Water and carbon cycles as systems

Systems in Geography

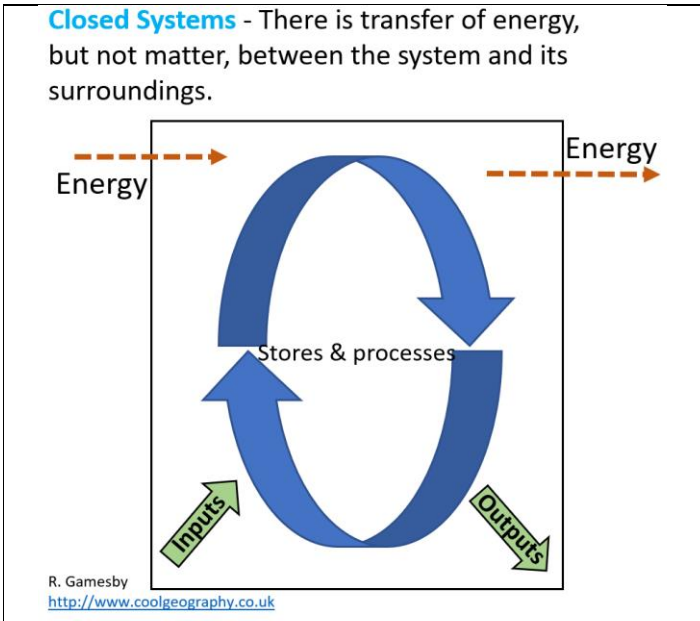
A systems approach is hugely important in Geography and can be applied to many of the human and physical geography concepts that we investigate. For example, from a human geography perspective, cities can be seen to operate as a system as they have inputs of energy and matter coming from outside of the city (such as electricity, raw materials), processes and stores within the city (such as manufacturing or the construction of new buildings) and then outputs of matter and energy (such as pollution, products and waste).

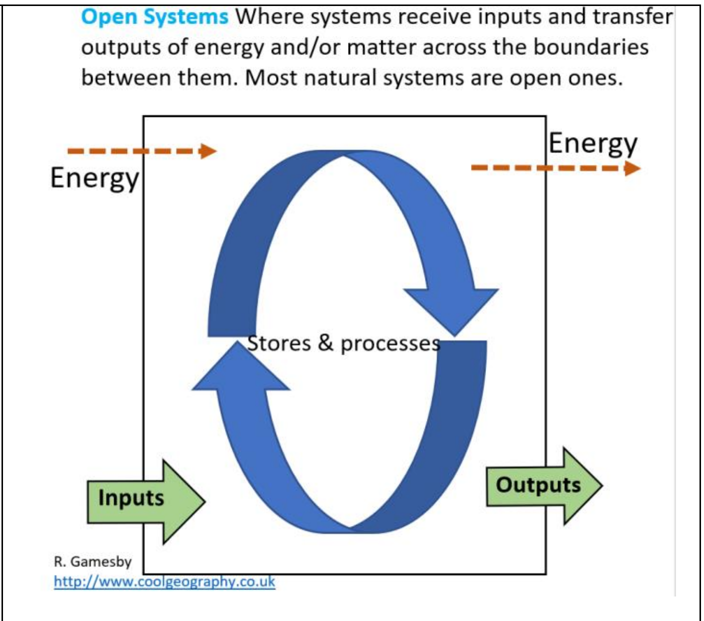
Indeed, when looking at systems, we must consider the TYPE of system, then its inputs, processes/stores and outputs.

Types of system:

- **Open Systems** – these are any system which has external inputs and external outputs of both energy AND matter. E.g. a drainage basin

- **Isolated systems** - these have no interactions with anything outside of the system boundary. There is no input or output of energy or matter. These are rare in reality and tend only to exist in scientific experiments
- **Closed systems** - these have transfers of energy both into and beyond the system boundary but NOT transfer of matter. Planet Earth is generally considered a closed system, with energy coming from the sun, balanced by radiant energy lost from the Earth.
- **Cascading system** - the transfer of mass and energy along a chain of component subsystems, such that the output from one subsystem becomes the input for the adjacent subsystem. River sediment cascades into the coastal zone for example.





Characteristics of systems in Geography

Most systems in Geography share the same ***common characteristics***. These common characteristics include the following:

1. Systems are a generalisation of reality – they give us an idea of what is happening in the system but the reality is often more complex and requires detailed study
2. They have a ***structure*** that is defined by its parts and processes.
3. Systems tend to ***function*** in the same way. This involves the **inputs** and **outputs** of ***material*** (***energy*** and/or ***matter***) that is then processed causing it to change in some way.
4. The various parts of a system have ***relationships*** between each other. They are often **Connected** and integrated together.

