DP IB Environmental Systems & Societies (ESS): HL

Your notes

4.1 Water Systems

Contents

Hydrological Cycle

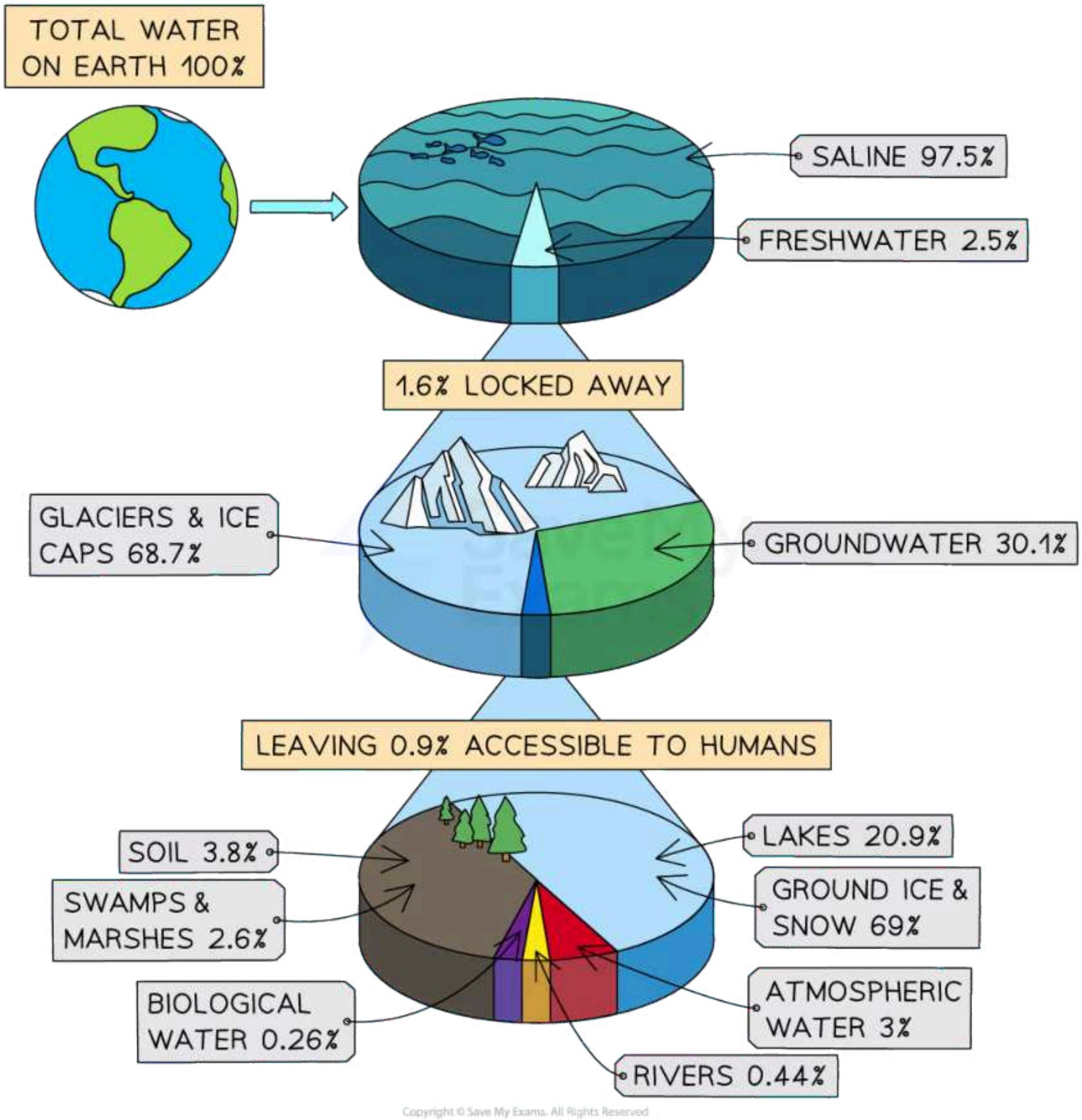
Your notes

Hydrological Cycle

Water on Earth

- The **hydrosphere** includes all Earth's water, such as oceans, rivers, lakes and atmospheric moisture
    - Fresh water only makes up a small fraction (approximately 2.5% by volume) of the Earth's water storages
    - Of this fresh water, approximately 69% is stored in glaciers and ice sheets and 30% is stored as groundwater
    - The remaining 1% of freshwater is in rivers, lakes and the atmosphere
- All water is part of the **hydrological cycle**

