# DP IB Environmental Systems & Societies (ESS): HL

Your notes

## 6.1 Introduction to the Atmosphere

### Contents

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# Atmospheric Composition & Function

- The atmosphere forms the boundary between Earth and space
- It is the outer limit of the biosphere
- The atmosphere **supports life** on Earth

## Atmospheric gases and their redistribution

- The atmosphere is mainly composed of **nitrogen** (about 78%) and **oxygen** (about 21%)
  - These two gases make up the majority of the atmosphere and play vital roles in supporting life on Earth
- The atmosphere contains smaller amounts of other gases, including:
  - **Carbon dioxide**
  - **Argon**
  - **Water vapour**
  - **Various trace gases**
- Carbon dioxide, although present in relatively low concentrations (around 0.04%), is essential for:
  - **Photosynthesis** in plants
  - Maintaining the **greenhouse effect**
- Argon is an inert gas that does not participate in chemical reactions but contributes to the overall composition of the atmosphere
- Water vapour plays an important role in:
  - **Photosynthesis** in plants
  - The Earth's **weather patterns**
  - The formation of **clouds** and **precipitation**
- Trace gases, such as methane, ozone, and nitrous oxide, are present in even smaller quantities
  - However, they still have significant impacts on climate and atmospheric chemistry

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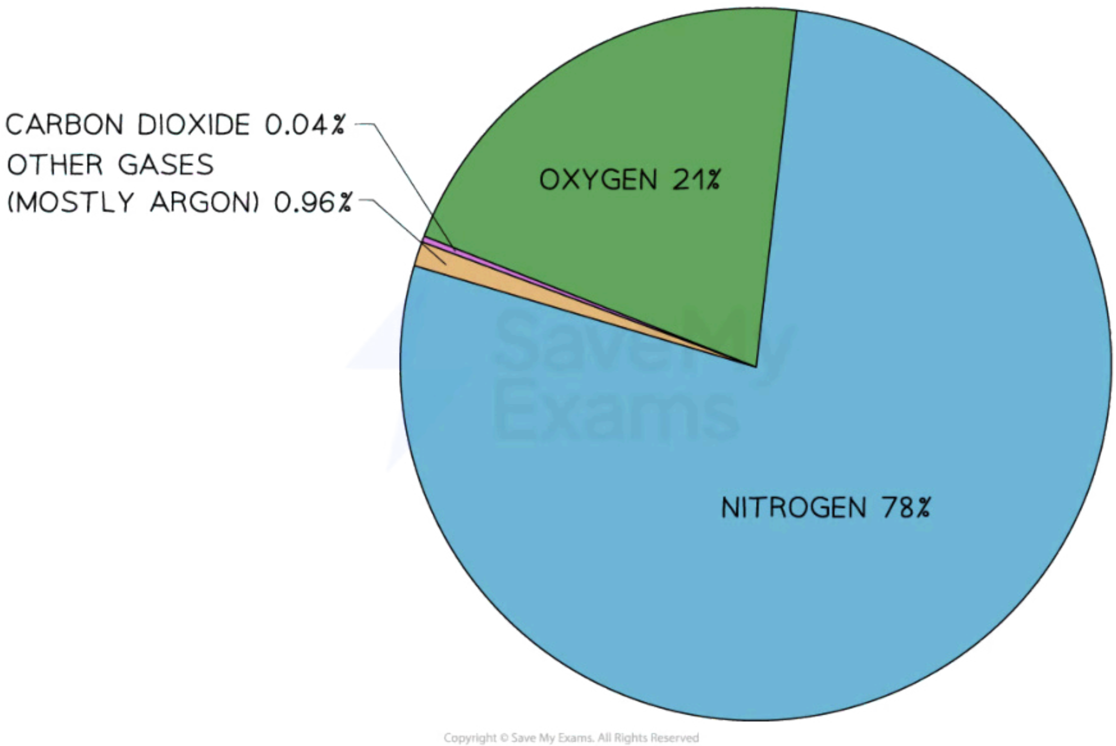


*The gaseous composition of the Earth's atmosphere*

## Redistribution through physical processes

- Gases in the atmosphere are moved around by various physical processes, including:
  - **Wind**: the main mover of gases, caused by differences in air pressure
  - **Convection**: warm air rises and cool air sinks, creating vertical movement
  - **Diffusion**: gases spread from areas of high concentration to areas of low concentration
  - **Turbulence**: irregular air flow caused by obstacles like mountains and buildings
  - **Jet streams**: fast-flowing, narrow air currents in the upper atmosphere

# Atmospheric layers

- **Atmospheric stratification**:
  - The atmosphere is divided into layers based on **temperature changes**
  - The key layers for living systems are the **troposphere** and the **stratosphere**

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- **Troposphere**:
  - The **lowest layer**, extending up to about **10 km** from the Earth's surface
  - Weather phenomena, such as clouds, precipitation, and gas mixing, occur here
  - Contains the highest concentration of water vapour, carbon dioxide and other important trace gases
- **Stratosphere**:
  - Located **above** the troposphere, extending from about **10 to 50 km** above the Earth's surface
  - Contains the **ozone layer**, which **absorbs** and **blocks** most of the Sun's harmful **ultraviolet (UV) radiation**
- **Importance of inner layers**:
  - Various reactions in the troposphere and stratosphere are vital for maintaining the balance of gases, **regulating climate** and **supporting life**
  - In the troposphere, chemical reactions involving pollutants, greenhouse gases and particles impact **air quality** and **climate**
  - In the stratosphere, chemical reactions involving **ozone** maintain the ozone layer and protect organisms on Earth from harmful UV radiation

