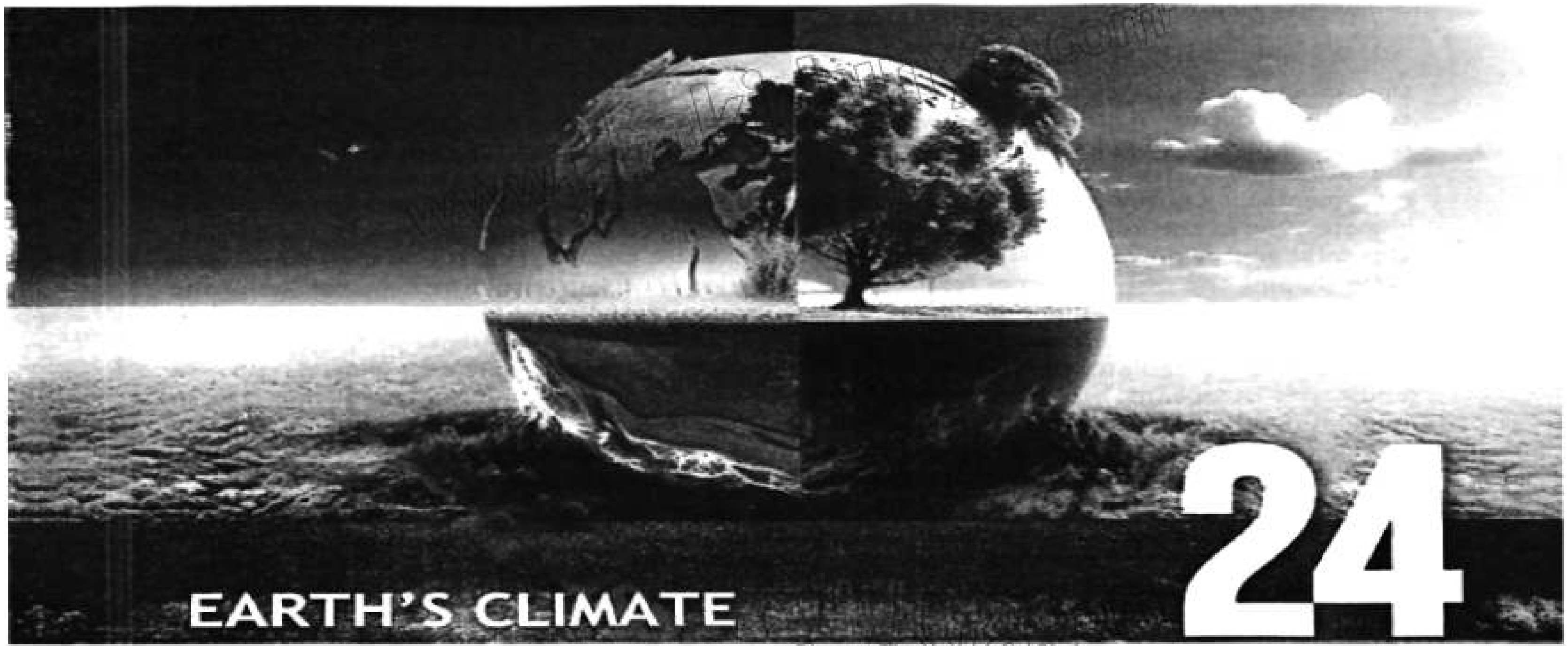



## Student Learning Outcomes (SLOs)

The student will

- Describe Earth's climate system as a complex system having five interacting components [the atmosphere (air), the hydrosphere (water), the cryosphere (ice and permafrost), the lithosphere (earth's upper rocky layer) and the biosphere (living things)]
- Relate ocean currents and wind patterns to the climate system [as the statistical characterization of the climate system, representing the average weather, typically over a period of 30 years, and is determined by a combination of processes in the climate system, such as ocean currents and wind patterns]
- Explain climate inertia as the phenomenon by which climate systems show resistance or slowness to changes in significant factors e.g. stabilization of greenhouse emissions might show a slow response due to the action of complex feedback systems]
- Explain that climate change can be categorized into internal variations and external forcing.
- Explain how global climate is determined by energy transfer from the Sun [with specific reference to the below factors and terms
  - state and use the term Earth energy budget
  - Explain how the energy imbalance between the poles and the equator can affect atmospheric circulation]
- Explain that due to the conservation of angular momentum, the Earth's rotation diverts the air to the right in the Northern Hemisphere and to the left in the Southern hemisphere, thus forming distinct atmospheric cells.
- Explain that ocean water that has more salt has a higher density and differences in density play an important role in ocean circulation.
- Explain how the thermohaline circulation transports heat from the, tropics to the polar regions.
- Explain how climate science is an example of a chaotic system, [using the metaphor of a butterfly's wing flaps may cause hurricanes in another part of the world, mathematics of chaos theory is not required; just the idea that with very complex systems it is very difficult to predict outcomes and they are very sensitive to initial conditions]

Understanding Earth's climate system is a complex interplay of various components that collectively determine the average weather conditions over time. Each component contributes its unique role to the global climate equilibrium. From the depths of oceans to the heights of the atmosphere, from the microscopic interactions of atoms and molecules to the grand *movements of* continents every facet of Earth's system influences and influenced by the climate. One of the key ingredients of this system is the radiant energy received from the Sun. This solar energy powers Earth's atmospheric circulations, ocean currents and the hydrological cycle shaping the distribution of heat and moisture across the planet. The composition of the atmosphere is primarily made up of gases like nitrogen, oxygen and greenhouse gases such as carbon dioxide and methane. Methane acts like a blanket, trapping some of incoming solar radiations and regulate the planet's temperature. The Earth's surface, with its diverse landscapes of oceans, ice caps, forests, deserts and urban areas play a significant role in modulating climate patterns. These surfaces absorb, reflect and emit radiations differently leading the complex patterns of temperature and precipitation across the globe. Meanwhile the biosphere which contains all living organism interact with the climate system through processes like photosynthesis, respiration and the release of greenhouse gases. In unrevealing the complexities of Earth's climate system, scientists employ a multitude of tools and techniques from satellite observations and computer models to field experiments and climate reconstructions. Through continuous advancements in technology our understanding of the Earth's climate system continues to evolve.

## 24.1 EARTH'S CLIMATE SYSTEM

Earth's climate system is a complex system with five interacting components the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere.