Your notes



Comparison of the world's freshwater stores

Driving forces of the hydrological cycle

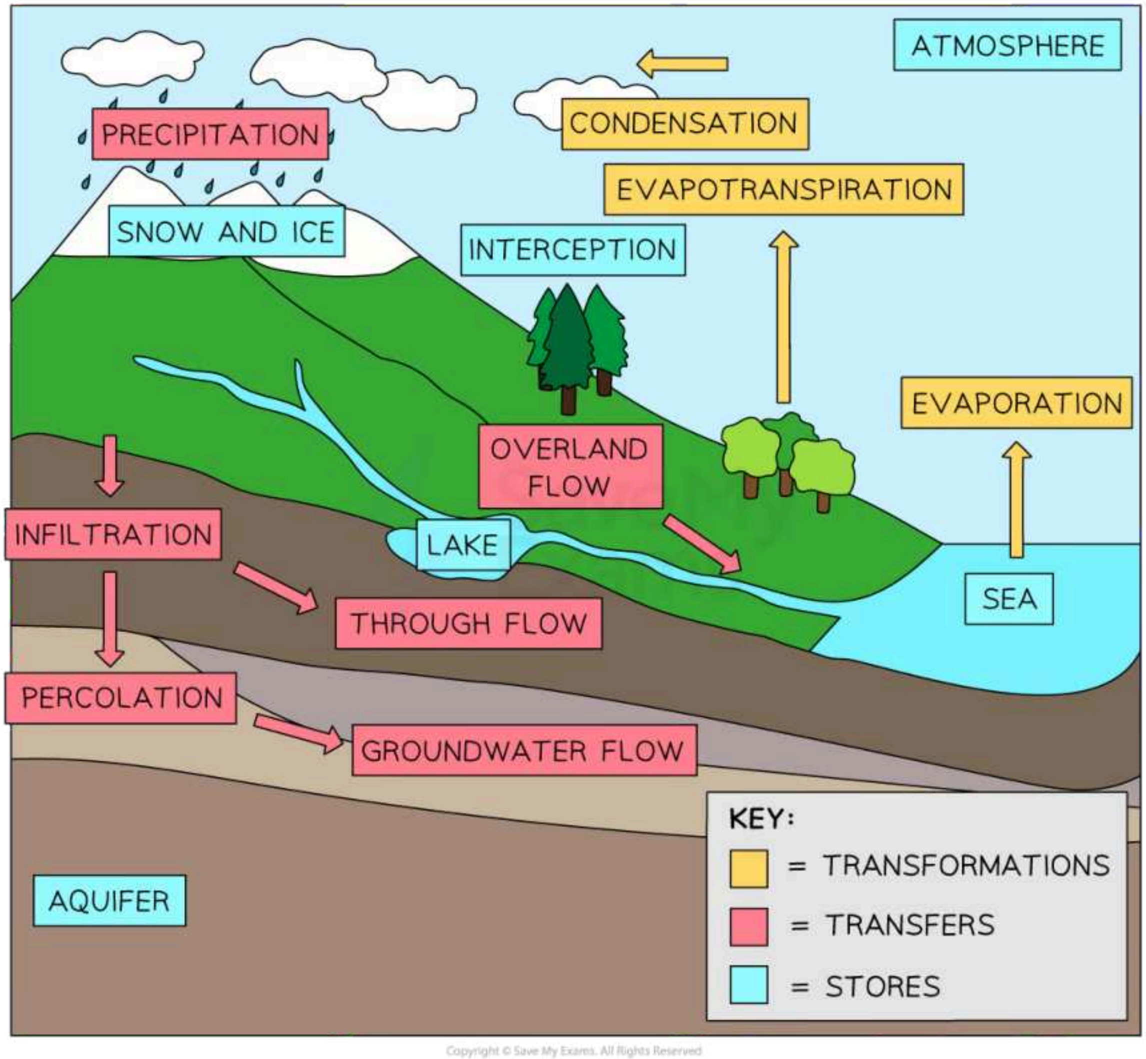
- **Gravity** and **solar radiation** both influence the movement of water in the hydrosphere
  - The Sun's heat causes water to evaporate from oceans, lakes, and rivers
  - Water vapour cools and condenses into clouds, releasing heat

- Gravity pulls condensed water back to Earth via the process of precipitation (rain, snow, sleet, or hail).
- Gravity causes water to flow over land into rivers and streams (runoff) and drain through soil
- Rivers flow downhill due to gravity, moving water from inland back to the oceans

Components of the hydrological cycle

- The global hydrological cycle is a **closed system**
- Within the hydrological cycle, there are **stores** and **flows**
- The hydrological cycle is a series of processes in which water is **constantly recycled** through the system
  - The cycle also shapes landscapes, transports minerals and is essential to life on Earth
- The main **stores** occurring within the hydrological cycle are:
  - Oceans
  - Glaciers and ice caps
  - Groundwater and **aquifers**
  - Surface freshwater (rivers and lakes)
  - Atmosphere
- The main **flows** occurring within the hydrological cycle are:
  - **Transformations**: processes where the state or form of water changes, e.g.
    - Evaporation (the sun evaporates surface water into vapour)
    - Condensation (water vapour condenses and precipitates)
  - **Transfers**: movements of water from one location to another without changing state, e.g.
    - Water runs off the surface into streams and reservoirs or beneath the surface as ground flow
- These flows **move** the water on Earth from one **store** to another (river to ocean or ocean to atmosphere)

Your notes



The hydrological cycle

Flows in the hydrological cycle

- Flows in the hydrological cycle include the following:

Flows in the Hydrological Cycle

Flow	Type	Description

Evaporation	Transformation	The process by which liquid water changes into a gaseous state (water vapour) and enters the atmosphere from water bodies such as oceans, lakes, and rivers
Transpiration	Transformation	The process by which plants absorb water from the soil through their roots and release it as water vapour through tiny openings called stomata in their leaves
Evapotranspiration	Transformation	The combined process of water vaporisation from the Earth's surface (evaporation) and the release of water vapour by plants (transpiration)
Sublimation	Transformation	The direct transition of water from a solid state (ice or snow) to a vapour state without melting first
Condensation	Transformation	The process by which water vapour in the atmosphere transforms into liquid water, forming clouds or dew, as a result of cooling
Melting	Transformation	The process by which solid ice or snow changes into liquid water due to an increase in temperature
Freezing	Transformation	The process by which liquid water changes into a solid state (ice or snow) due to a decrease in temperature
Advection	Transfer	The wind-blown movement of water vapour or condensed/frozen water droplets (clouds)
Precipitation	Transfer	The process of water falling from the atmosphere to the Earth's surface in the form of rain, snow, sleet, or hail
Surface run-off	Transfer	The movement of water over the Earth's surface typically occurs when the ground is saturated or impermeable, leading to excess water
Infiltration	Transfer	The process of water seeping into the soil from the surface, entering the soil layers and becoming groundwater

Your notes

Percolation	Transfer	The downward movement of water through the soil and underlying rock layers, eventually reaches aquifers or groundwater reservoirs
Streamflow	Transfer	The movement of water in streams, rivers, or other water bodies, driven by gravity and the slope of the land, ultimately leads to oceans or lakes
Groundwater flow	Transfer	The movement of water through the pores and spaces in underground soil and rock layers, often moving towards rivers, lakes or oceans

Your notes

Examiner Tips and Tricks

Remember that percolation and infiltration are not the same. Percolation happens **after** the water has infiltrated the soil.

Human Impacts on the Hydrological Cycle

Your notes

Human Impacts on the Hydrological Cycle

- Human activities have significant impacts on the hydrological cycle
  - They alter the natural processes of **surface run-off** and **infiltration**
- These activities include:
  - Agriculture (specifically irrigation)
  - Deforestation
  - Urbanisation

Agricultural irrigation has a significant impact on the hydrological cycle (photo by Przemyslaw Stroinski on Unsplash)

Your notes

Impact of agriculture and irrigation

- Irrigation is the process of artificially supplying water to crops
  - It has a direct impact on the hydrological cycle by modifying the water **distribution** and **availability** in a region
- Increased irrigation leads to:
  - **Artificially high evapotranspiration** rates
  - This is because more water is supplied to plants than would occur naturally
  - This results in increased atmospheric moisture levels
  - This can lead to localised **increases in precipitation** downwind of irrigated areas, altering rainfall patterns in the region
- Excessive irrigation can also result in **increased surface run-off**
  - Water is applied faster than the soil can absorb it
  - This causes water to flow over the soil surface, carrying sediments, fertilisers, and pesticides
  - This leads to **water pollution** and **nutrient imbalances**