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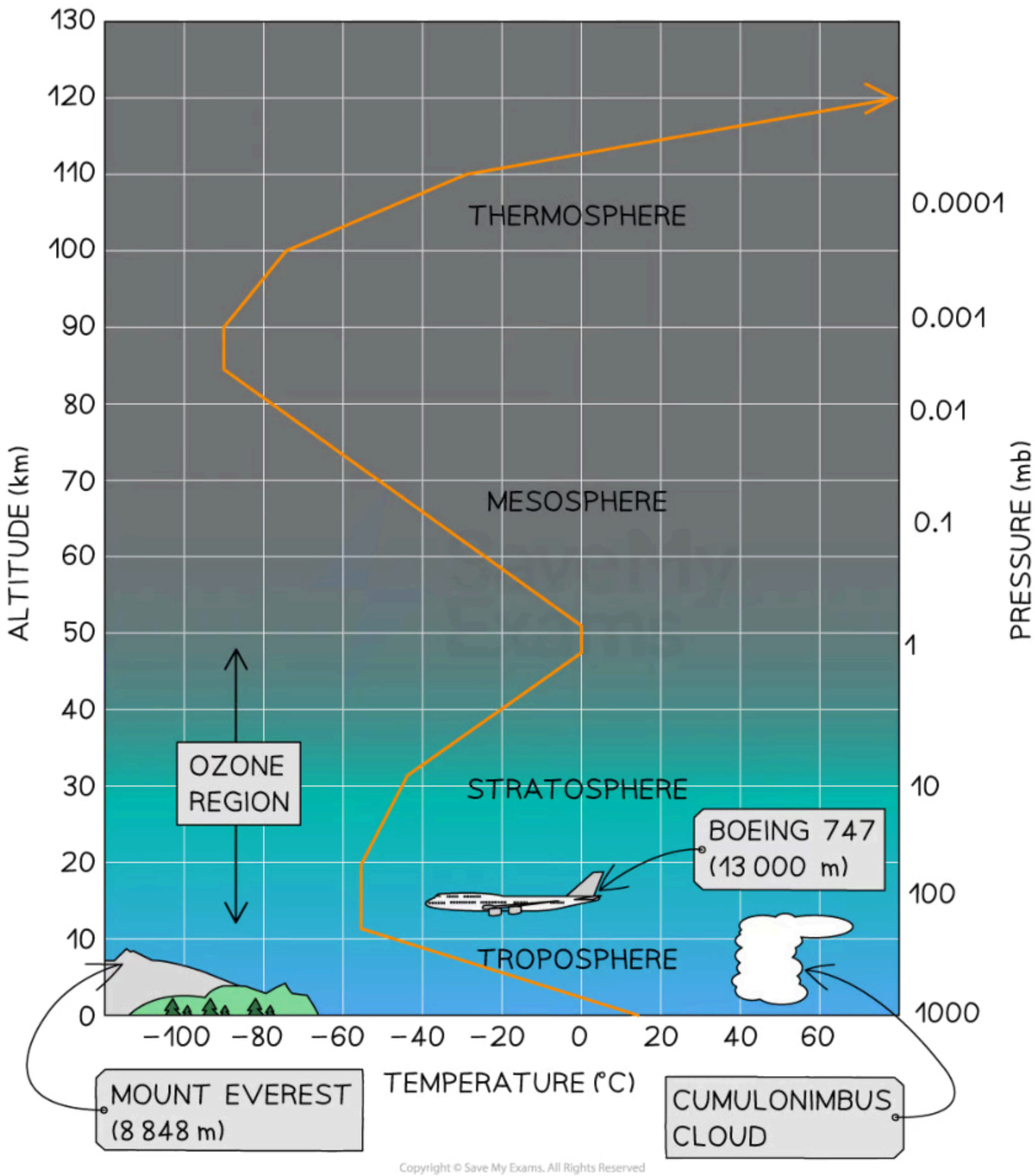


***Approximate atmospheric temperatures and pressures up to an altitude of about 120 km—note the warmer temperatures in the troposphere, below the zone of maximum ozone concentration (in the stratosphere)***

## Differential heating and the tricellular model

- Differential heating of the atmosphere:
  - The Sun heats the Earth and its atmosphere **unevenly**

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- The equator receives more direct sunlight, making it warmer
- The poles receive less direct sunlight, making them cooler
- This results in an effect known as the tricellular model of atmospheric circulation
  - This model explains how heat is **distributed** from the **equator** to the **poles**

## Atmospheric Systems

- The atmosphere is a highly **dynamic system**
  - It plays a crucial role in the Earth's climate and weather patterns
  - As with other systems, the atmospheric system is made up of storages, flows, inputs and outputs
- **Storages**:
  - The atmosphere acts as a storage for **gases**
  - These gases are present in different concentrations
  - These concentrations can vary over time due to natural and human activities
  - This includes greenhouse gases like carbon dioxide and methane
    - These gases contribute to the greenhouse effect and influence the Earth's temperature
- **Flows**:
  - Within the atmosphere, there are constant flows of gases and particles
  - These flows are driven by processes such as air currents, weather patterns and atmospheric circulation
  - These flows contribute to the movement and redistribution of gases and other substances within the atmosphere
- **Inputs**:
  - The atmosphere receives inputs from various sources
  - Natural inputs include:
    - Gases emitted from **volcanic eruptions**
    - Gases emitted from **plants** and other **living organisms**
    - **Dust** particles from **desert regions**
  - Anthropogenic inputs, resulting from **human activities**, include:
    - Greenhouse gases (e.g. from fossil fuel combustion and livestock)