Global climate is influenced by many factors including the Sun, Earth's position in space relative to the Sun and human made factors (such as greenhouse gas emission). The five interacting components of the Earth's climate system are shown in Fig. 24.1, and are discussed below:


**Figure 24.1: Five components of Earth's climate system.**

### 1) The Atmosphere (Air)

The atmosphere envelops the Earth and extends hundreds of kilometers from the surface. It mainly consists of nitrogen which is 78%, oxygen which is 21% and argon which is 0.9%. Additionally, there are trace gases such as water vapors ($H_2O$), carbon dioxide ($CO_2$), ozone ($O_3$) and methane ($CH_4$). These trace gases play a significant role in the climate system.

The role of the atmosphere is the shielding: as it protects life on Earth by shielding it from incoming ultraviolet radiations. It insulates the planet as it keeps the planet warm by acting as an insulating layer. The atmosphere prevents extreme temperature variations between day and night. It is responsible for convection and weather patterns as the solar heating causes layers of the atmosphere to convert, driving the air movement and influencing global weather patterns. Some trace gases like carbon dioxide and water vapors act as greenhouse gases. These gases allow visible light from the Sun to penetrate to the surface but block some of infrared radiations emitted by the Earth's surface which traps heat within the atmosphere contributing to the overall warming effect. The atmosphere is divided into different layers depending upon their altitude and functioning, as shown in Fig. 24.2.

- **Troposphere:** The lowest layer extending from the ground (the surface of the Earth) to about 16 km. It's the layer where weather occurs.
- **Stratosphere:** Above the troposphere, from 16 km to 50 km, is the stratosphere. The ozone layer is found here which prevents us from the harmful ultraviolet radiations coming from the Sun.
- **Mesosphere:** Above the stratosphere from 50 km to 136 km is the mesosphere. Meteors burn out in this part of the atmosphere.
- **Thermosphere:** Above the mesosphere from 136 km up to about 600 km is the thermosphere. It is where the auroras occur due to solar radiations.
- **Exosphere:** The exosphere is outer most layer into which extends from 600 km up to merging into the space. Satellites orbit in this region.

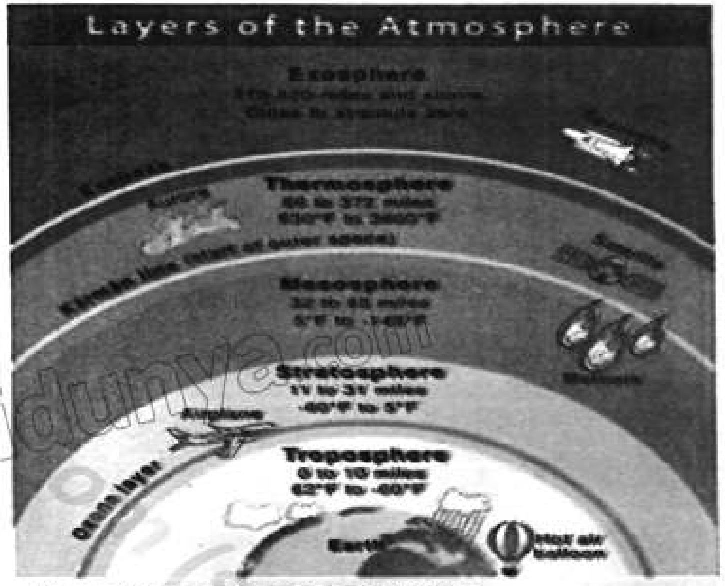


Figure 24.2: Layers of atmosphere.

## 2) The Hydrosphere (Water)

The hydrosphere encompasses all the water on the Earth whether it is in liquid water, solid ice or the gaseous water (vapors form). The Earth contains 70 % water on its surface. Most of the hydrosphere consists of liquid water primarily found in the oceans. Our planet's abundant surface waters give Earth its distinct appearance as a blue globe and set it different from the all-other planets in the solar system. Some of the characteristics of hydrosphere are:

- The hydrosphere plays a critical role in regulating Earth's climate.
- It influences patterns of precipitation and affects the movement of energy throughout the climate system.
- Ocean currents, evaporation and condensation are all parts of hydrological cycle which redistributes the water around the planet.

The hydrological cycle is shown in Fig. 24.3. The water balance equation is the fundamental equation tool for understanding the movement and distribution of water in the hydrosphere. This equation relates inputs, outputs and changes in the water storage over time and *can be given as:*

$\Delta S = P - E - Q$ ___ (24.1)

Here '$\Delta S$' is the change in the storage of hydrosphere (which may be a specific region like lake sea etc.), 'P' is the precipitation (which is the amount of water falling from the atmosphere), 'E' is the evapotranspiration (which is the evaporation from the Earth's surface and plants) and 'Q' is the runoff (which is the water that moves across the surface to rivers or lakes and also the water which infiltrates into the groundwater).

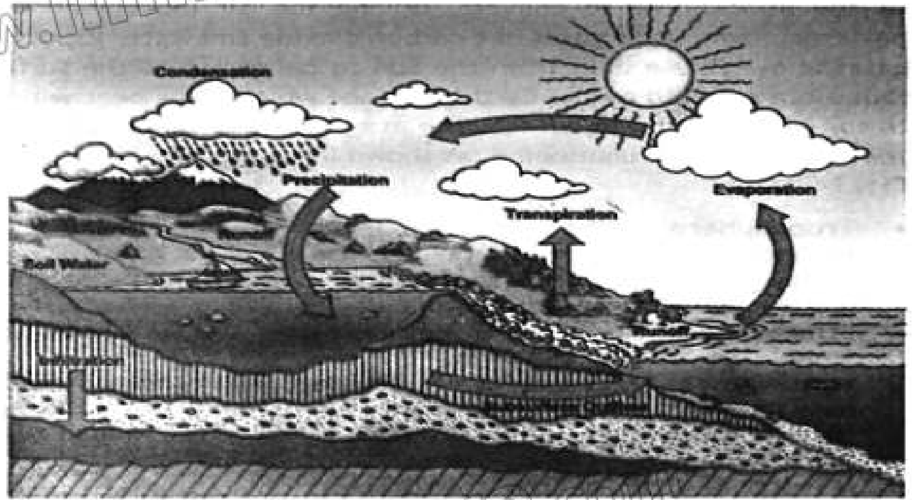



Figure 24.3: Hydrological cycle

## 3) The Cryosphere (Ice)

The cryosphere refers to any place on Earth where water is in its solid form, where low temperatures freeze water and turn it into ice. The frozen water can be found in the form of solid ice or snow and occurs in many places around the Earth. The cryosphere exists in the polar-regions but is also found wherever snow, sea ice, glaciers, permafrost, ice sheets and icebergs exist. In Pakistan, the examples of cryosphere are the ice caped mountains and glaciers in the Himalaya, Karakorum and Hindu Kush Mountain ranges in the north. Snow and ice are the basic elements of the cryosphere as they interact throughout Earth's different environments to create sea ice, glaciers, ice shelves, icebergs and frozen ground. Although direct measurement of the cryosphere can be difficult to obtain due to the remote locations of many of these areas, satellite observations help scientists monitor changes in the global and regional climate by observing how regions of the Earth's cryosphere shrink and expand. Some of the components of the cryosphere are explained as:

- **Snow:** Snow is the precipitation that forms when water vapors freeze into ice crystals. It can form whenever there is high humidity and cold temperatures in the atmosphere. Because of its reflective property it regulates the climate by reflecting incoming sunlight back into the space and hence cooling the planet
- **Ice:** Ice forms when liquid water becomes a solid at temperatures below the freezing point. It is the part of sea ice, glaciers, ice shelves, icebergs and frozen ground. The ice in polar-regions has important impact on polar regions and Earth's climate. The sea ice layer

increases the salinity of sea water. It also restricts wind and wave action near coastlines. It also reflects much of the sunlight into the space back. Ice currently covers 10 percent of the Earth's surface and is disappearing rapidly

- **Permafrost:** Permafrost refers to permanently frozen ground found mainly in high altitude regions. It contains ice and soil that remain frozen for extended periods.

The components of cryosphere are shown in Fig. 24.4.

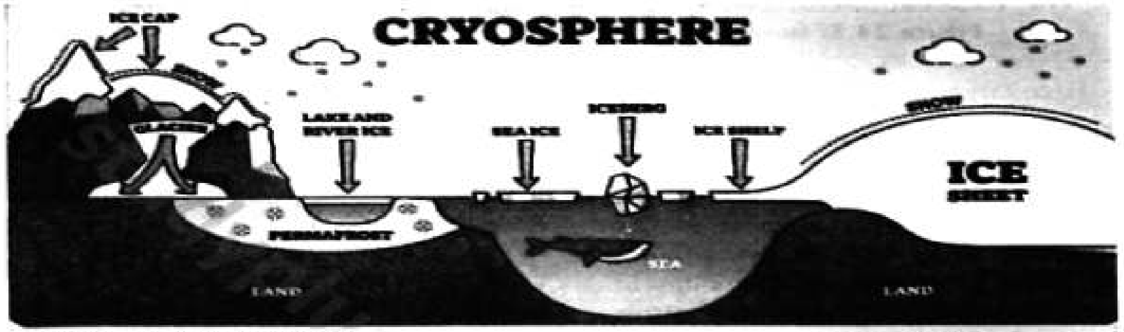


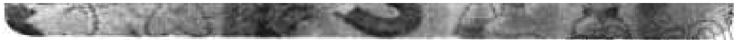

Figure 24.4: Cryosphere.

## 4) The Lithosphere (Earth's Upper Rocky Layer)

The lithosphere is the outermost solid shell of the Earth consisting of the crust and the uppermost part of the mental. It composed of various types of rocks and minerals. The lithosphere interacts with other components such as the atmosphere, hydrosphere and biosphere. Some important features of lithosphere are as:

- **Land surface:** The lithosphere provides the surface on which climate processes occur. Different types of land surfaces have different influences on the Earth's climate for example forests can moderate the temperatures while deserts tend to have extreme temperature fluctuations.
- **Carbon cycle:** Lithosphere plays a major role in carbon cycle which is essential for regulating Earth's climate. Rocks weather and erode over time releasing carbon dioxide into the atmosphere. On the other hand, some types of rocks like lime stone are carbon sinks which takes carbon from the atmosphere over a geological time scale.
- **Tectonic Activity:** Processes like tectonics, which involves the movement and interaction of lithosphere plates, can have significant impact on climate over a large timescale. Due to movement of tectonic plates mountain ranges are formed which affect atmospheric circulation patterns and precipitation distribution influencing regional climate.
- **Volcanic Activity:** Volcanic eruption which is related to tectonic activity can release large number of gases and particles into the atmosphere these emissions can temporarily cool the climate by blocking sunlight, leading to short term cooling events known as "*volcanic winters*"

The movement of tectonic plates and volcano formation is shown in Fig. 24.5.



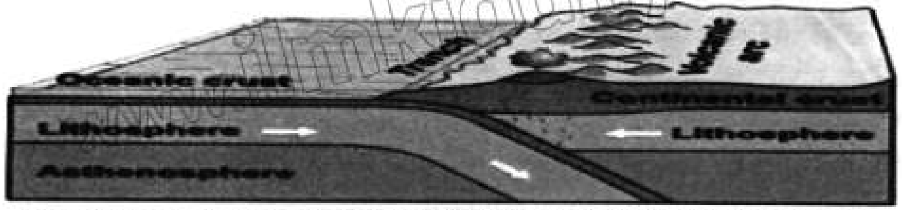



**Figure 24.5: Movement of tectonic plates and volcano formation.**

## 5) The Biosphere (Living Things)

The biosphere refers to the relatively thin life supporting layer of Earth's surface. It extends from a few kilometers into the atmosphere to the deep-sea vents in the ocean. Biosphere deals with the living things and their impact on the Earth's climate system. It consists of living organisms (plants, animals, fungi and microorganisms) and the non-living factors from which they derive energy and nutrients. The role of biosphere in the Earth's climate system can be given as:

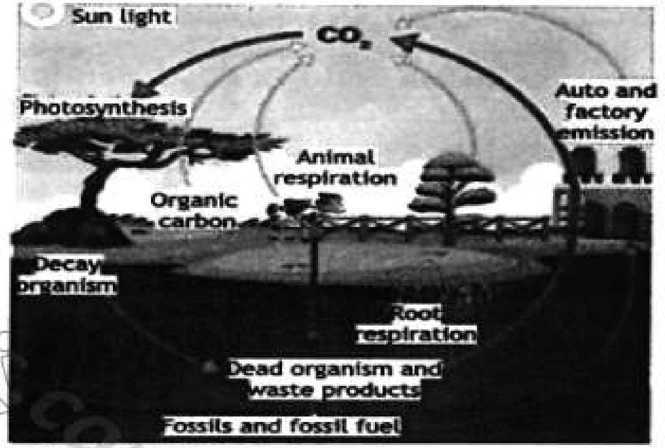



**Figure 24.6 (a): Carbon cycle**

- **Climate regulation:** The biosphere plays a crucial role in regulating the Earth's climate. Changes in the biosphere can directly impact climate patterns
- **Carbon cycle:** The biosphere is an integral reservoir in the carbon cycle. Through processes like photosynthesis living organisms absorb carbon dioxide ($CO_2$) from the atmosphere and convert it into organic matter. The carbon cycle is shown in Fig. 24.6 (a).
- **Energy flow:** Solar energy is captured by the plants during photosynthesis and this energy flows through the food chain as organisms consume each other. This energy transfer affects climate dynamics.
- **Water cycle:** The biosphere is closely linked to the water cycle. Evaporation, condensation, precipitation and transpiration all involve living organisms.
- **Nutrient cycles:** Elements like carbon (C), nitrogen ($N_2$) and phosphorous (P) cycle through the biosphere impacting both living organisms and the environment.