Impact of deforestation

- Deforestation refers to the clearing or removal of forests
  - This is primarily for agriculture, logging or urban development purposes
- Forests play a crucial role in the hydrological cycle
  - They act like natural **sponges**
  - They absorb rainfall and facilitate infiltration
    - This helps to **recharge groundwater** and maintain stream flows
- When forests are cleared, **surface runoff increases** significantly
  - Without the tree canopy and vegetation to intercept and slow down rainfall, more water reaches the ground surface
  - This leads to higher surface runoff rates

Your notes

- Deforestation also **reduces evapotranspiration** rates
  - As trees are removed, there is less transpiration and evaporation occurring
  - This results in reduced moisture release into the atmosphere
- Overall, deforestation disrupts the balance between surface run-off and infiltration
  - This can lead to **increased erosion**, reduced groundwater recharge and altered stream flow patterns

Impact of urbanisation

Urbanisation has a significant impact on the hydrological cycle (photo by Chris Gallagher on Unsplash)

- Urbanisation involves the transformation of natural landscapes into urban areas with buildings, roads and infrastructure
- Urban development significantly alters the hydrological cycle by:
  - Replacing permeable surfaces (such as soil and vegetation) with **impermeable surfaces** (concrete, asphalt)
    - Impermeable surfaces **prevent infiltration**

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    - This leads to **reduced groundwater recharge**
    - Instead of infiltrating into the soil, rainfall quickly becomes surface run-off
    - This results in **increased flooding** and diminished water availability during dry periods
- Urban areas typically have efficient drainage systems designed to quickly remove excess water
  - This further accelerates surface run-off
  - This can **overload natural water bodies** and cause downstream flooding
- Urban areas often experience higher temperatures due to the urban heat island effect
  - This effect is caused by the concentration of buildings and paved surfaces
  - It can lead to increased evaporation rates
  - This can alter local precipitation patterns

Steady State of Water Bodies

- Understanding the steady state of a water body involves analysing the **balance** between **inputs** and **outputs**
  - This balance ensures that the water level remains **constant over time**

Flow diagrams of inputs and outputs

- Flow diagrams visually represent the water inputs and outputs for a water body
- **Inputs**: e.g.
  - **Precipitation**: rain, snow, or other forms of water falling directly into the water body
  - **Surface run-off**: water flowing over the land into the water body
  - **Groundwater Inflow**: water moving into the water body from underground sources
- **Outputs**: e.g.
  - **Evaporation**: water turning into vapour and leaving the water body
  - **River outflow**: water leaving the water body through rivers or streams
  - **Groundwater outflow**: water moving out of the water body into underground aquifers
  - **Agricultural extraction**: water that is extracted for irrigation
- For example, a lake that is at a steady state may have the following inputs and outputs:
  - **Inputs**: river inflow (80 units), rainfall (30 units), groundwater inflow (40 units), surface run-off (30 units)

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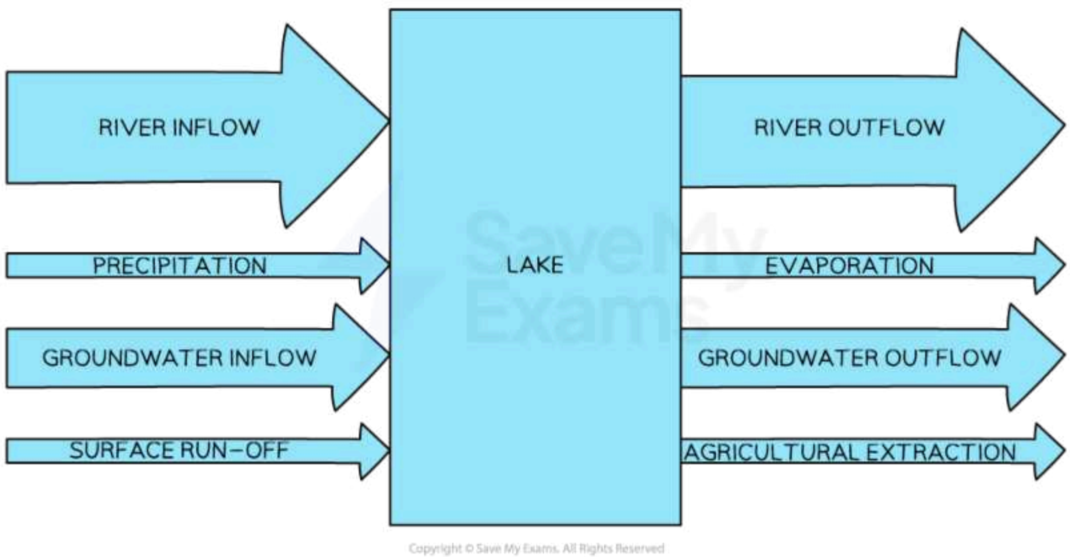
- **Outputs**: river outflow (80 units), evaporation (30 units), groundwater outflow (40 units), agricultural extraction (30 units)
- **Steady state**: inputs (180 units) equal outputs (180 units)

- This is an example of **sustainable water harvesting**
  - Sustainable harvesting means taking water from a water body at a rate that does **not exceed** the rate of **natural replenishment**
  - Assessing the total inputs and outputs of a water body can help calculate sustainable rates of water harvesting
  - This ensures the harvested water amount does not disrupt the steady state