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    - Air pollutants from industrial processes
    - Aerosols from combustion

***Human activities such as emissions from industrial chimneys create inputs into atmospheric systems (Photo by Michal Pech on Unsplash)***

- **Outputs**:
  - Gases maybe be removed from atmospheric systems through natural processes like **respiration** and **photosynthesis**
  - **Pollutants** and **aerosols** can be removed from the atmosphere through, e.g. **precipitation** and **dry deposition**
- **Exchanges and interactions with other Earth systems**:
  - The atmosphere interacts with other components of the Earth system
    - This includes the **biosphere** (plants, animals, and microorganisms), **hydrosphere** (oceans, lakes, and rivers), and **lithosphere** (landmasses and rocks)
  - It exchanges gases and particles with these systems through various mechanisms

- E.g. the exchange of carbon dioxide occurs through photosynthesis by plants and respiration by organisms
- These interactions involve the exchange of gases, energy and particles
  - This shapes climate patterns, weather events and overall Earth system dynamics

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### Examiner Tips and Tricks

You need to be familiar with the tricellular model of atmospheric circulation, as this is an important part of Topic 2.4 (Climate & Biomes).

You should recall how this model explains the behaviour of atmospheric systems and the distribution of **precipitation** and **temperature** at **different latitudes**.

It also explains how these factors influence the structure and relative **productivity** of **different terrestrial biomes**.

Go back and have a look at this revision note again if you need to revise it!

The Greenhouse Effect

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# Greenhouse Gases & the Greenhouse Effect

- Greenhouse gases (GHGs) and aerosols play an important role in Earth's climate by trapping heat in the atmosphere

## Greenhouse gases and aerosols

- **GHGs**: gases in the atmosphere that trap heat
  - Key GHGs:
    - **Water vapour**
    - **Carbon dioxide**
    - **Methane**
    - **Nitrous Oxides**
- **Aerosols**: tiny particles or droplets in the atmosphere
  - Key aerosols:
    - **Black carbon**
      - A type of aerosol produced from incomplete combustion of fossil fuels, wood and other biomass
      - Found in emissions from, e.g. diesel engines, cooking stoves and open burning of vegetation
      - Absorbs sunlight and warms the atmosphere
      - Can darken snow and ice surfaces, reducing their reflectivity and accelerating melting

**Key Greenhouse Gases**

| Name of GHG | Sources | Other Information |
|---|---|---|
| **Water vapour** | Evaporation from oceans, lakes and rivers<br>Transpiration from plants<br>Sublimation from ice and snow | Most abundant GHG<br>Concentration varies with temperature<br>Amplifies effects of other GHGs |

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| | | |
|---|---|---|
| | Combustion of fossil fuels | Positive feedback loop: warmer atmosphere holds more water vapour, leading to more warming and greater evaporation<br><br>It is often excluded from climate models due to its dynamic levels and essential role in life, meaning it cannot be mitigated against |
| **Carbon dioxide** | Burning fossil fuels: coal, oil and natural gas (e.g. vehicle emissions)<br><br>Deforestation (when forests are cleared or burned, the carbon stored in trees is released back into atmosphere as carbon dioxide)<br><br>Industrial processes (e.g. cement production) | Significant contributor to the greenhouse effect due to high concentration and long lifespan in the atmosphere |
| **Methane** | Agriculture: livestock digestion (e.g. from large-scale cattle farming)<br><br>Landfills<br><br>Natural gas extraction (methane leaks)<br><br>rice paddies<br><br>Wetlands | More effective at trapping heat than carbon dioxide (over 20 times more potent over 100 years)<br><br>Found in much lower concentrations than carbon dioxide, so overall warming effect is less |
| **Nitrous oxides** | Agricultural practices (use of synthetic and organic fertilisers)<br><br>Fossil fuel combustion<br><br>Industrial processes | Potent GHG with a warming effect nearly 300 times that of carbon dioxide per molecule<br><br>Found in much lower concentrations than carbon dioxide, so overall warming effect is less |

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***Rice paddies produce methane due to the anaerobic conditions created by flooded cultivation, which promote the growth of methane-producing microorganisms that decompose organic matter in the soil (photo by Steve Douglas on Unsplash)***

# The Greenhouse Effect

## What is the Greenhouse Effect?

- The Sun emits energy in the form of solar radiation
  - This includes visible light and ultraviolet rays
- This solar radiation enters the Earth's atmosphere
- Some thermal energy is **reflected** from the Earth's surface
- Most thermal energy is **absorbed** and **re-emitted** back from the Earth's surface
  - This energy **passes through the atmosphere**
- Some thermal energy passes straight through and is emitted into **space**
- However, some thermal energy is **absorbed** by **greenhouse gases**

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- This causes thermal energy to be re-emitted in all directions
- These gases act like a blanket
  - They allow sunlight to pass through while preventing a significant amount of the infrared radiation from escaping back into space
- This reduces the thermal energy lost into space and **traps** it within the Earth's atmosphere
  - This keeps the Earth warm
- This process is known as the **greenhouse effect**
  - The greenhouse effect is a **naturally occurring phenomenon**
  - The greenhouse effect is important to ensure that Earth is warm enough for **life**
  - Without the greenhouse effect, the average temperature would be much **colder**, making the planet **uninhabitable**
    - For example, the average surface temperature of Earth is about 15 °C
    - Without the greenhouse effect, it would be about -18 °C