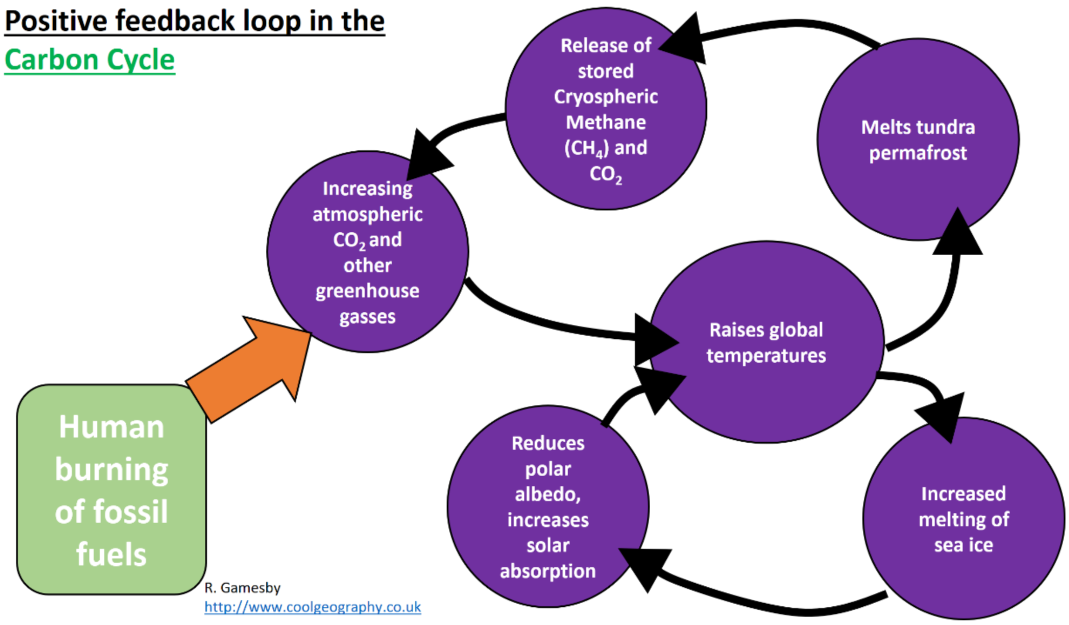
5. The fact that functional relationships exist between the parts suggests the ***flow*** and ***transfer*** of some type of ***energy*** and/or ***matter***.
6. SOME systems often exchange energy and/or matter beyond their defined boundary with the outside environment, and other systems, through various **input** and **output** processes.
7. Functional relationships can only occur because of the presence of a ***driving force***.

   SOURCE – Adapted from http://www.physicalgeography.net/fundamentals/4b.html (this website is thoroughly recommended, it is an amazing Geographical resource)

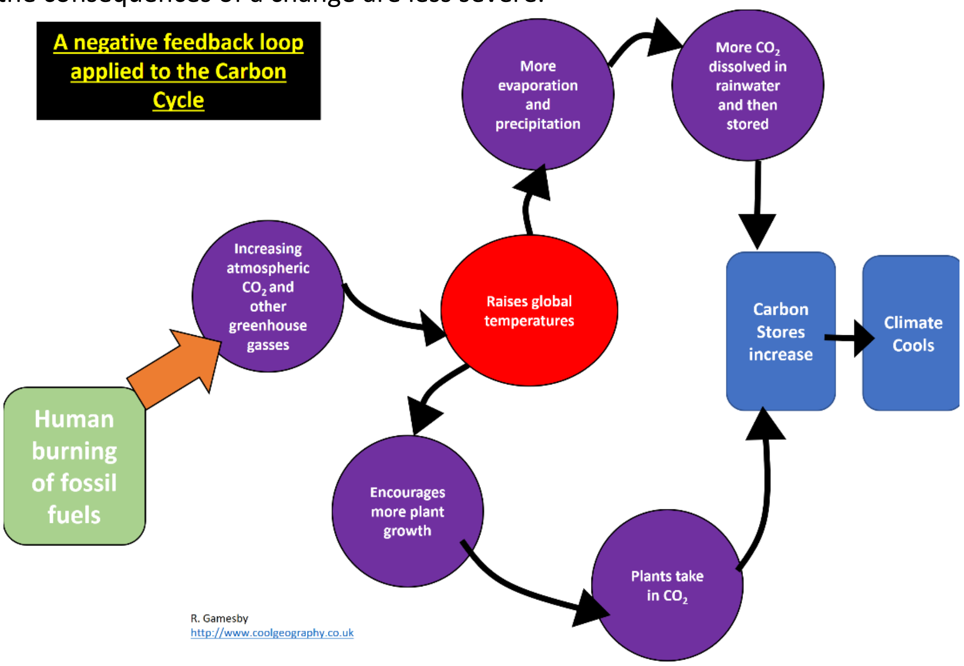
FEEDBACK in SYSTEMS

Within systems we also get different types of feedback.

Positive feedback - enhances or amplifies an effect by it having an influence on the process which gave rise to it. Often, this means that the consequences of the change are ironically more severe.



Negative feedback - dampens or reduces an effect by it having an influence on the process that gave rise to it. This often means that the consequences of a change are less severe.



Most systems are said to be in **dynamic equilibrium -** lack of change in a system as inputs and outputs remain in balance over periods of time. A good example of this would be a river system, rivers are generally in balance between the inputs of energy and outputs. Water and sediment budgets will balance out over years. However, at times big storms might disrupt this balance for a short period of time, resulting in flooding and huge changes to sediment budgets. Eventually, after a flood event, rivers will return to their normal functions, and dynamic equilibrium will be restored.

The Earth's major systems

Our planet has 4 major systems, which are all interconnected. There are also subsystems in those 4 systems – the lithosphere contains soil and rock systems for example.

1. **Atmospheric system** - the inputs, flows and outputs all associated with the layer of gasses surrounding our planet
2. **Lithospheric system** - the inputs, flows and outputs all associated with the **cold, hard solid land** of the planet's crust (surface)
3. **Hydrospheric system** - the inputs, flows and outputs all associated with the **water** on our planet
4. **Biospheric system** - the inputs, flows and outputs all associated with the **biology and ecosystems** of our planet

Source - http://www.cotf.edu/ete/ess/essspheres.html

The Water Cycle

The water cycle is also known as the hydrological cycle or the hydrologic cycle, and can be defined as;

"the continuous movement of water on, above and below the surface of the Earth."

The amount or mass of water on Earth remains fairly constant over time but the location of that water into the major reservoirs of saline water, ice, fresh water, and atmospheric water is variable and depends on a wide range of climatic variables. Water on Earth moves from one reservoir or store to another, such as from river to ocean, or from the ocean to the atmosphere, by the physical processes of evaporation, condensation, precipitation, infiltration, surface runoff, and subsurface flow. Movement between these stores often involves the water changing form between liquid, solid (ice) and vapour.