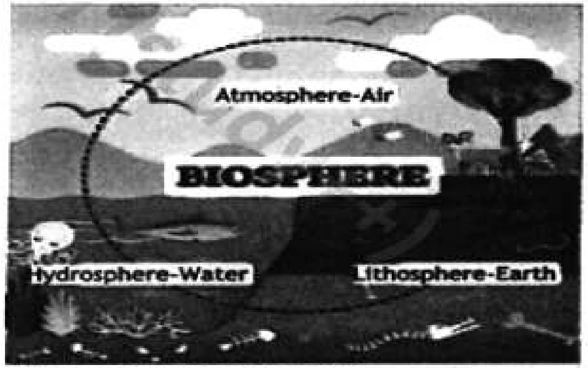



**Figure 24.6 (b): Biosphere**

The biosphere is essential for maintaining species diversity, regulating climate and supporting life on the Earth. The biosphere is shown in Fig. 24.6 (b).

**Example 24.1: Find the change in storage of hydrosphere in terms of volume whose area of the watershed is 120 km², with precipitation of 110 mm while evapotranspiration and runoff are 60 mm and 30 mm respectively.**

**Given:** Area of watershed = A = 120 $km^2$ Precipitation = P = 110 mm

Evapotranspiration = E = 60 mm Runoff = Q = 30 mm

**To Find:** Change in storage: $\Delta S$ = ?

**Solution:** First of all we have to find the volumes of all these using:

Precipitation volume = P x A

$P_v = 0.11\ m \times 120{,}000{,}000\ m^2$ or $P_v = 13{,}200{,}000\ m^3$

Now Evapotrans portation volume = E x A

$E_v = 0.06\ m \times 120{,}000{,}000\ m^2$ or $E_v = 7{,}200{,}000\ m^3$

Also Roundoff volume = Q x A

$Q_v = 0.03\ m \times 120{,}000{,}000\ m^2$ or $Q_v = 3{,}600{,}000\ m^3$

Now to calculate the change in storage volume, we use:

$$\Delta S_v = P_v - E_v - Q_v$$

**Putting values:**

$$\Delta S_v = 13{,}200{,}000\ m^3 - 7{,}200{,}000\ m^3 - 3{,}600{,}000\ m^3$$

$$\Delta S_v = 2{,}400{,}000\ m^3$$

**Assignment 24.1**

**Find the precipitation in mm if the change in storage of water is 20 mm, while evapotransportation is 50 mm and runoff is 30 mm.**

## 24.2 OCEAN CURRENTS AND WINDS

Ocean currents and wind patterns are interconnected phenomenon that play crucial role in regulating the Earth's climate and distribute heat around the globe.

Ocean currents are the continuous, predictable and directional movement of seawater driven by gravity, wind and water density. Ocean water moves in two directions i.e. horizontally and vertically. Horizontal movements are called as currents while vertical changes are called up-welling and down-welling. The movement of ocean water is continuous and is broadly categorized into three types i.e., waves, tides and currents. Ocean currents can be defined as:

**The streams of water that flow constantly on the ocean surface in definite directions are called ocean currents.**

Ocean currents help distribute heat globally influencing climate patterns. They carry nutrients and food to marine organisms supporting sea life. Ocean currents can be categorized into two group i.e. surface ocean currents and deep ocean currents.

### 1) Surface Ocean Currents

The ocean currents which produced on shallower waters near the surface are called surface ocean currents. These currents are produced due to various factors like:

- **Wind:** Major surface ocean currents are primarily set in motion by the wind. As the wind blows across the ocean surface it drags the water along with it creating currents.
- **Subtropical Gyres:** Large rotating currents that start near the equator are called subtropical gyres. These gyres transfer heat from the equator towards the poles helping moderate climate and concentrating plastic trash in certain areas of the ocean.

### Coriolis Effect

The rotation of Earth influences the path of these currents. A force resulting from the Earth's rotation is called coriolis force. In the northern hemisphere predictable winds called trade winds blow from east to west just above the equator. These winds pull surface water and the Coriolis effect deflects the currents. Then they bend to the right heading north. At about 30 degrees north latitude another set of winds called westerlies push the currents back to the east creating a closed clockwise loop. Similar patterns occur in the southern hemisphere but currents in this side are counter-clock wise i.e. bend to the left, as shown in Fig. 24.7.

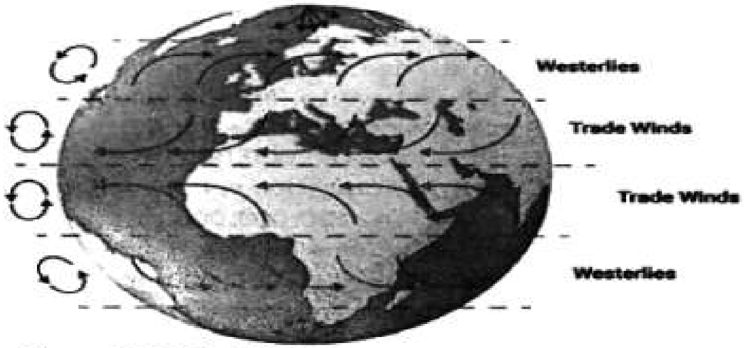



Figure 24.7: Coriolis force.

## 2) Deep Ocean Currents

The ocean currents beyond the depth of 500 meters are known as deep ocean currents. These currents are formed due to the differences in temperature and density of the water in different parts of the ocean. Some of them are explained below.