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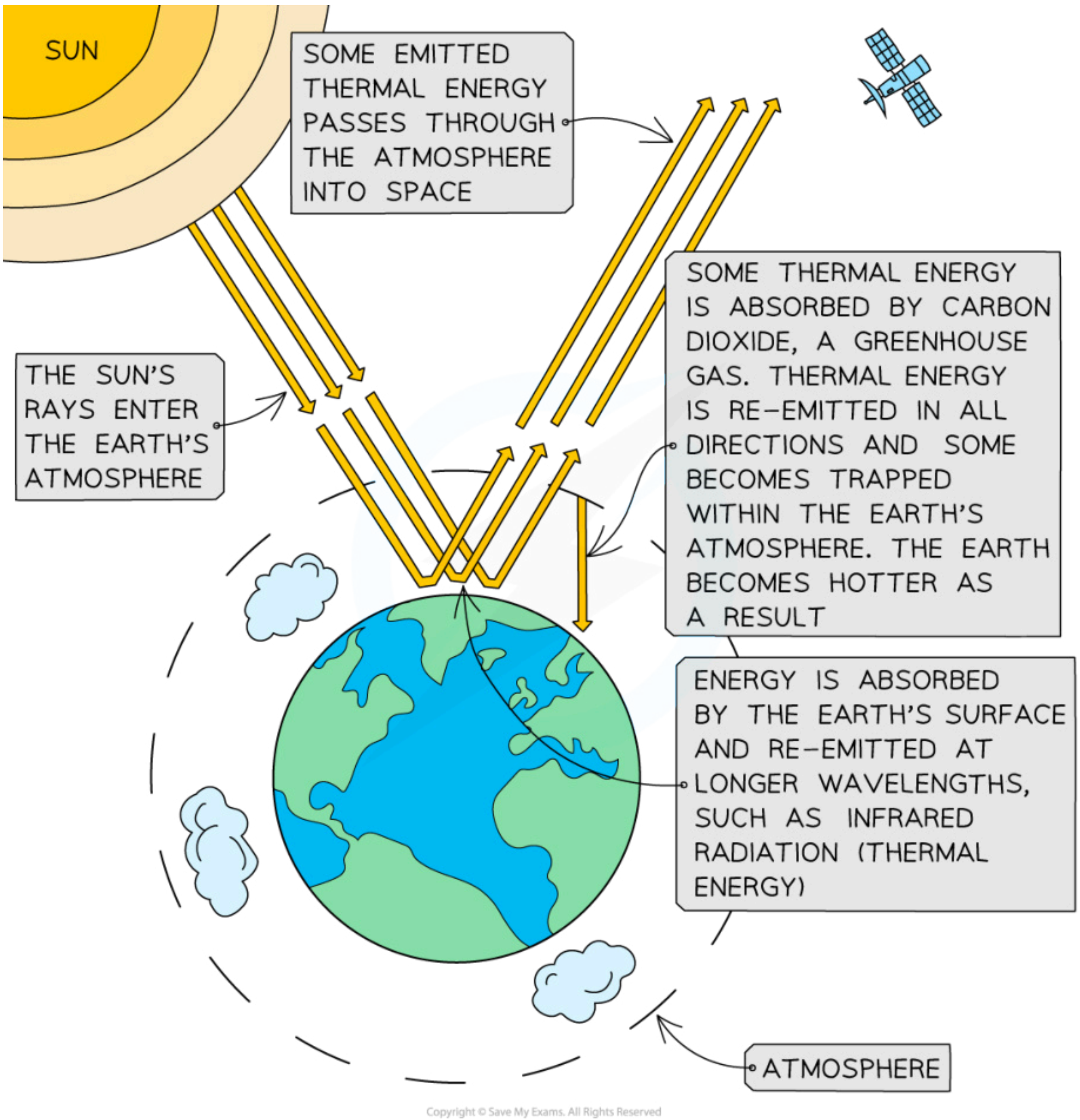


***Greenhouse gases absorb the radiation that is re-emitted from the Earth's surface, trapping it in the atmosphere***

## Examiner Tips and Tricks

Don't get confused—the greenhouse effect is a natural process and is necessary for life on Earth. The **accelerated** or **enhanced** greenhouse effect refers to the changes in the greenhouse effect (mostly due to human activity) that are commonly referred to as global warming. This is discussed further in Causes of Climate Change.

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# Atmospheric Dynamics & Processes

- The atmosphere is a **dynamic system** that surrounds the Earth
- It is composed of various components and layers, each with distinct characteristics
  - These result from continuous **physical** and **chemical processes** occurring over time

## Physical processes

### Global warming

- The **enhanced greenhouse effect** is the main cause of global warming
- The enhanced greenhouse effect is **different** from the **natural** greenhouse effect
  - Human activities primarily drive the effect through releasing excessive amounts of greenhouse gases into the atmosphere
  - This leads to an intensified trapping of heat
- The natural greenhouse effect is a necessary process that helps regulate the Earth's temperature by trapping some heat to maintain a **habitable climate**
- In contrast, the enhanced greenhouse effect **disrupts this balance**
  - This occurs because greenhouse gas concentrations have been **artificially increased** beyond natural levels