The water cycle also involves the exchange of energy, which leads to temperature changes. When water evaporates, it takes up energy from its surroundings and cools the environment. When it condenses, it releases energy and warms the environment. These heat exchanges influence climate. 1

The water cycle is a series of processes by which water is evaporated from the sea and eventually condenses and precipitates over the land.

The water cycle starts with water evaporating from the ocean, this warm moist air rises in thermals where it cools as it rises through the troposphere (at the dry adiabatic lapse rate of 9.7°C per 1000m). As the air rises and cools it loses its capacity to hold water vapour as its relative humidity rises, and condensation occurs releasing latent heat. This forms clouds at the dew point, and these clouds are blown inland.

Relief features can force the clouds higher, water droplets collide with one another and get bigger, and eventually the droplets are big enough to fall to earth as precipitation. This precipitation can be stored on the surface as snow or ice, or can be intercepted by trees and vegetation. On the trees or vegetation the water can be dripped off leaves, flow down the vegetation as stem flow or be taken up and lost as transpiration.

The combined losses of water through transpiration and evaporation are known as EVAPOTRANSPIRATION. It could also fall straight into the ground where it can percolate into the soil then infiltrate into the rock underneath if the soil and rock are permeable. If the rock is not permeable or the soil stores are full then surface runoff will occur. This water will then work its way through the soil (soil flow) or rock (through flow) or over the land and into streams and rivers. These small tributary streams join together at confluences and the river will grow in size and strength.

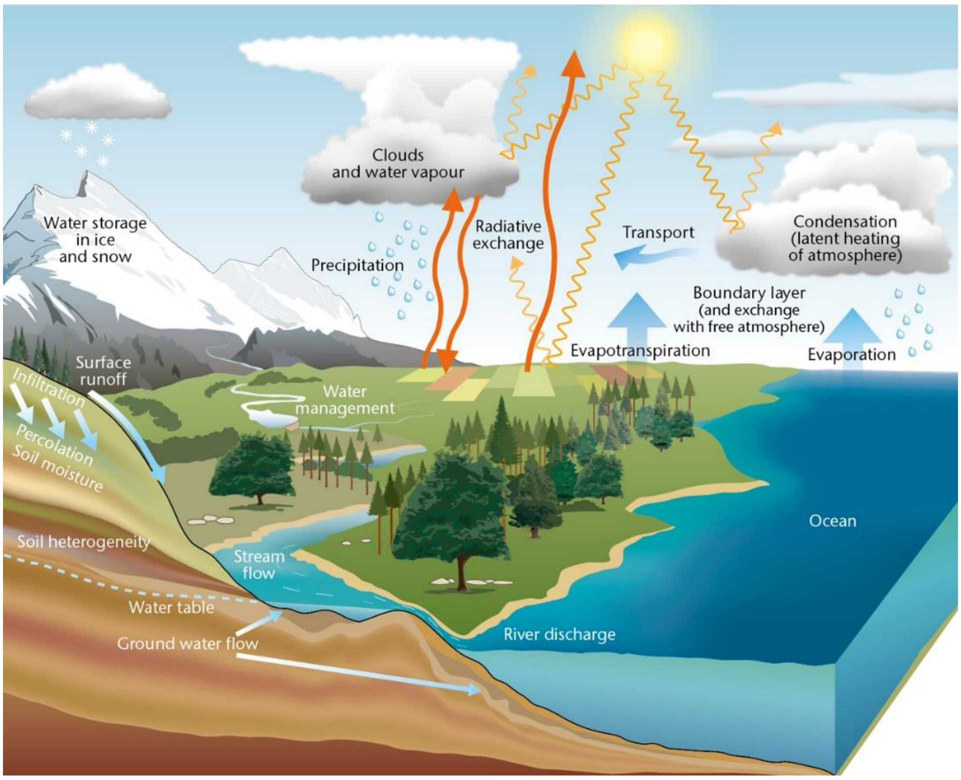


Figure 1 - the hydrological cycle https://www.metoffice.gov.uk/learning/learn-about-the-weather/how-weather-works/water-cycle

https://www.youtube.com/watch?time_continue=2&v=zBnKgwnn7i4

Global distribution and size of major stores of water – lithosphere, hydrosphere, cryosphere and atmosphere

Water on Planet Earth

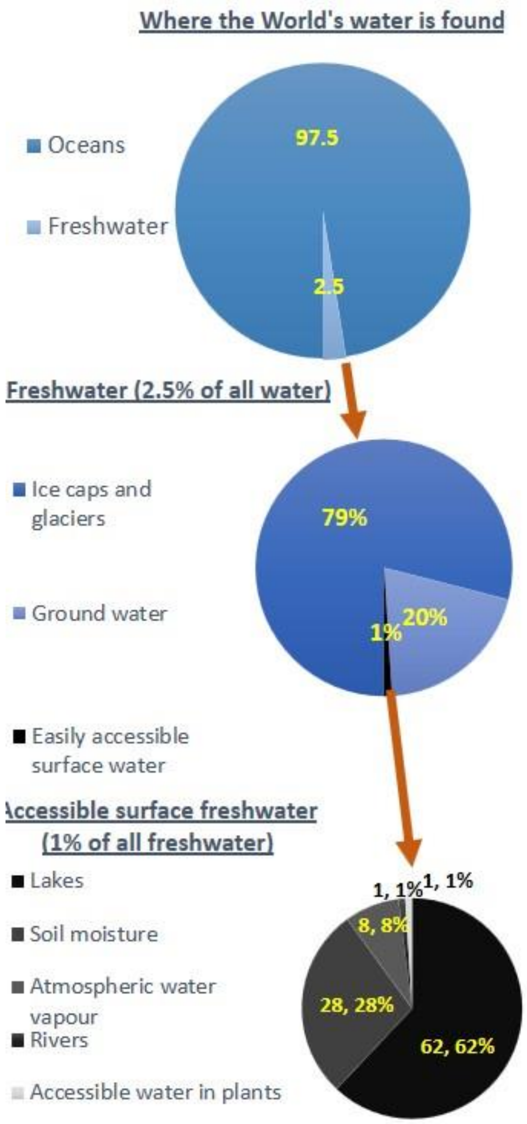
Water found on or close to the Earth's surface is called the hydrosphere. [2] The Hydrosphere is defined as a discontinuous layer of water at or near the earth's surface. It includes all liquid and frozen surface water, groundwater, and atmospheric water vapour.