- **Warm Water Northward:** The surface currents carry warm water north from the equator as this water moves into higher northern latitudes it cools down
- **Density:** The density of sea water plays a major role in producing ocean currents and circulating heat as cooling process increases the water's density. Sea water density varies due to its salinity and temperature, high salinity makes water denser because more salt is packed into it. Denser water sinks and flows back toward the equator at deeper levels creating deep ocean currents. On the other hand, high temperature makes the water less dense. Near the ocean surface a combination of high salinity and low temperature makes water dense enough to sink into deep-ocean. The weight of

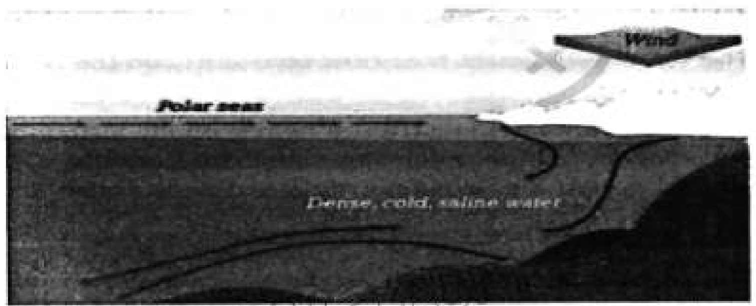



Figure 24.8: Water movement due to density difference.

water above pushes deep water molecules together making them denser. Deep circulation affects the entire ocean and significantly impacts abyssal properties (abyssal is the region in deep oceans where there is no light and very little oxygen with very high concentration of salts and density, this region has very few examples of life in it) where wind driven currents have no effect. The movement of water due to density is shown in Fig. 24.8.

### Thermohaline Circulation

The Deep Ocean currents are caused by differences in water density. This process is called thermohaline circulation where "*thermo*" refers to temperature and "*haline*" to saltiness. Thermohaline circulation is a large-scale ocean circulation driven by density gradients created by surface heat and freshwater fluxes. The wind driven surface currents move toward poles from the equatorial region and cool the water during their movement and this cooled water sinks at high latitudes and this cycle continues which transport energy and mass. Thermohaline circulations act like a giant conveyor belt moving warm surface waters downward and forcing cold nutrient rich deep waters upward, as shown in Fig. 24.9.

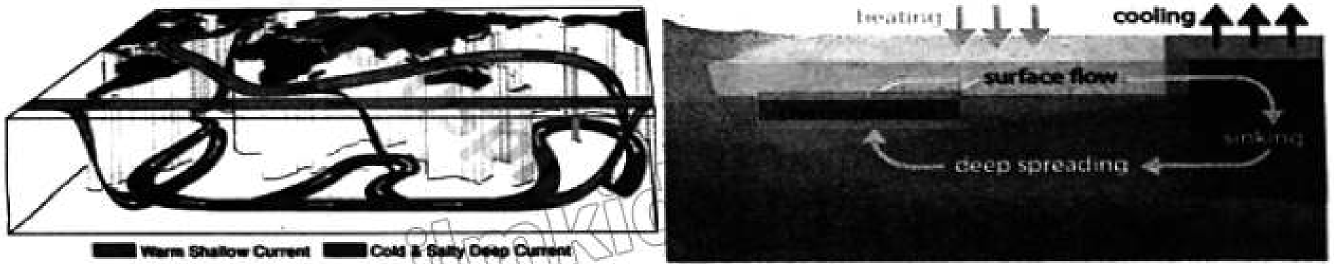



**Figure 24.9:** Thermohaline circulation.

## Earth's Angular Momentum and Wind Patterns

The conservation of angular momentum plays a crucial role in determining the wind patterns on the Earth. This is closely related to the Earth's rotation and is responsible for the Coriolis effect which deflects the movement of air masses in different directions depending on the hemisphere. Angular momentum is a property of rotating objects depends upon velocity of rotation and the perpendicular distance from the axis of rotation. Due to this phenomenon the air moves from high latitudes (near the poles) to low latitudes (towards the equator). It experiences a change in velocity due to Earth's spherical shape and varying rotational speeds. The turning of winds due to the rotation of Earth is called as Coriolis effect, as shown in Fig. 24.7, and the force which bends the winds due to change in speeds is called as Coriolis force which can be given as:

$$F_c = 2mv\omega \sin\theta \qquad \text{\_\_\_\_\_\_ (24.2)}$$

Here '$F_C$' is the Coriolis force, 'm' is the mass of the moving air packet, 'v' is the wind speed, '$\omega$' is the angular velocity of the Earth's rotation (which is approximately $7.292 \times 10^{-5}$ $rads^{-1}$) and '$\theta$' is the angle with latitude (at equator it is $0°$ while at poles it is $\pm 90°$)

At the equator the Coriolis force is zero due to $\sin 0^\circ = 0$, while this force is maximum at the poles due to $\sin 90^\circ = 1$. The Coriolis effect causes winds to be deflected more strongly at the higher latitudes closer to the poles. It is important to note that the magnitude of wind speed is not directly influenced by the Coriolis force but the direction of the wind will change significantly as we move from equator towards the pole.

As from the equator where the distance of the surface of Earth from the axis of rotation is large i.e., it has large moment of inertia at this point, here the speeds of winds will be low but near poles the moment of inertia becomes small and hence increases the speed of winds. This difference in the speed of winds accounts for the weather patterns on Earth. The deflection of air due to Coriolis effect helps to create distinct atmospheric circulation cells as shown in Fig. 24.10.

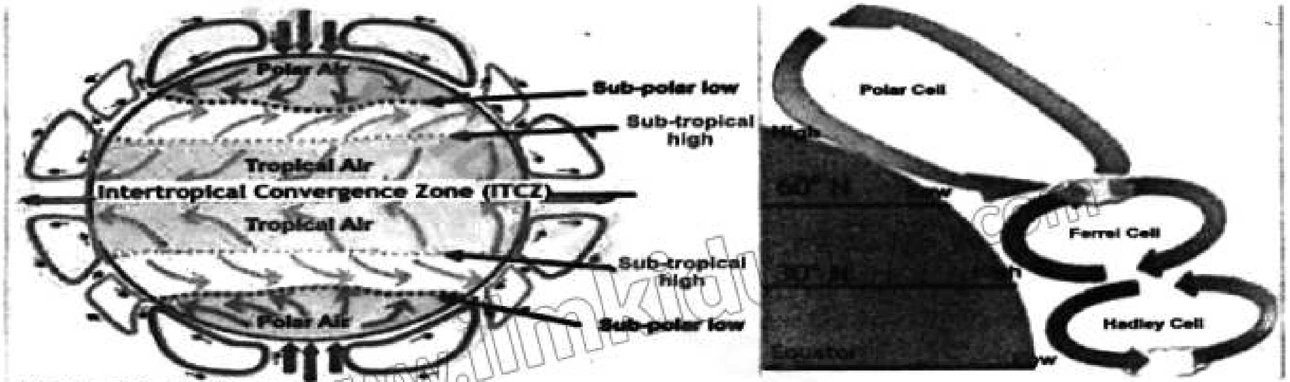



**Figure 24.10:** Wind circulation cells.

- **Hadley Cells:** Between the equator and 30° latitude, warm air rises at the equator due to intense heating and moves towards poles at high altitudes and finally descends around 30° latitude creating a cycle.
- **Ferrell Cells:** Between 30° to 60° latitude air descends around 30° and moves towards pole at the surface and rises at 60° latitude with movement towards equator at high altitudes.
- **Polar Cells:** Between 60° latitude and the poles air rises at 60° latitude and moves towards pole at high altitude. Finally, air descends at the pole.