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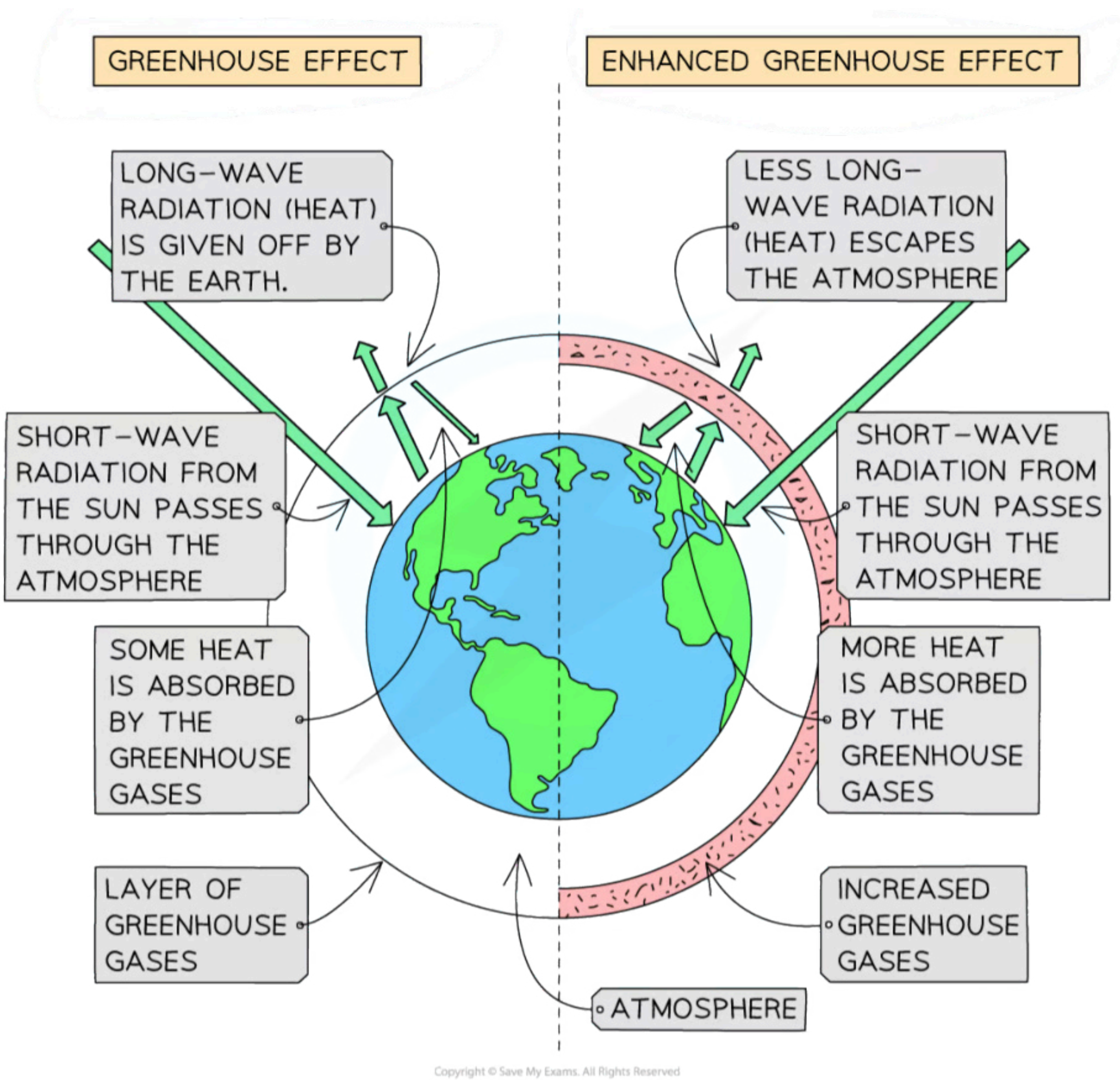


***Human activities lead to the emission of greenhouse gases that enhance the natural greenhouse effect, contributing to global warming***

## Air movements

- Differences in the **atmosphere's temperature** and **pressure** have an impact on air movements
  - Warm air is less dense and rises, while cold air is denser and sinks
  - This creates convection currents that drive wind patterns and weather systems
    - E.g. the tricellular model of atmospheric circulation

# Chemical processes

## Ozone production

- Ozone is a molecule composed of three oxygen atoms (**$O_3$**)
  - It is mainly formed in the Earth's stratosphere through chemical reactions involving sunlight and oxygen
- Ozone plays a crucial role in **protecting life on Earth** by **absorbing** a significant portion of the Sun's harmful ultraviolet (UV) radiation
- When UV radiation from the Sun interacts with ozone molecules, some of the ozone **absorbs** the energy and **breaks apart**
  - This forms an oxygen molecule (**$O_2$**) and a free oxygen atom (**O**)
- The free oxygen atom can then combine with another oxygen molecule to form ozone again
- This ozone destruction and reformation create a **dynamic equilibrium** in the stratosphere
  - This is a **continuous cycle** of ozone molecules being broken apart and reformed
  - This dynamic equilibrium ensures that the concentration of ozone in the stratosphere remains relatively **stable** over time