It is an essential resource for human survival, but its distribution and availability vary within countries and across the planet. Only 2.5% of the water on the Earth is freshwater, the rest is found in the oceans. Unfortunately, a lot of the freshwater is "locked up" in ice caps and glaciers so is unavailable for human use. This poses problems for people as freshwater is a scarce resource.

About 71 percent of the Earth's surface is water-covered, and the oceans hold about 96.5 percent of all Earth's water. Water also exists in the air as water vapour, in rivers and lakes, in icecaps and glaciers, in the ground as soil moisture and in aquifers, and even in biological systems. [3]

The amount of water on planet Earth has been estimated at 1,386,000,000 (1.386 billion) cubic kilometres (km^3) by NASA. [3]

The second issue with water availability is that it is in continuous movement across the globe. It moves in a cycle called the hydrological cycle. Global freshwater supplies are affected by three major factors;
1. Geology – This affects where water is stored and the location of aquifers and groundwater
2. Climate – influences the availability of rainfall, snowfall and rates of evaporation. Climate can vary over time, with wetter and drier periods, hotter and colder periods. This can affect water availability.
3. Rivers – which move or transfer water across river basins



The distribution of this water can be seen in the pie charts and the divided bar graphs. Be careful, there is a slight difference, as the final pie chart shows "accessible fresh water" whilst the final bar chart shows surface water and other freshwater. This classification leads to differences in the proportions quoted.

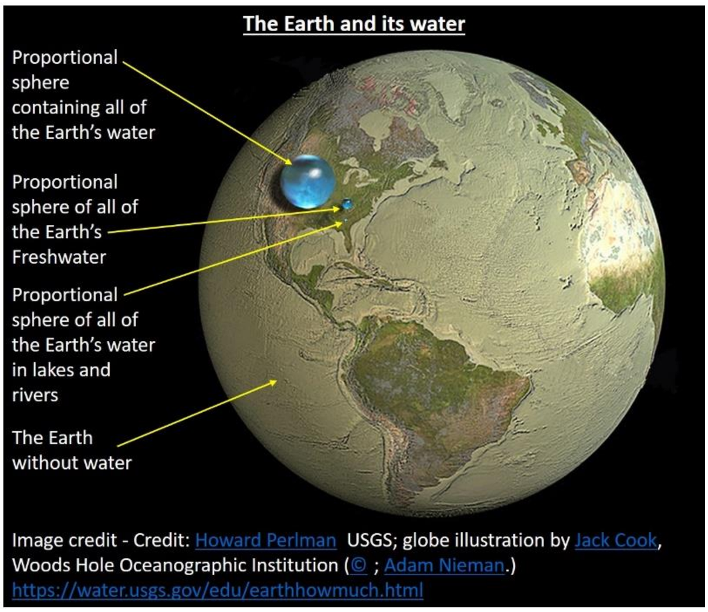


Image credit - Credit: Howard Perlman USGS; globe illustration by Jack Cook, Woods Hole Oceanographic Institution (© ; Adam Nieman.) https://water.usgs.gov/edu/earthhowmuch.html

Atmospheric stores of water

The atmosphere is the layer of gasses surrounding our planet. The atmosphere has water held in the air as gas, clouds, and precipitation. The Amount of water found in the atmosphere is only 12,900km^3, 8% of all easily accessible freshwater. Most of this is found in the gaseous state, water vapour, which is a colourless and odourless gas. Water vapour is produced from evaporation or liquid water or from the sublimation of ice. Visible water can be seen in clouds - visible masses of water droplets or ice crystals suspended in the atmosphere.

Atmospheric water is very important despite it being one of the smallest stores of water on planet Earth. It is important because;

1. It is a greenhouse gas that absorbs, scatters and reflects incoming solar energy and outgoing terrestrial energy, so plays a role in modifying our climate
2. It redistributes water around the globe
3. It helps to "clean" the air, removing impurities when it rains