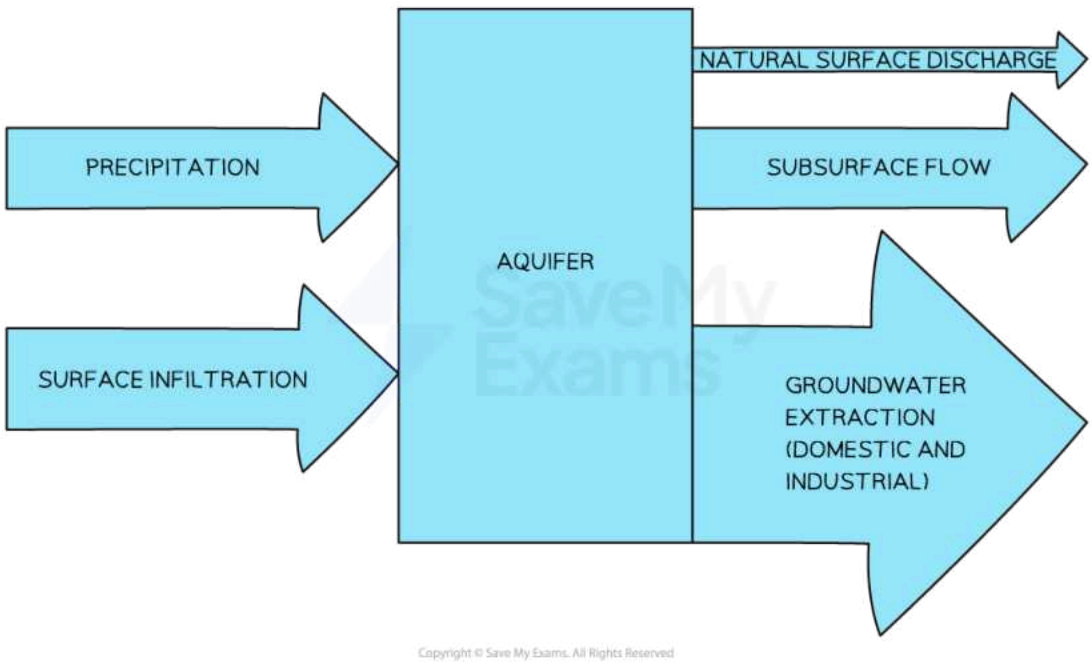


Sustainable water harvesting

- If total outputs are greater than total inputs, then the water body will **decrease in size**
  - This may be due to unsustainable water harvesting for **agriculture** or for **domestic** and **industrial purposes,** e.g. water used in drinking, cleaning, heating and cooling systems, and manufacturing processes
  - Water may be extracted faster than it can be naturally replenished
- For example, an aquifer that is being unsustainably harvested (and therefore is not at a steady state) may have the following inputs and outputs:
  - **Inputs**: precipitation (70 units), surface infiltration (80 units)

Your notes

- **Outputs**: natural surface discharge (30 units), subsurface flow (70 units), groundwater extraction for domestic and industrial use (150 units)
- **Steady state disruption**: inputs (150 units) are less than outputs (250 units), causing a **water deficit** of 100 units
- This is why groundwater extraction must be **balanced** with recharge rates—to **prevent aquifer depletion**



Unsustainable water harvesting

Physical & Chemical Properties of Water (HL)

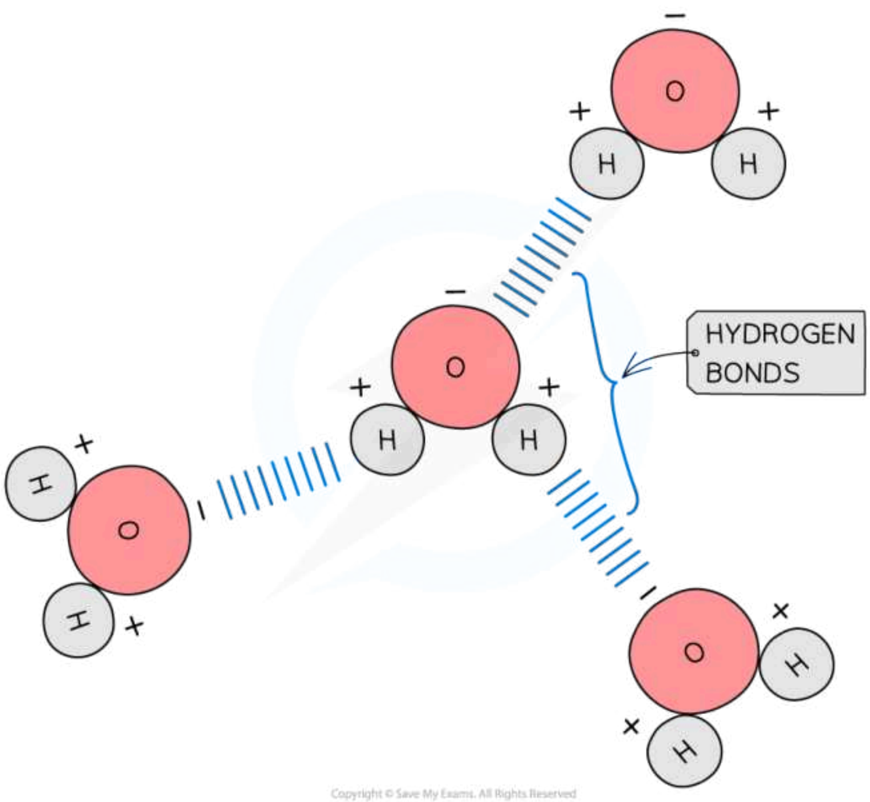
Your notes

Physical & Chemical Properties of Water

- Water has some unique physical and chemical properties
- These properties make water crucial to life on Earth

Polarity and hydrogen bonding

- Water molecules are **polar**
  - This means they have a slight **positive** charge on one side (near the hydrogen atoms) and a slight **negative** charge on the other (near the oxygen atom)
- This uneven distribution of charge is called **polarity**
  - Polarity allows water to form **hydrogen bonds** between its molecules
  - The slightly positive hydrogen atom in one water molecule is attracted to the slightly negative oxygen atom in another
  - This creates weak bonds between water molecules
  - Collectively, however, these bonds are strong enough to give water its unique properties



The polarity of water molecules allows hydrogen bonds to form between adjacent water molecules