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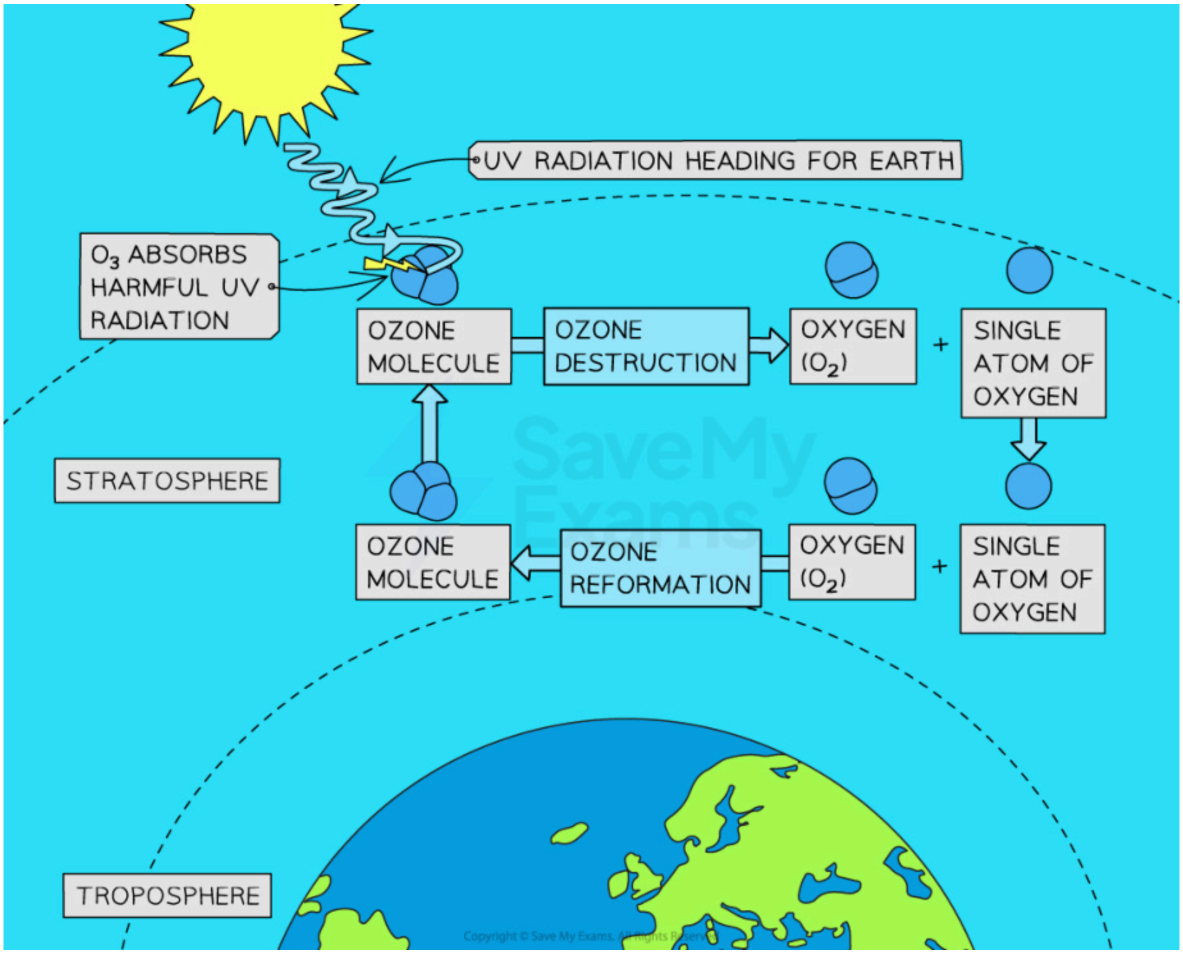


*Ozone destruction and reformation creates a dynamic equilibrium in the stratosphere—there is a continuous cycle of ozone molecules being broken apart and reformed*

## Atmosphere & Altitude (HL)

Your notes

# Atmosphere & Altitude

## Atmosphere and gravity

- The atmosphere is made up of **layers of gases** surrounding the Earth
  - **Gravity** keeps these layers in place
- Gravity pulls atmospheric molecules towards the Earth's surface
  - This makes the air **denser** at **lower altitudes**
- As altitude **increases**, the strength of gravitational pull **decreases** because:
  - Gravitational force is **inversely proportional** to distance from the Earth
  - This inverse relationship means that atmospheric pressure and density decline with altitude
  - This causes the atmosphere to become **thinner**

## Atmospheric thinning with altitude

- **Atmospheric thinning** refers to the gradual decrease in air density as altitude increases
  - This means fewer molecules are present in a given volume of air at higher altitudes
  - At **sea level**, the atmosphere is **dense**, containing a higher concentration of oxygen and other gases
  - As altitude increases, oxygen levels decrease, which can affect breathing and cause altitude sickness
    - For example, high-altitude locations, such as **Mount Everest**, have significantly thinner air, requiring climbers to use oxygen tanks

## Standard lapse rate

- The **standard lapse rate** describes how temperature decreases with an increase in altitude
  - On average, temperature drops by about **1 degree Celsius for every 100 metres** of altitude gained
  - This change in temperature affects weather patterns as well as plant and animal life
    - For example, temperatures at mountain summits are often much colder than temperatures at the base, even though they are geographically close to each other

- Lower altitudes may have forests, while higher altitudes may be covered in snow or only support low-growing plants

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## Examiner Tips and Tricks

Note that the standard lapse rate applies up to an altitude of **around 10 km** (i.e. within the **troposphere**).

You do **not** need to know any specific volumes or pressures of atmospheric gases at specific altitudes for your exams.