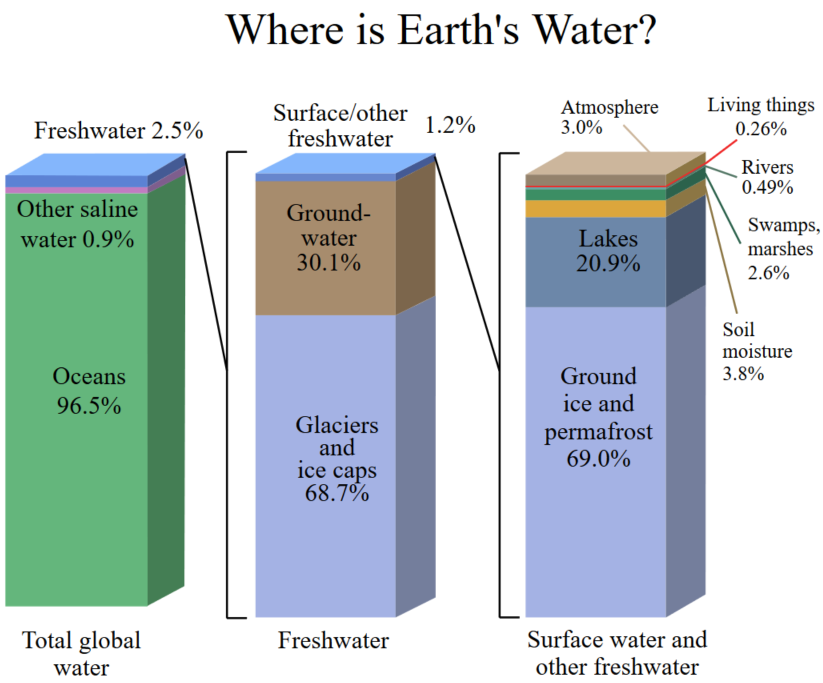


Figure 2 By USGS [Public domain], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File:Earth%27s_water_distribution.svg

Warmer air can hold more water vapour that cooler air. For a 1°C increase in the air temperature, the atmospheric water content should increase by about 7%. [4] This means that water vapour levels in air will vary according to temperature around the globe, with high levels at the Equator (where there is available water for evaporation) and lowest levels at the Poles.

Cryospheric stores of water

The Cryosphere includes all of the frozen water in the Earth's system. This means that frozen parts of ocean, glaciers, and ice sheets are all parts of the cryosphere. Frozen water can be found in the following forms;

- **Sea ice** – this is ice that floats at the surface of our seas and oceans. The extent of this ice varies between summer and winter, growing in the winter and shrinking in the summer. The Arctic is an example of an area of extensive sea ice, and its extent and thickness has reduced in recent decades. Whilst sea ice has no impact on changing sea levels as it melts, scientists are concerned about its reduction. This is because sea ice reflects a lot of solar energy back to space as it has a high albedo (a measure of surface reflectivity). Without this ice, more solar energy is ABSORBED in these regions rather than reflected. Sea ice tends to freeze at temperatures slightly below 0°C because of the salinity of sea water.
- **Ice Shelves** are another type of sea ice – they are platforms of ice where ice sheets and glaciers extend out over the oceans from the land. They are common in Antarctica and when the separate from the main ice sheet they become ice bergs. In 2017 a giant section of the Larsen C ice shelf in the Antarctic peninsula broke off, unleashing a 5,000 km^2 iceberg – about a quarter of the size of Wales. [5]
- **Ice sheets** – these are a mass of glacial land ice extending more than 50,000km^2. The Antarctic ice sheet is one of the two polar ice caps of the Earth. It covers about 98% of the Antarctic continent and is the largest single mass of ice on Earth. It covers an area of almost 14 million square kilometres (5.4 million square miles) and contains 26.5 million cubic kilometres (6,400,000 cubic miles) of ice. [6] The Greenland ice sheet (is a vast body of ice covering 1,710,000 square kilometres (660,000 sq mi), roughly 80% of the surface of Greenland. Together, Antarctica and Greenland ice contains more than 99% of the freshwater ice on planet Earth. If the Greenland Ice Sheet melted, scientists estimate that sea level would rise about 6 meters (20 feet). If the Antarctic Ice Sheet melted, sea level would rise by about 60 meters (200 feet). [8]
- **Permafrost** – this is soil, rock or sediment that is frozen for more than two consecutive years. The thickness of this layer varies from just a few metres to over a kilometre in Northern regions of Canada and Russia. The permafrost generally was created during previous ice ages and is now under threat of melting due to global warming. This has the potential for a positive feedback loop as melting permafrost releases methane, a highly potent greenhouse gas.
- **Ice caps** – these are smaller than ice sheets and are a mass of ice that covers less than 50,000 km^2 of land area (usually covering a highland area). They are found in mountainous areas such as the Himalaya and the Rockies, and are the source areas for many of the worlds **valley glaciers.** These glaciers occupy many of the world's valleys and their meltwater is significant as a water source for millions of people.

Terrestrial or land-based water
Terrestrial water may be considered as falling into four broad classes:

1. Surface water – the free-flowing water of streams and rivers, and the water of ponds and lakes:
2. Ground water – the water held in saturated strata below:
3. Soil water – the water held in association with air in unsaturated superficial layers of the earth.
4. Biological water – all of the water stored in plant and animal matter on Earth.

The lithosphere is the solid outer section of Earth, including Earth's crust as well as the underlying cool dense and rigid upper part of mantle. This is the zone we are concerned with when considering terrestrial water.
Only 3% of the World's water is freshwater and 79% is unfortunately locked up in ice sheets and glaciers. Another 20% of freshwater is found in the GROUND and needs to be accessed by drilling into the earth.
Rivers and lakes are the most accessible water in the terrestrial system.

Oceanic water
The Oceans are by far the biggest store of water. They dominate the amount of water available, 97% of all water is found in our oceans. Ocean water contains dissolved salts and ocean pH is 8.14 but is falling, linked to the increase in atmospheric carbon and ocean acidification. The world's oceans contain enough water to fill a cube with edges over 1000 kilometres (621 miles) in length. The oceans contain 326 million cubic miles (1.332 billion cubic kilometers), according to a recent study from the U.S. Geological Survey..