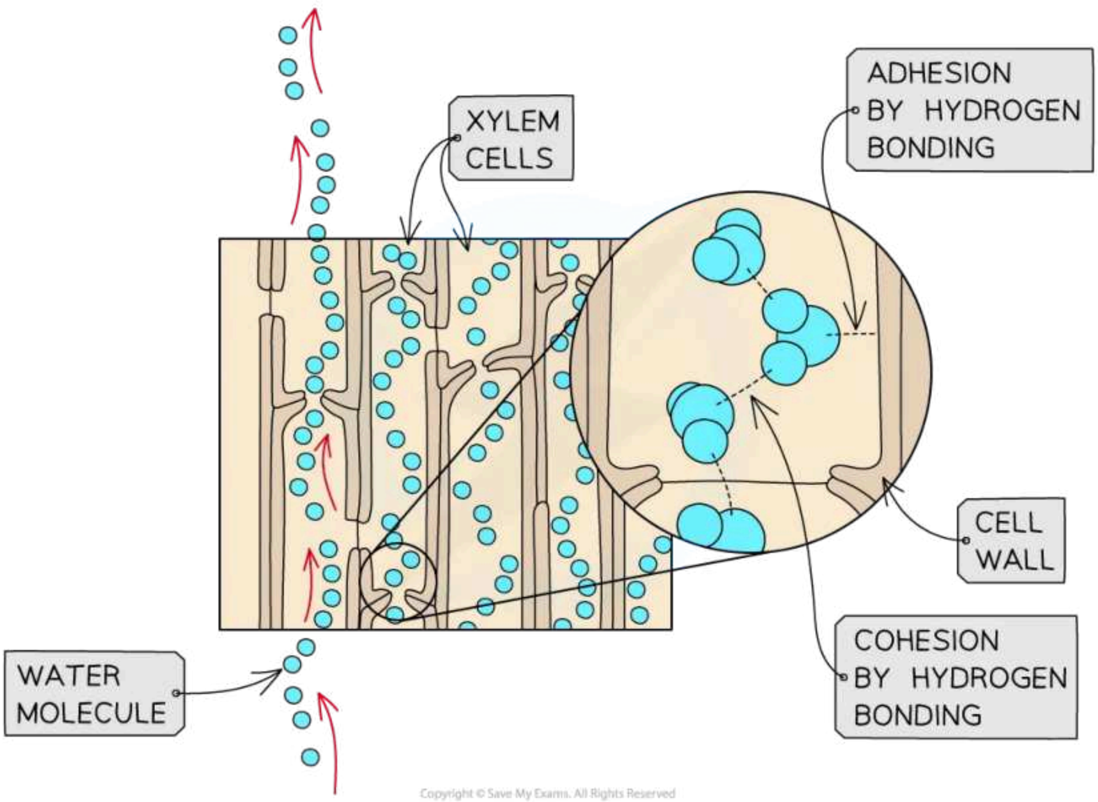
Cohesion

- Cohesion is the result of hydrogen bonding **between water molecules**
- This makes water molecules 'stick' together, allowing it to form droplets and maintain surface tension
  - For example, water droplets form beads on a waxy surface, and insects like water striders (also known as pond skaters) can move across water without sinking

Adhesion

- Adhesion occurs when water molecules stick to **other materials**
- This can help water to move through narrow spaces
  - This is seen in capillary action, an import process occurring in the xylem during transpiration
  - This is where water moves up plant stems against gravity, which is essential in order for plants to transport water from their roots to their leaves

Your notes



Hydrogen bonding results in cohesion and adhesion forces in xylem which allows water molecules to flow through the plant in a continuous stream

Solvent properties

- The polarity of water also makes it an **effective solvent**
  - This means it can **dissolve** many substances, especially salts and polar molecules
- This ability is essential for life because it allows water to **transport** important substances like nutrients, minerals, and gases within living organisms
  - For example, in the human body, water dissolves salts, sugars, and proteins
  - This enables them to be carried in the bloodstream to cells

Transparency

- Water is **transparent**, meaning light can pass through it
- This transparency is essential for aquatic ecosystems because it allows sunlight to penetrate underwater

Your notes

- This enables photosynthesis in aquatic plants and algae, which support aquatic food webs
  - In lakes and oceans, the depth to which sunlight penetrates determines the zone where photosynthetic organisms can survive

High specific heat capacity

- Water has a **high specific heat capacity**
  - This means it can absorb a large amount of heat energy without significantly increasing its temperature
- This property allows water to regulate environmental and body temperatures, maintaining **stable conditions for life**
  - For example, oceans absorb heat from the sun during the day and release it slowly at night
    - This moderates coastal climates and prevents extreme temperature changes
  - This property is also essential in **maintaining body temperature** in animals, as water in blood helps distribute heat evenly
    - This prevents rapid overheating or cooling

Artic and sub-artic species, such as the ringed seal (Pusa hispida) are able to survive throughout the year due to stable sea temperatures (photo by NOAA Seal Survey, Public domain, Wikimedia)

Your notes

Density and temperature

- Water has an unusual density pattern; **it is most dense at 4 °C**
- As it cools below this temperature and freezes, water expands, making ice less dense than liquid water
  - This is why ice floats
- This property is vital for life in cold environments
  - For some species, it provides a valuable habitat, e.g. the floating sea ice enables polar bears to hunt seals
- Also, when ice forms on the surface of lakes or oceans, it acts as an insulating layer
- This protects aquatic life by preventing the water below from freezing completely
  - Without this property, whole bodies of water could freeze solid in cold climates, disrupting ecosystems and killing many species

Gas solubility in water

- Water can **dissolve gases** like oxygen and carbon dioxide
- The solubility of these gases varies with **temperature** and **pressure**.
  - **Cold water generally holds more dissolved oxygen** than warm water
  - This is why cold aquatic environments can often support more life.
    - For example, the Arctic and Antarctic oceans, with their cold temperatures, support rich ecosystems due to the high oxygen levels in the water
  - When water gets too warm, its ability to hold oxygen **decreases**
    - This can lead to problems like **oxygen depletion** in warmer waters, causing "dead zones" where aquatic life struggles to survive

Examiner Tips and Tricks

COhesion = water particles sticking to **each other**.

ADhesion = water particles sticking to **other materials**.

Carbon Sequestration & Ocean Acidification (HL)

Your notes

Carbon Sequestration & Ocean Acidification

The role of oceans in carbon sequestration

- The oceans act as a **carbon sink**, absorbing large amounts of carbon dioxide (CO_2) from the atmosphere
  - This helps **slow** the increase of CO_2 in the atmosphere, which has been rising due to human activities like the burning of fossil fuels
  - By absorbing CO_2, the oceans have been moderating the pace of climate change
  - Without this natural process, the effects of global warming would be even more severe
- **Carbon sequestration** in the ocean occurs when CO_2 dissolves in seawater
- It is stored either as:
  - Dissolved carbon
  - In marine organisms
  - In sediments on the ocean floor
- This process of CO_2 dissolving into the water at the ocean's surface is responsible for much of the carbon stored in oceans
- Over the **long term**, carbon is also sequestered through biological processes, such as when marine organisms absorb CO_2 to build their **shells** or **tissues**
- While the oceans play a vital role in sequestering carbon, they may eventually reach a **saturation point**
  - This would occur when they can no longer absorb CO_2 as efficiently
  - If this happens, CO_2 levels in the atmosphere could rise even faster, **accelerating climate change**

Ocean acidification

- As CO_2 is absorbed by the ocean, it reacts with seawater to form **carbonic acid**
- This lowers the **pH** of the water and causes **ocean acidification**
  - Ocean acidification harms marine life, especially species with calcium carbonate shells or skeletons, e.g. corals, molluscs, and some plankton
  - Their ability to form and maintain their shells is reduced, affecting marine food webs

Your notes

    - The continued acidification of the oceans could have significant **ecological impacts**, including the collapse of certain marine ecosystems, such as coral reefs
- **Short-term sequestration** of carbon in the ocean mainly occurs as dissolved CO_2, which contributes to this acidification process