These cells distribute heat and moisture around the globe which influences weather patterns and climate.

Wind patterns are integral components of the climate system playing a significant role in shaping regional and global climate. Wind patterns are the result of complex interactions between various atmospheric and oceanic processes. They are necessary for distribution of heat, moisture and energy across the Earth's surface influencing weather conditions and climate for both short and long timescales. The basic relationship between atmospheric pressure and horizontal wind can be described using the geostrophic balance.

This balance occurs when we disregard friction and changes in wind direction and speed. The geostrophic wind blows parallel to isobars and is influenced by two main forces as:

- Horizontal pressure gradient force (the change in pressure measured across a given distance is called a pressure gradient) derives the air movement from higher to lower pressure areas.
- Coriolis force results from the Earth's rotation and causes the deflection of wind to the right in the northern hemisphere and to the left in the southern hemisphere.

Wind speed increases as the distance between isobars decreases or pressure gradient increases. The impact of wind on climate can be given as:

- **Heat Transport:** Wind carries heat from one region to another. For example, ocean currents driven by wind transport warm water from the equator towards the poles.
- **Moisture Transport:** Wind transports moisture affecting precipitation patterns (precipitation is any liquid or frozen water that forms in the atmosphere and falls back to the Earth). Trade winds, westerlies and polar easterlies play essential roles in distributing moisture globally. These winds on globe are shown in Fig. 24.10.
- **Pollutant Dispersion:** wind disperses pollutants like dust, smoke and industrial emissions across the large area.
- **Pollen Distribution:** Wind help disperse pollen helping plant reproduction.
- **Daily weather Patterns:** Coastal regions experience daily changes in wind direction due to differential heating of land and water (the difference in how land and water surfaces absorb heat is called as differential heating).

Over a 30-year period these wind patterns exhibit statistical regularities that contribute to the climate of the region. Variations in these patterns over long-time scales can result in changes to regional climate and even global climate. Understanding and monitoring wind patterns are crucial for predicting weather events, mapping natural resources and assessing the impacts of climate change. Advanced modeling techniques and observational technologies continue to improve our understanding of these complex interactions within the climate system.

**Do You Know?**

**As the air mass starts to move it is deflected to the right by the coriolis force. The deflection increases until the coriolis force is balanced by the pressure gradient force. At this point the wind will be blowing parallel to the isobars (having same pressures) when this happens the wind is referred to as the "geostrophic wind".**

Example 24.2: Find the magnitude of the Coriolis force which bends the path of air mass 200,000 kg up to 25°, while the mass of air is moving at the speed of 80 km $h^{-1}$.

**Given:** Mass of air packet= m = 200,000 kg  Speed of air = v = 80 km $h^{-1}$

Angle = $\theta$ = 25°  Angular velocity of Earth = $\omega$ = $7.3\times10^{-5}$ rad $s^{-1}$.

**To Find:** Coriolis Force = $F_C$ = ?

**Solution:** First we need to convert the velocity into SI units as:

$$v = 80 \text{ km h}^{-1} = \frac{80\times1000}{3600} \text{ m s}^{-1} \quad \text{or} \quad v = 22.2 \text{ m s}^{-1}$$

To find the Coriolis force, we use: $F_C = 2mv\omega\sin(\theta)$

Putting values, we get: $F_c = 2(200000)(22.2)(7.3\times10^{-5})\sin(25) = 274 \text{ N}$

**Assignment 24.2**

**Find the angle through which a Coriolis force of 200 N will deflect the air mass of 100,000 kg moving at the speed of 60 $km\ h^{-1}$.**

## 24.3 CLIMATE INERTIA

Climate inertia refers to the tendency of the Earth's climate to resist or respond slowly to changes in external factors like greenhouse gas concentrations and solar radiations. This phenomenon occurs due to various complex feedback mechanisms and processes within the Earth's climate system. These feedback mechanisms include:

- **Positive feedback:** Some feedbacks amplify initial changes for example as the arctic ice melts due to warming it reduces the Earth's reflectivity leading to further warming.
- **Negative feedback:** Other feedbacks dampen changes for example increased carbon dioxide ($CO_2$) levels stimulate plant growth which absorbs some carbon acting as negative feedback.

The climate inertia is time dependent as for example if greenhouse gas emissions were to stabilize immediately the Earth's climate would continue to warm for some time due to heat already stored in the oceans. Climate processes operate on various timescales from days to centuries like:

- **Short-term Inertia:** The ocean and land surfaces absorb and release heat relatively slowly leading to short term inertia this is why daily temperature fluctuations occur
- **Long-term Inertia:** changes in greenhouse gas concentrations like carbon dioxide take decades to centuries to fully impact the climate system. When we stabilize greenhouse gas emission the climate system does not respond immediately.

Oceans play a main role in climate inertia as they have high heat capacity means they absorb and release heat slowly. Changes in ocean temperature occur gradually affecting climate patterns over extended periods. Similarly, the carbon cycle involves exchanges of carbon dioxide between the atmosphere, oceans, land and vegetation. It also takes time due to slow decomposition of organic matter. The melting of ice sheets and glaciers contributes to sea level rise but this process occurs over centuries leading to inertia in the response to climate change. Climate inertia underscores the importance of adaptation (adjusting to existing changes) and mitigation (reducing emission) strategies. Even if we take immediate actions the effects of past emissions will persist. Earth's climate change can be categorized into two main components i.e. internal variations and external forcing.

### 24.3.1 Internal Variations

Internal variations refer to natural fluctuations within the climate system itself. These variations occur due to interactions between different components of the Earth's climate system such as the atmosphere, oceans, land and ice etc. some of the examples of the internal variations are:

**For Your Information**

Jet streams are fast-moving bands of air in the upper atmosphere, typically between 6 km to 15 km above the Earth's surface. They play a significant role in shaping weather patterns and atmospheric circulation.

- **Atmospheric Circulation Patterns:** Changes in atmospheric circulations like jet streams, monsoons lead to regional climate variability.

- **Solar Radiations:** Variations in solar radiation due to sunspots and solar cycles impact climate over shorter time scales.
- **Volcanic Activity:** Volcanic eruptions release aerosols into the atmosphere affecting global temperatures temporarily. Internal variations are often cyclic and occur over decades to centuries.
- **Ocean Oscillations:** ocean currents and oscillations i.e. El-Nino southern oscillations (ENSO), Atlantic multi-decadal oscillations (AMO) and Pacific Decadal Oscillations (PDO) cause variations in the sea surface temperatures affecting weather patterns globally. Some oscillations are shown in Fig. 24.11.