Store	Size (km^3 x 10 000 000)	% of all water
Oceans	1370.0	97.0
Polar ice and glaciers	29.0	2.0
Groundwater	9.5	0.7
Lakes	0.125	0.01
Soils	0.065	0.005
Atmosphere	0.013	0.001
Rivers	0.0017	0.0001
Living things	0.0006	0.00004

1 - https://en.wikipedia.org/wiki/Water_cycle accessed 23rd September 2018

2 – "Geography for A-level and AS", page 4, Skinner et al, Hodder Education, 2016

3 - https://water.usgs.gov/edu/earthhowmuch.html accessed 23rd September 2018

4 - https://www.e-education.psu.edu/earth103/node/558 accessed 23rd September 2018

5 - https://www.theguardian.com/world/video/2017/jul/12/vast-iceberg-splits-from-antarctic-ice-shelf-video-explainer

6 - https://en.wikipedia.org/wiki/Antarctic_ice_sheet accessed 23rd September 2018

7 - https://en.wikipedia.org/wiki/Greenland_ice_sheet accessed 23rd September 2018

8 - https://nsidc.org/cryosphere/quickfacts/icesheets.html
Factors affecting the magnitude of stores in the Hydrosphere

Factors affecting the magnitude of stores in water cycle

The water cycle is variable over time and over space. It does not operate in exactly the same way in different parts of the world for example. Although the component parts are similar, the stores and flows of the water cycle would vary significantly for tropical humid climates and for those in the Arctic Tundra for example. There are several processes (that you need to understand) that drive change in the magnitude of these stores over time and space, including:

1. Evaporation,
2. Condensation,
3. Cloud formation,
4. Causes of precipitation and
5. Cryospheric processes

All of these can vary and the exam board expect you to understand how these things change at hill slope, drainage basin and global scales, and with reference to varying timescales involved.

WATER STORES RESIDENCE TIMES

Water Store	Equivalent Depth in Meters	Residence Time
Oceans/Seas	2500	~4,000 years
Lakes/Reservoirs	0.25	~10 years
Swamps	0.007	~1 to 10years
Rivers	0.003	~2 weeks
Soil Moisture	0.13	~2 weeks to 1 year
Groundwater	120	~2 weeks to 10,000 years
Ice Caps/Glaciers	60	~10 – 1,000 years
Ice sheets (e.g. Antarctica)	58.3 [4]	~20,000 years
Atmospheric Water	0.025	~10 days
Biospheric water	0.001	~ 1 week

[1] Source: Freeze, R.A. and Cherry, J.A, 1979. P.5, Groundwater, Prentice-Hall

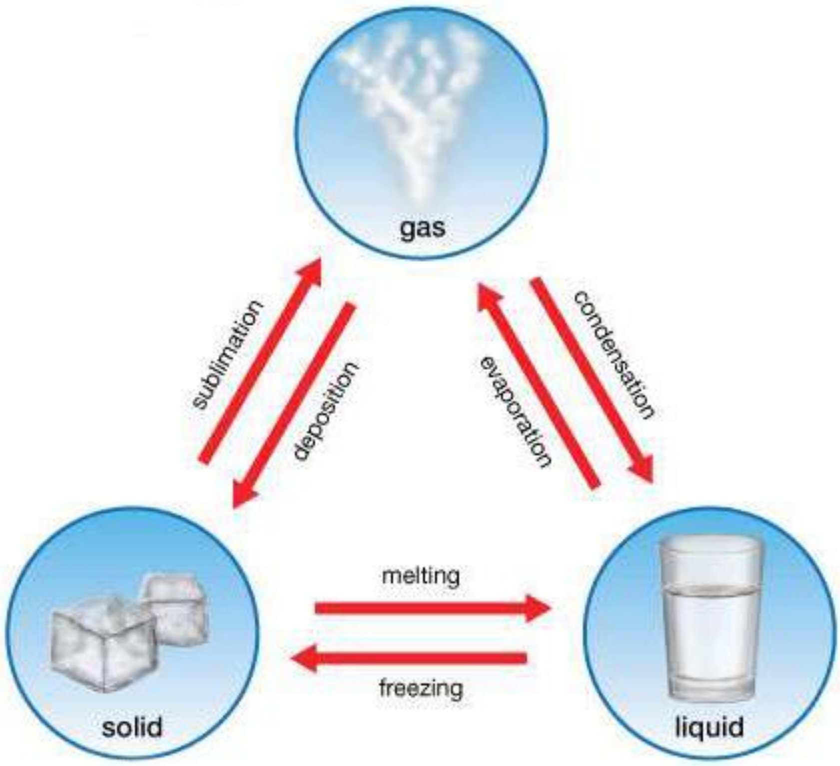
Stores within the Water Cycle have different residence times. Residence time is defined as the amount of water in a store divided by either the rate of addition of water to the store or the rate of loss from it. [2]

Stores such as Ice caps and sheets have incredibly long residence times. Water gets "locked up" in these stores and has to travel through the cryospheric system or wait for changing climatic conditions before it is released again. The oceans also store water for long periods of time, water can be transferred to incredible depths and remains in the oceanic store for long periods of time. Surface sea and ocean water is recycled between stores more rapidly. In the atmosphere the residence time of water vapour relative to total evaporation is only about 10 days. Water is rapidly moved in and out of this store via various processes in the water cycle. Lakes, rivers, ice, and groundwaters have residence times lying between these two extremes and are highly variable.

Phase changes of water as matter

It is useful to consider the change in, and transfer between water stores via a simple diagram shown below. The relative size of the **stores (the circles)** and **processes (the arrows)** can be adjusted to reflect different places and different periods in time.

PLACE DIAGRAM HERE Source [3]



The processes

Latent heat of fusion

- Melting: the substance changes from a solid to a liquid (in this case ice to water), extra energy needed
- Freezing: the substance changes from a liquid to a solid (in this case water to ice), loss of energy

Latent heat of vaporisation

- Vaporisation: the substance changes from a liquid into a vapour (in this case water to water vapour), extra energy needed
- Condensation: the substance changes from a vapour to a liquid (in this case water vapour to water), loss of energy to atmosphere

Latent heat of sublimation

- Sublimation: The substance has a 2-phase change (in this case from ice to gas), extra energy needed
- Deposition: The substance has a 2-phase change and loses energy (gas to ice in deposition)

Essentially, the diagram shows which processes move water from each of its states of matter: gas, liquid water and ice (the solid form). If water is transformed from ice to liquid water, ice to gas or liquid water to gas additional energy is required. If water is transformed in the opposite direction, i.e. gas to liquid water or ice, liquid water to ice the energy is lost.