Long-term carbon sequestration

- **Seabed sediments** contain both **organic** and **inorganic** carbon
    - **Organic carbon** is stored in the remains of dead marine organisms, e.g. plankton
        - This organic matter sinks to the ocean floor after these organisms die
        - Over time, some of this organic matter becomes buried in sediments and is not fully decomposed, thus trapping carbon.
    - **Inorganic carbonates** are formed when dissolved CO_2 in seawater reacts with minerals like calcium to form compounds such as calcium carbonate ($CaCO_3$)
        - Marine organisms use these compounds to build their skeletons and shells
        - When these organisms die, their shells and skeletons accumulate on the seabed, becoming part of the sediments
        - This process sequesters carbon in a more stable form, often for millions of years
- Over geological time, these seabed sediments may undergo further changes due to **pressure** and **temperature**
    - This eventually transforms them into **fossil fuels** such as coal, oil, and natural gas
    - This long-term carbon storage process helps regulate the global carbon cycle by preventing large amounts of CO_2 from re-entering the atmosphere
        - However, the extraction and burning of fossil fuels by humans to generate energy is rapidly releasing all this previously stored carbon into the atmosphere

Examiner Tips and Tricks

Make sure you are familiar with the difference between **short-term** and **long-term carbon sequestration**. Short-term is CO_2 dissolving in seawater, while long-term involves the accumulation of carbon in sediments and organisms.

Your notes

Water Stratification (HL)

Water Stratification

What is water stratification?

- Water stratification refers to the **layering** of water that occurs in a body of water due differences in **temperature** and **density**
- In most large bodies of water:
  - **Warmer**, **less dense** water stays on the **surface**
  - **Colder**, **denser** water sinks to the **bottom**
- This separation into layers **restricts the mixing of water between these different layers**
  - This leads to a stable and persistent stratification in deep lakes, oceans, and seas

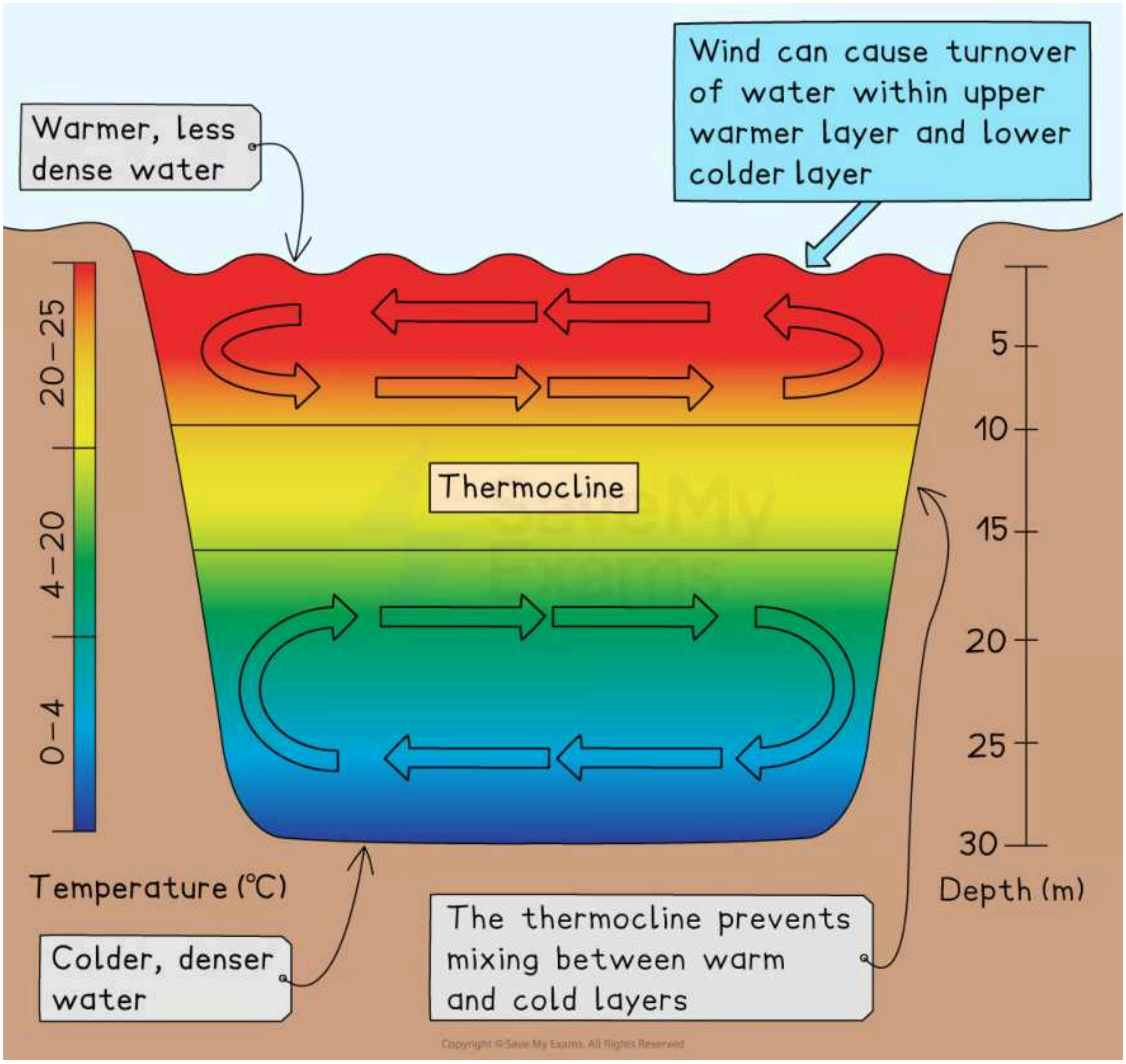
Temperature and density in water

- Water temperature varies with depth
  - Typically, water near the surface is warmer due to sunlight, while deeper water is cooler.
- Water is **most dense** at **4°C**
- This means colder water (below 4°C) will float above it
- As a result, a lake or pond can freeze from the top downwards
  - This allows aquatic life to survive beneath a layer of ice during winter
  - This phenomenon is crucial for **freshwater ecosystems**
  - The insulating ice layer protects life below from freezing temperatures

Formation of the thermocline

- A **thermocline** is a **transition layer** between the warmer, mixed water at the surface and the cooler, denser water below
  - In this layer, temperature drops rapidly with increasing depth
  - The **thermocline** creates a barrier that restricts the vertical movement of nutrients, oxygen, and organisms between the upper and lower layers
- Stratification occurs in deeper lakes, coastal regions, enclosed seas, and the open ocean