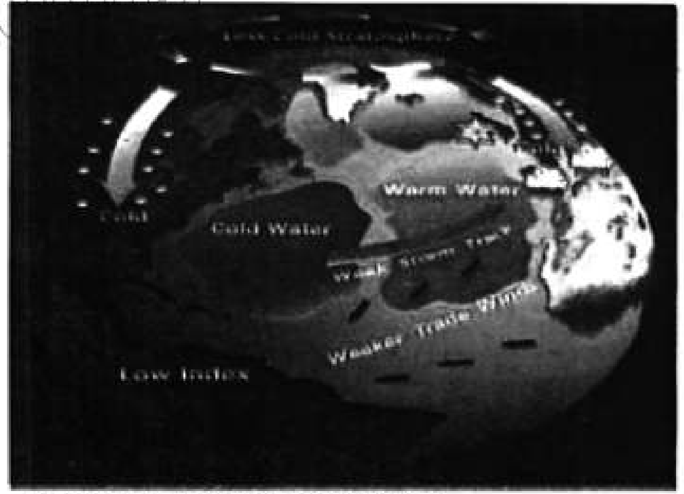



**Figure 24.11:** Ocean oscillations.

## 24.3.2 External Forcing

External forcing refers to factors outside the climate system that influence the behavior of the climate system. These factors can alter the Earth's energy balance leading to long term climate changes. Some of the examples of the external forcing are:

**Greenhouse Gas Concentrations:** Increased levels of greenhouse gases like carbon dioxide and methane etc. due to human activities enhance the greenhouse effect trapping more heat and causing global warming.

**Solar Variability:** Changes in solar output over longer time scales impact Earth's climate.

**Orbital Variations:** Earth's orbit around the Sun undergoes periodic variations. Eccentricity and axial tilt affect the distribution of solar energy, as shown in Fig. 24.12. But these effects are long time scales changes extended up to thousands of years.

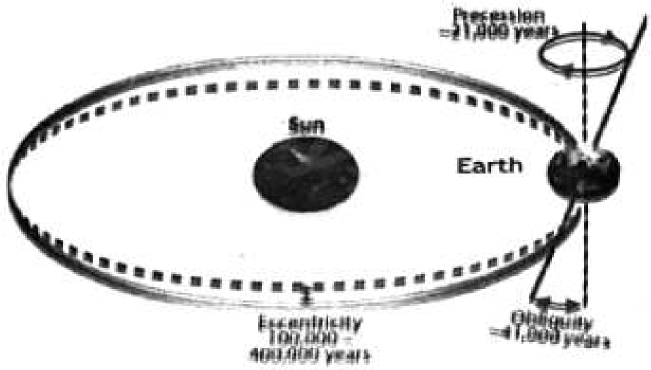



**Figure 24.12:** Eccentricity, tilt and precession of Earth.

**Aerosols and Pollution:** Anthropogenic aerosols (a suspension of particles or droplets in the air and includes dust, mist, fumes or smoke and anthropogenic mean such particles from the industrial sources or from combustion processes) can cool the climate by reflecting sunlight back into space.

External forcing factors operate over longer time frames like centuries and contribute to gradual climate shifts.

## 24.4 EARTH ENERGY BUDGET

The Earth's energy budget is a way of accounting for the balance between the energy that Earth receives from the Sun and the energy it radiates back into the space. It is simple the balance between the incoming solar radiation (insolation) and outgoing terrestrial radiations. The Earth's energy budget can have the components like:

- **Incoming Solar radiations:** The Sun emits energy in the form of sunlight. Approximately 49% of this solar energy is absorbed by the Earth's surface primarily by land, ocean and vegetation.
- **Atmospheric Absorption:** About 20% of solar radiation is absorbed by the atmosphere itself.
- **Outgoing Terrestrial Radiations:** The Earth which absorbs radiation can also re-emit these radiations as heat. This process occurs through infrared radiations emitted by the surface and the atmosphere.

The greenhouse effect also plays a role in the energy distribution in the Earth's climate in regulating the globe's temperature. It involves the interaction of solar radiation with greenhouse gases in the atmosphere. It can be explained in terms of steps like in first step sunlight penetrates the atmosphere and warms the Earth's surface. In second step the heated surface of the Earth emits infrared radiations. In third step greenhouse gases absorb some of these outgoing radiations preventing them from escaping directly into the space. Instead, they re-radiate part of this energy back towards the surface effectively trapping heat. Without the greenhouse effect Earth's average temperature would be well below freezing.

### 24.4.1 Solar Variability and Climate

While the Sun is essential for maintaining Earth's habitable conditions, its influence on climate change is relatively small compared to other factors. Some of the factors are as follows:

- **Solar Cycles:** The Sun undergoes 11-years solar cycles during which its activity varies. These cycles affect solar radiation, sunspots and solar flares.
- **Long-term Trends:** Over the past 40-years satellites have observed the Sun's energy output. However, changes in solar activity account for less than 0.1% of the warming observed since 1750.
- **Human Induced Warming:** Human activities particularly the burning of fossil fuels release greenhouse gases. The warming caused by these gases is over 270 times greater than any sunlight warming from the Sun itself during the same period.

### 24.4.2 Energy Imbalance

The uneven distribution of solar energy across the Earth's surface creates an energy imbalance. The energy imbalance on the Earth is the main cause of the atmospheric circulations. For example, equator receives more solar energy due to direct sunlight while the pole regions receive less solar energy due to oblique sunlight, as shown in Fig. 24.13.

This energy imbalance drives the atmospheric circulations as:

- Warm air rises at the equator creating low-pressure zones.
- Cooler air sinks at the poles forming high pressure zones.
- The resulting pressure gradients lead to winds like trade winds, westerlies and polar easterlies.
- Ocean currents also play a role in redistributing heat globally.

Changes in energy balance can impact atmospheric circulation patterns, affecting weather systems, ocean currents and climate zones. As the Sun's energy is vital for Earth's climate, human induced greenhouse gas emissions have a more significant impact on global warming. Understanding these processes helps us to address climate change and its consequences.