## Milankovitch Cycles (HL)

Your notes

# Milankovitch Cycles

- Milankovitch cycles describe **three long-term changes in Earth's position and movement relative to the Sun**
  - These cycles impact the **amount of solar radiation** Earth receives
  - This influences the **climate** over very **long timescales** (tens to hundreds of thousands of years)
- The cycles contribute to natural climate patterns such as:
  - Ice ages
  - Warmer interglacial periods

## Three types of Milankovitch cycles

### 1. Eccentricity (shape of Earth's orbit)

- **Eccentricity** refers to the **shape of Earth's orbit** around the Sun
- This orbit changes from a more circular shape to a more elliptical shape over a cycle of about **100,000 years**
  - When the orbit is **more elliptical**, Earth's distance from the Sun varies more
    - This creates larger differences in solar radiation received at different times of the year
  - When the orbit is **more circular**, the distance from the Sun remains more constant
    - This leads to smaller differences in seasonal temperatures
- **Climate impact**:
  - Lower eccentricity (circular orbit) results in **milder seasonal differences**
  - This milder climate can allow **ice sheets** to slowly **build up** over time, especially in polar regions
  - If the Earth's tilt is also smaller, the poles receive less direct sunlight, making it harder for ice to melt
  - As a result, **snow and ice accumulate**
  - This can lead to the onset of a **glacial period** or **ice age**

### 2. Obliquity (tilt of Earth's axis)

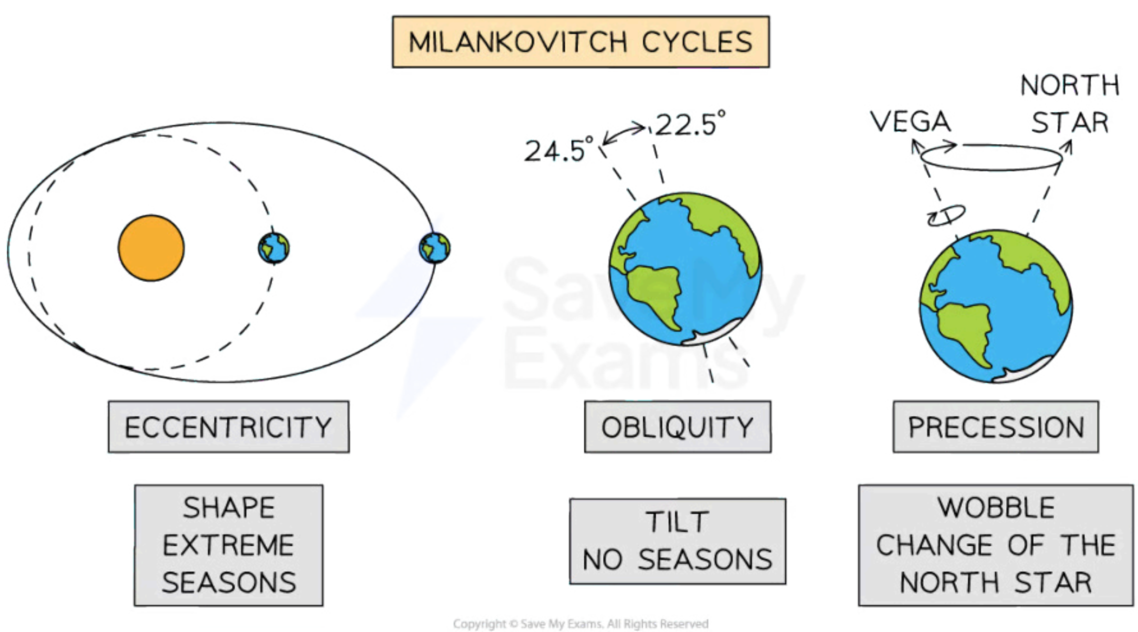
- **Axial tilt** refers to the **angle at which Earth's axis tilts** in relation to its orbit around the Sun

- The tilt angle changes from about **22.5° to 24.5°** over a cycle of approximately **41,000 years**
- Greater tilt increases the intensity of seasons, making summers warmer and winters colder

- **Climate impact**:
  - A **higher tilt** (closer to 24.5°) creates stronger seasonal contrasts
    - This can reduce the buildup of polar ice by making summers warmer
  - A **lower tilt** (closer to 22.1°) reduces seasonal contrasts
    - This allows ice to persist at the poles and contributes to glaciation

## 3. Precession (wobble of Earth's axis)

- **Axial precession** is the **wobble in Earth's rotational axis**
  - This cycle takes approximately **26,000 years** and causes the timing of seasons to shift
  - As Earth wobbles, the position of the North Star gradually changes
- **Climate impact**:
  - Precession affects the **seasonal distribution of solar radiation**
  - This can lead to warmer or cooler summers and winters
    - This depends on where Earth is in its orbit when each season occurs




***The shape, tilt and wobble of Earth's movement, over thousands of years, affects long-term climate***

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## Milankovitch cycles and climate change

- The combined effects of **eccentricity, obliquity, and precession** drive long-term climate shifts, like the Ice Ages
  - **Positive feedback loops** amplify these climate shifts
    - For example, cooling from reduced solar radiation can lead to **glaciation**
      - This snow and ice reflect sunlight (albedo effect) and cause further cooling
    - Warming increases carbon dioxide, enhancing the greenhouse effect and leading to **interglacial periods**
- **Role of carbon dioxide**:
  - Lower temperatures reduce carbon dioxide in the atmosphere, enhancing cooling
    - Cooler temperatures make the atmosphere less able to hold gases like carbon dioxide, which the oceans or soils then absorb
  - Higher temperatures release more carbon dioxide, enhancing warming
    - This occurs because warmer temperatures increase the rate at which carbon dioxide is released from sources like soils, oceans, and plant life
    - This increases atmospheric carbon dioxide levels

## Real-world examples

- **Last glacial maximum**:
  - It occurred approximately **20,000 years ago** when eccentricity, axial tilt, and precession aligned to favour cooling
  - Resulted in extensive ice sheets covering parts of North America and Europe
- **Current interglacial period**:
  - We are currently in a warmer interglacial period called the **Holocene**, which began around 11,700 years ago
  - This period has allowed the development of human civilisation due to the relatively stable and warmer climate

### Examiner Tips and Tricks

> Although Milankovitch cycles explain natural long-term climate patterns, they do **not** explain **recent, rapid global warming**, which is mainly due to **human activities** like fossil fuel burning.