The Major processes in the water cycle.

1. Evaporation

Evaporation is the process of turning from a liquid to a gas. Evaporation occurs when energy from the sun hits the surface of the water/land and causes liquid to change from liquid to gas.

Rates of evaporation depend on:

- Amount of solar energy
- Availability of water
- Humidity of the air - *The more humid the air the closer to saturation point the air is so less evaporation will occur*
- Temperature of the air – *Warmer air can hold more water than cold air.*

Humidity

Humidity measures how much water vapor is in a parcel of air at any given time. **Absolute humidity** is the mass of water vapour in an air mass measured in grams per cubic metre (g/m^3). This can also be expressed in a slightly different way by talking about specific humidity, which is measured in grams per kilogram of air. Warmer air can hold more water vapour than cooler air, and this is a vital concept to understand when discussing the weather. The warmer the air gets the more and more water vapour that air can hold. This means that humidity can vary from place to place and time to time. Obviously, globally the air in the Tropics can hold much more water vapour than higher latitudes because the air is warmer throughout the year. For the UK, the air can hold more water vapour as a gas in summer than it can in cooler winter months. In addition, there are diurnal or daily variations, as temperatures rise during the day and fall at night.

Relative humidity is therefore important, this is the amount of water vapour in the air at a given temperature compared to how much the air could possibly hold at that temperature. If the air has 100% relative humidity it is said to be SATURATED and therefore holds as much water vapour as it can give the temperature. [5] This is known as the dew point and any change in pressure or temperature will mean that water vapour is condensed into water droplets or ice crystals if the air is cool enough.

HUMIDITY GRAPH NEEDED

2. Condensation

Condensation is the conversion of a vapour or gas into a liquid. Water that exists as vapour in the atmosphere is converted into droplets during this process. If the water vapour converts directly into a sold form as ice crystals this is known as **sublimation**.

Condensation occurs because air is either;

- cooled or
- there is a fall in pressure.

As air cools or if there is a fall in pressure it is able to hold less water vapour. The **dew point** is the temperature at which water vapour in the air turns into liquid water.

Air can cool by **conduction** – the ground loses heat rapidly and this chills the air above, this can result in frosts, dew and mist. Air can also cool by uplift through the atmosphere caused by relief features, fronts or convective uplift, as explained below. A final method of cooling is by advection, where warm moist air moves over a cooler surface, for example, where air warmed over land passes over cold ocean currents as it does on the West coast of South America.

3. Cloud formation

Cloud formation and condensation require "dirty" air, as it is the pollen and dust particles around which water droplets form. As the air reaches saturation point or Dew point, water droplets form around pollen or dust particles (**condensation nuclei**). These water droplets are tiny, and **coalesce or collide** to form larger droplets. In the case of sub zero temperatures, it is ice crystals that form and join together in the ice crystal mechanism proposed by Bergeron and Findeisen. [6] When the water droplets or ice crystals in clouds grow to a certain size, gravity causes them to fall because of their own weight. There are different types of cloud dependent upon height and composition. [7]

4. Causes of precipitation

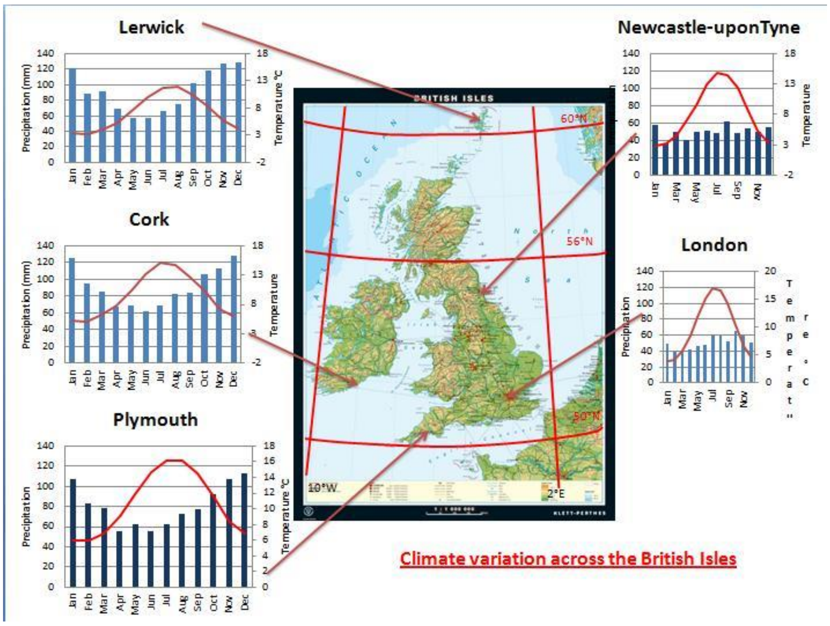
Precipitation is any product of the condensation of atmospheric water vapor that falls under gravity. The main forms of precipitation include drizzle, rain, sleet, snow, graupel and hail. Precipitation is the main input into the drainage basin system. There are 3 basic types, all involve the uplift of air, a subsequent cooling and fall in air pressure, condensation follows and then either coalescence of droplets or fusing of ice crystals.

