It emphasizes the interconnectedness of the hydrologic cycle and the critical role of water in sustaining life and ecosystems on Earth.

4.17 SAMPLE QUESTIONS

Q.1. Fill in the blanks.

- 1 ----- are the water saturated geological formation, sandwiched between impervious or semi-pervious unsaturated zone at pressure greater than atmospheric pressure (Confined aquifers).
- 2 -----is the simplest method of computing the average rainfall over a basin (Arithmetic Average Method).
- 3 ----- is a term that describes the conversion of liquid water to water vapour through two pathways: evaporation and transpiration(Evapotranspiration).
- 4 The -----involves the continuous circulation of water in the Earth-Atmosphere system (hydrologic cycle).
- 5 The -----is a natural geomorphic unit. It may be defined as the area which contributes water to a particular stream or sets of streams (Watershed).

Q. 2. Write short notes on the following.

- 1 Branches of hydrology.
- 2 Hydrological cycle
- 3 Characteristics of watershed
- 4 Watershed Input and Output Balance
- 5 Earth's water balance

Q. 3. Answer the following questions.

- 1 Discuss different methods of precipitation calculation / measurement.
- 2 Explain characteristics of rain-storm.
- 3 Elaborate factors controlling surface runoff.
- 4 Explain different forms of saturated water in the watershed.

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