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## Hothouse Earth (HL)

# Hothouse Earth

- **Global warming** is moving the Earth away from the natural glacial-interglacial cycles of the **Quaternary period**
  - The Quaternary period began **2.5 million years ago**
  - It was characterised by alternating ice ages and warmer interglacial periods
- Natural climate changes have previously occurred over very long time periods (i.e. tens to hundreds of thousands of years)
- However, **human activities** are now driving **unprecedented rapid** changes in the climate
  - Some scientists suggest that these changes mark the beginning of the **Anthropocene epoch**

# What is Hothouse Earth?

- The **Hothouse Earth** concept refers to a potential future state where the Earth's climate becomes **much hotter** than the natural variability of the past
  - Scientists researching Earth's historical climate and its reaction to greenhouse gases were the first to propose this idea
  - Hothouse Earth describes a scenario where warming **self-amplifies** through positive feedback mechanisms
  - This leads to:
    - extreme global temperatures
    - severe climate and weather events
    - significant changes in ecosystems
  - In the Hothouse Earth climate change scenario, the Earth's average temperature rises irreversibly to **4–5°C above pre-industrial levels**

# The role of tipping points

- **Climate tipping points** are thresholds where small changes can lead to significant, irreversible shifts in the climate
  - Even an increase of just **2°C** could trigger a series of **positive feedback loops** that intensify the global warming process

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- Once these feedbacks are triggered, they can drive further warming and climate change
- This creates a **feedback cycle that is difficult to reverse**

## Positive feedback mechanisms

- **Positive feedback loops** amplify global warming and its effects
  - **Melting ice**
    - As the ice melts, the Earth's surface becomes **darker**, absorbing more sunlight and further increasing warming
  - **Methane release**
    - Warming leads to the release of **methane** from thawing **permafrost**, which is a powerful greenhouse gas
  - **Reduced carbon storage**
    - As temperatures rise, oceans may become **less effective at absorbing carbon**
    - This may lead to higher levels of greenhouse gases in the atmosphere

***Awaiting image: Hothouse earth***

***Image caption: "Hothouse Earth" is a potential future climate state where self-amplifying feedback loops drive the Earth's temperature far beyond natural limits, causing extreme, irreversible warming***

Atmospheric Composition & Evolution of Life (HL)

Your notes

# Atmospheric Composition & Evolution of Life

- The composition of the atmosphere has **changed significantly over time**
  - The evolution of life has been largely responsible for these changes.
- Early life forms on Earth influenced changes in the atmosphere, which impacted the evolution of life

## Composition of the pre-biotic atmosphere

- Earth's early atmosphere was very different from the atmosphere we have today
  - It is sometimes referred to as the pre-biotic *(before life)* atmosphere
- It is likely to have contained:
  - High levels of carbon dioxide ($CO_2$) and methane ($CH_4$)
  - No Oxygen ($O_2$), or only trace amounts
  - Nitrogen ($N_2$) was probably present in high concentrations, similar to today
- The early atmosphere had no protective ozone layer
  - This exposed Earth to harmful UV radiation

## Changes in atmospheric composition due to evolution of life

### Photosynthesis and oxygenation

- Around 2.5 billion years ago, cyanobacteria developed **photosynthesis,** altering Earth's atmosphere
  - These photosynthetic organisms absorbed $CO_2$ and released $O_2$
  - This led to a gradual **decrease in $CO_2$ levels** and an **increase in $O_2$ levels**
- The rise in $O_2$ allowed for the development of **aerobic life forms** that rely on oxygen

### Formation of the ozone layer

- Increased oxygen in the atmosphere led to the formation of **ozone** ($O_3$) in the **stratosphere**
  - Ozone absorbs harmful UV radiation, creating a protective layer around Earth
  - This allowed for **more complex life forms** to evolve on land, protected from UV damage

### Oxidation and mineral formation

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- The process of **iron ore formation** occurred in ancient oceans, where photosynthetic organisms released oxygen into the seawater
- Oxygen reacted with dissolved iron, forming **iron oxides** like **hematite** and **magnetite**
- These iron oxides settled on the ocean floor in distinct layers
  - This created what are known as **banded iron formations** (BIFs)
  - Banded iron formations are significant **geological evidence** of **early oxygenation of the oceans and atmosphere**
- This oxidation process changed Earth's surface and influenced the types of minerals present

***Banded iron formation, Karijini National Park, Western Australia (photo by Graeme Churchard, taken from Wikimedia Commons, CC BY 4.0)***

- The presence of oxygen allowed for the process of **aerobic respiration** to evolve
  - This was more energy-efficient than anaerobic processes
  - This enabled the evolution of more **complex** and **energy-demanding organisms**
- The protective ozone layer made life on land **viable**

- This allowed the spread of diverse **terrestrial species**

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## Examiner Tips and Tricks

You do **not** need to memorise the specific chronology (timeline) of changes, such as oxygenation, that have occurred to Earth's atmosphere throughout the planet's history.