**Figure 24.13: Energy imbalance between poles and equator.**

## 24.4.3 Climate Science as a Chaotic System

Climate science provides a fascinating example of a chaotic system. In a chaotic system there is no equilibrium and no repeatable patterns emerge. Chaotic systems exhibit extreme sensitivity to initial conditions. This means that even small changes in the starting conditions can lead to vastly different outcomes over time. Climate being a complex and interconnected system can exhibit chaotic behavior as we often think of climate as having predictable seasons and weather patterns (like the news inform us about a rain today but it does not happen) it can also undergo sudden and rapid changes due to chaotic dynamics.

**Butterfly Effect:** Consider the metaphor of a butterfly flapping its wings in one part of the world then according to chaos theory this seemingly insignificant event could potentially set off a chain reaction of interactions that eventually lead to a hurricane forming in another part of world, this phenomenon is popularly known as the "*butterfly effect*". The butterfly effect illustrates how small perturbations can amplify and propagate through a complex system ultimately influencing large scale events.

**Predictability and Uncertainty:** Climate scientists sometimes refer to the effects of chaos as intrinsic or unforced variability. These are unpredictable changes arising from dynamic interactions within the climate system rather than being directly caused by external factors. Our atmosphere and oceans do not behave in simple easily predictable ways they are non-linear chaotic systems. As a result, we can only predict large-scale weather features with relative certainty and only for a few days in advance. In this scenario the weather forecasting for an extended time period is less reliable, these predictions may be more reliable only for short time scale afterward.

Climate science exemplifies the delicate balance between predictability and chaos. While we strive to understand and model climate dynamics the inherent complexity and sensitivity to initial conditions remind us that some aspects of our climate remain inherently uncertain and difficult to predict.

## SUMMARY

- Earth's climate system is a complex system with five interacting components the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere.
- Hydrosphere encompasses all the water on the Earth whether it is in liquid water, solid ice or the gaseous water vapors form.
- Cryosphere refers to any place on Earth where water is in its solid form, where low temperatures freeze water and turn it into ice.
- Permafrost refers to permanently frozen ground found mainly in high altitude regions. It contains ice and soil that remain frozen for extended periods.
- Biosphere refers to the relatively thin life supporting layer of Earth's surface. It extends from a few kilometers into the atmosphere to the deep-sea vents in the ocean.
- Nutrient cycles: Elements like carbon (C), nitrogen ($N_2$) and phosphorous (P) cycle through the biosphere impacting both living organisms and the environment.
- Large rotating currents that start near the equator are called subtropical gyres.
- Coriolis force: The rotation of Earth influences the path of these currents. A force resulting from the Earth's rotation is called coriolis force.
- The Deep Ocean currents are caused by differences in water density this process is called thermohaline circulation.
- Horizontal pressure gradient force is the change in pressure measured across a given distance is called a pressure gradient.
- Precipitation is any liquid or frozen water that forms the atmosphere and falls back to the Earth.
- Climate inertia refers to the tendency of the Earth's climate to resist or respond slowly to changes in external factors like greenhouse gas concentrations and solar radiations.
- Aerosol is a suspension of particles or droplets in the air and includes dust, mist, fumes or smoke.
- Chaotic system is system in which there is no equilibrium and no repeatable patterns emerge it exhibits extreme sensitivity to initial conditions.
- Butterfly Effect: the metaphor of a butterfly flapping its wings in one part of the world can lead to a hurricane forming in another part of world.

## EXERCISE

### Multiple Choice Questions

**Encircle the Correct option.**

1) Which of the following gases has the maximum contribution to global warming?
   A. Chlorofluorocarbons (CFCs) B. Methane ($CH_4$)
   C. Sulfur hexa-fluoride ($SF_6$) D. Carbon dioxide ($CO_2$)
2) Which of the following gas is not responsible for global warming?
   A. $N_2O$ B. $H_2O$ C. $SO_2$ D. $CO_2$
3) In global warming the temperature of ________________ increases:
   A. Troposphere B. Ionosphere C. Mesosphere D. Stratosphere
4) Which type of climate is found in our country Pakistan?
   A. Tundra B. Equatorial C. Monsoon D. Western
5) What is the height of troposphere near the poles and the equator in kilometers?
   A. 8 and 18 B. 6 and 16 C. 4 and 16 D. 10 and 20
6) What happens in the ionosphere?
   A. Meteors burns B. Airplanes fly C. Radio waves reflected D. Satellites move
7) Which atmospheric layer contains ions and helps in wireless communications?
   A. Troposphere B. Thermosphere C. Mesosphere D. Stratosphere
8) The part of the Earth atmosphere which contains about 70% of the total air in the atmosphere is:
   A. Troposphere B. Thermosphere C. Mesosphere D. Stratosphere
9) Hot and dry winds blowing in the northern plains of Punjab and Sindh are:
   A. Trade winds B. Loo C. Westerlies D. Easterlies
10) Pakistan is located in the region of __________ winds:
   A. Trade B. North easterlies C. Westerlies D. South easterlies

### Short Questions

1) Where in the atmosphere is water vapor most concentrated and why?
2) What is the difference between the weather and the climate?
3) Warm air has a greater capacity to hold water vapors. Why?
4) How does the atmosphere retain itself?
5) Describe global latitudinal air movements due to uneven heating at different latitudes.
6) What would be the consequences if all the polar ice melts?
7) Is the lithosphere a part of mental? Justify your answer.
8) What are the four components of the biosphere?
9) Why stratosphere is called a calm and stable layer?

### Comprehensive Questions

1) Describe Earth's climate system as a complex system having five interacting components.
2) What is climate inertia? Explain.
3) Explain how global climate is determined by energy transfer from the Sun.

4) Discuss the Earth energy budget in detail.
5) Explain how the energy imbalance between the poles and the equator can affect atmospheric circulation.
6) *Explain that due* to the conservation of angular momentum, the Earth's rotation diverts the air to the right in the Northern Hemisphere and to the left in the Southern hemisphere, thus forming distinct atmospheric cells.
7) Discuss that how differences in density of ocean water play an important role in ocean circulation.
8) How the thermohaline circulation transports heat from the, tropics to the polar regions? Explain.
9) Show that the climate science is a chaotic system in terms of butterfly effct.
10) Differentiate between surface ocean currents and deep ocean currents.
11) What are coriolis force and thermohaline circulations?

## Numerical Problems

1) If the volume of change in storage of the hydrosphere, whose area is 30 $km^2$ is 600,000 $m^3$, find net precipitation (P) if the volume of evapotranspiration is 1,500,000 $m^3$ and runoff volume is 600,000 $m^3$. (Ans: 90 mm)

2) If a Coriolis force of 30 N deflects a mass of air at $30^0$ moving with speed of 40 km $h^{-1}$. Find the mass of this air packet (where $\omega = 7.3 \times 10^{-5}$ rad $s^{-1}$). (Ans: 369,900 kg)