- **Lakes** typically show greater stratification during summer and winter, with mixing occurring in spring and autumn
- **Oceans** experience more stable stratification throughout the year due to their depth and larger thermal gradients



Stratification and thermocline formation in a deep lake

Effects on oxygen and nutrients

- Stratified water layers have different amounts of dissolved **oxygen** and **nutrients**:
  - The relatively warmer surface water is usually **oxygen-rich** because of contact with the atmosphere and photosynthesis by aquatic plants and phytoplankton

Your notes

Your notes

- The direct contact with the air leads to **oxygen replenishment**
- Normally, colder water can hold more oxygen
    - However, in stratified water systems, the deep colder layer may be oxygen-poor due to the **lack of mixing** with the oxygen-rich surface waters and **absence of light for photosynthesis**
    - The lack of mixing means that oxygen levels can become very low (**hypoxic**) in deeper layers, which can sometimes harm aquatic organisms living at those depths
- Cold, deep water often contains **higher concentrations of nutrients**
    - This is because dead organisms sink and decompose, releasing nutrients that become trapped in lower layers

Impact of global warming on stratification

- Global warming has **intensified ocean stratification**, particularly in the upper 200 metres of water
    - Warming surface waters are becoming **less and less dense** than colder, deeper water
    - This is **increasing the separation** between layers and reducing vertical mixing
    - This is trapping heat at the surface and preventing the mixing of oxygen and nutrients between layers
    - As a result, **deeper waters are becoming increasingly oxygen-depleted**, and fewer nutrients are reaching the surface, where marine organisms need them for growth
- **Salinity** also affects stratification, particularly in polar regions
    - Salinity refers to the concentration of salt in the water, which affects water density
    - **Higher salinity** makes water **denser**, while **lower salinity** makes water **less dense**
    - In places like Antarctica, **melting ice caps** reduce the salinity of surface waters
    - This makes them **less and less dense** compared to the deeper, saltier waters below
    - This **intensifies ocean stratification** because the difference in density between the layers becomes more pronounced

Upwellings & Ocean Circulation (HL)

Your notes

Upwellings

What are upwellings?

- Upwellings are areas in oceans and freshwater bodies where **cold, nutrient-rich water rises** from deep below to the **surface**
  - Surface waters move vertically as a result of currents or winds pushing them away
  - This causes deeper water to rise and replace it
  - Upwelling is important because it **brings nutrients** like nitrates and phosphates from deep waters to the surface
  - These nutrients are essential for **phytoplankton** growth, which forms the base of marine food webs

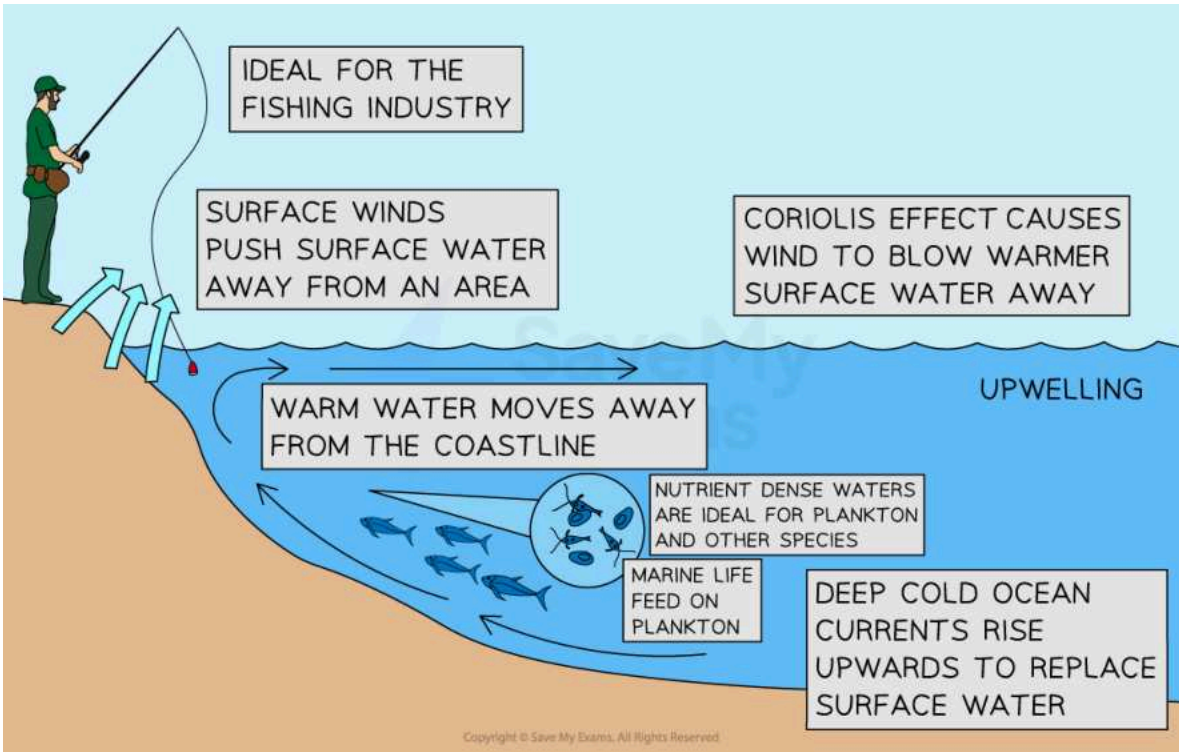
Causes of upwellings

- **Wind-driven upwellings** occur when strong winds blow across the surface of the ocean, particularly along coastlines
  - Winds push warm surface water away from the coast
  - Cold water from the deep ocean is **pulled up** to replace it
  - This process often occurs along the **west coasts of continents**, such as in **California**, **Peru**, and **Namibia**
- **Seasonal upwellings** can occur in **stratified lakes** and **oceans**
  - This occurs where layers of water are separated by temperature
  - As seasonal winds blow across these bodies of water, they disrupt the layers and bring up nutrients
- ENSO (El Niño Southern Oscillation) is a phenomenon that can also trigger or disrupt upwellings
  - During **La Niña**, stronger trade winds **increase upwelling**, while **El Niño** reduces it, affecting global fish stocks

Benefits of upwellings

- **Nutrient supply**:
  - The nutrient-rich water supports large populations of **phytoplankton**
  - This in turn attracts fish, marine mammals, and seabirds

- Upwellings are some of the most **productive marine ecosystems** in the world
  - For example, the **Peru upwelling system** supports a major fishery for anchovies
  - This is a very important species for both marine food webs and commercial fishing
- **Fisheries:**
  - The enhanced nutrient availability supports fish stocks and marine biodiversity
  - This is crucial for **fisheries** and **local economies**



The process of upwelling in transferring nutrient-dense waters

Limitations and risks of upwellings

- **Overfishing** can exploit these nutrient-rich waters
  - This can lead to the depletion of fish populations and the collapse of ecosystems if not managed sustainably
- **Climate change** could affect wind patterns
  - This could disrupt upwelling cycles and alter nutrient availability in these regions
  - This could potentially cause the breakdown of marine food webs or fisheries in these regions

Your notes

Thermohaline Circulation Systems

What is thermohaline circulation?

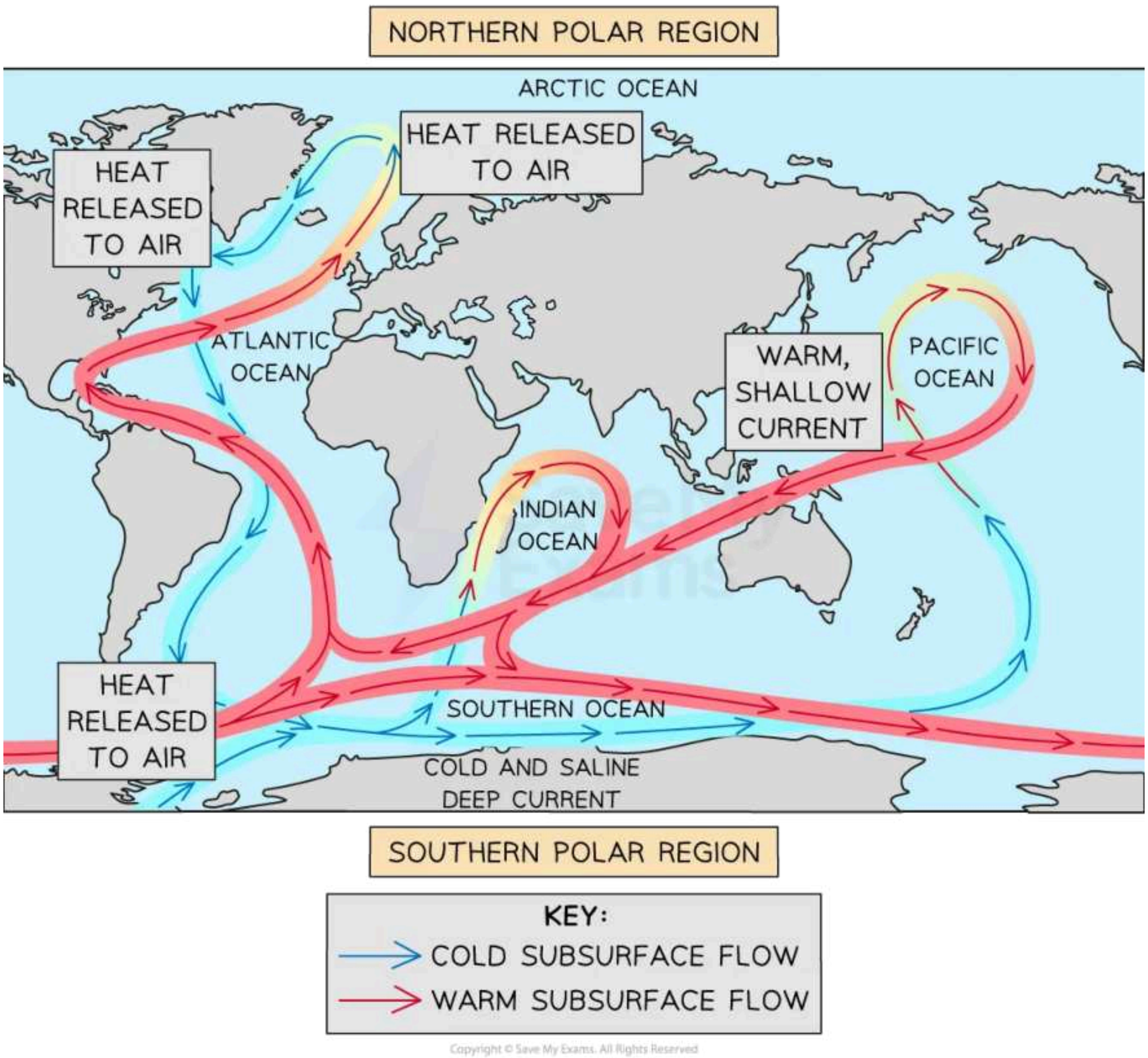
- The global ocean current system known as the thermohaline circulation is due to variations in **temperature** and **salinity**, which affect water density
  - This system is also known as the **ocean conveyor belt**
  - This system plays a critical role in **regulating the Earth's climate** by **distributing heat** across the globe

How thermohaline circulation works

- **Cold, salty water** is **denser** than warm, fresh water
- In polar regions, surface waters are **cooled** and become **more saline** due to **evaporation** and **sea ice formation**
  - Evaporation increases salinity because, as water evaporates, it leaves salt behind, concentrating the remaining salt in the water
  - Similarly, when sea ice forms, only the water freezes while the salt is left in the surrounding water, increasing the salinity of the remaining liquid water
- The circulation starts in the **North Atlantic**, where cold, salty water sinks and flows southward towards the equator
  - This is known as the **North Atlantic conveyor belt**
- As the water sinks, it pulls surface water along with it, creating a continuous flow
- This process repeats, forming deep currents
- These currents then make their way around the world, into areas where the water will heat up again
- This warmer (less dense) water returns to the surface, moving further around the world and eventually reaching the point where the process started
  - Warm water from the tropics moves northward to replace the sinking water, bringing heat with it and warming coastal regions
- The cycle repeats
- One full loop of the Oceanic Conveyor Belt could take anywhere between **100 and 1000 years**
- The process helps to **regulate the climate** by transferring heat from the **tropics** to the **poles**

Your notes

Your notes



The thermohaline circulation process

Impacts of thermohaline circulation

- The **Gulf Stream** is part of the thermohaline system
    - It brings **warm water** from the Gulf of Mexico up the eastern coast of the US and across to Western Europe
    - This is why regions like Western Europe have a **milder climate** than other areas at the same latitude
- The sinking of cold water in the North Atlantic drives the entire conveyor belt, but this process is being threatened by **climate change**

- **Melting ice caps** in Greenland and Antarctica are adding large amounts of **freshwater** to the oceans
  - This is reducing the salinity and density of surface waters
  - This could potentially slow down or even stop the conveyor belt
- If the thermohaline circulation slows significantly, it could lead to **major climate shifts**
  - E.g. cooling Northern Europe while warming tropical regions and disrupting global weather patterns

Your notes