Frontal Rainfall

This occurs where warmer air meets colder and the former is forced to rise. The warm air is rising, so it cools initially at the Dry Adiabatic Lapse Rate (9.8°C per 1000m ascent) and then at the MORE VARIABLE Saturated Adiabatic Lapse Rate as latent heat is released during condensation. This eventually results in cloud formation and eventually rain (once the droplets have collided enough to be big enough to fall).

https://www.youtube.com/watch?time_continue=14&v=D88dYNFyBq8

Relief rainfall



Climate variation across the British Isles

Relief rainfall is a dominant method of precipitation formation in the UK and relates to the precipitation that is created as air masses are pushed up and over mountainous or upland areas. **Relief rainfall** occurs where moist air is **forced to rise over a physical barrier such as a mountain range**. For example, warm air is carried to the West coast of Britain by our prevailing (dominant) winds, the South Westerlies. This air encounters the high land on the coast of Ireland, then the Lake District and the Pennines and it is forced to rise above this barrier. As it rises, the warm air cools with height at a rate of 9.8°C per 100om (the DALR). As the air cools water vapour condenses to form clouds and eventually it rains over Britain's highland areas. As the air descends to the East coast of Britain or the Lee slope it warms slightly and there is less rainfall. This results in a rain shadow on Britain's east coast. It is for this reason that the West coast of Britain is wetter than the East, Blackpool receives 950mm of rainfall per year, the Pennines 2000mm+, and Newcastle 700mm.

Convectional rainfall

This is where the Sun's energy hots the surface of the planet which heats the air above. This air then has extra energy and rises upwards in thermals. The heat energy also causes rapid evaporation and evapotranspiration so the air that is rising is humid. The air cools as it rises, and water vapour will condense once dew point is reached. Large quantities of water vapour and fast condensation causes storm clouds. It often results in towering cumulonimbus clouds. This type of rainfall is common in hot tropical areas but is also known in the UK in summer.

5. **Cryospheric processes**

Cryospheric process are those processes that affect the total mass of ice at any scale from local patches of frozen ground to global ice amounts. They have a direct impact on the major stores of water, they lock up water as ice from the hydrosphere lowering sea levels, or release water during melting in warm periods rising sea levels.

The Crysophere includes: seasonal snow, frozen ground, sea ice, glaciers, ice caps, and ice sheets. It contains 1.8% of all water on Earth but nearly 70% of the freshwater.

The formation of ice.

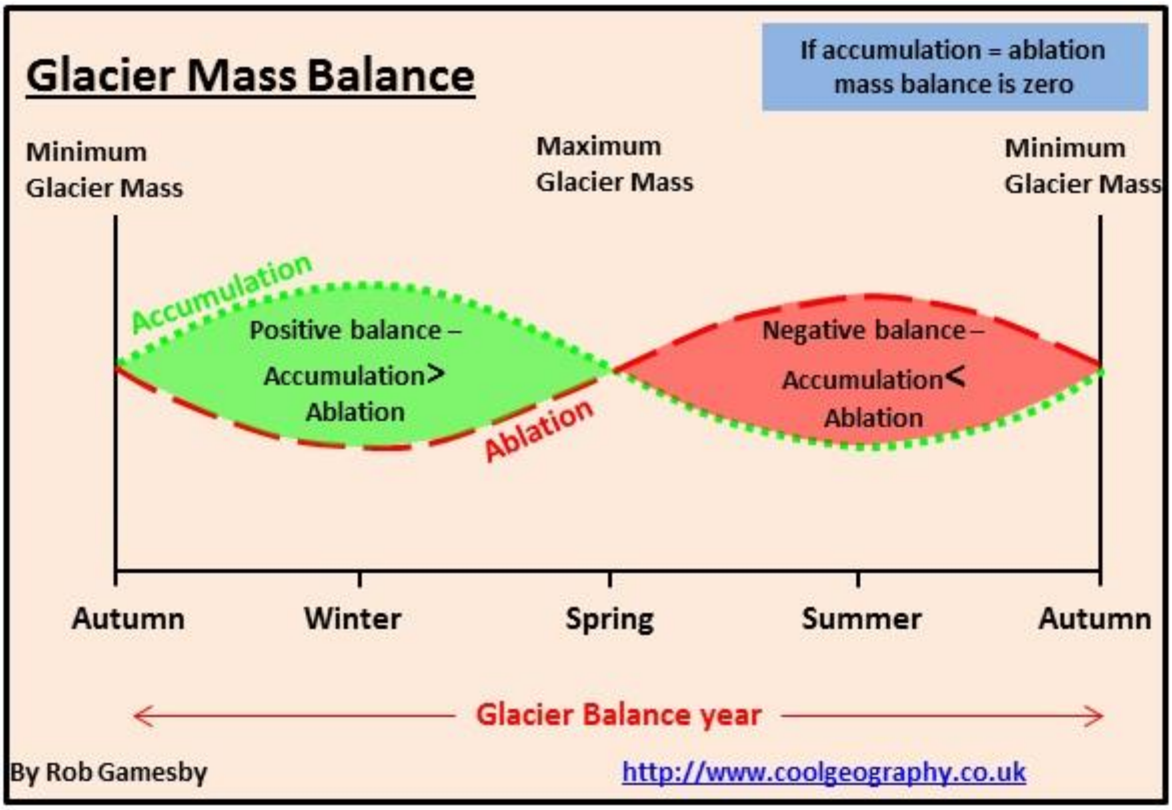
Ice forms from the compression of falling snow. As layer upon layer of snow is added it can exert a pressure on the snow at the base, compressing that snow and forcing air out of it. This will slowly form a denser substance called Névé and eventually ice. Melting and refreezing of previously fallen snow can also assist in this process.

Within an ice mass we need to consider 2 variables;

1. Accumulation is the build-up of ice mass
2. Ablation is the loss of ice mass

Where accumulation and ablation are equal the glacier is said to be in a steady state. This rarely happens, and 2 other states exist;

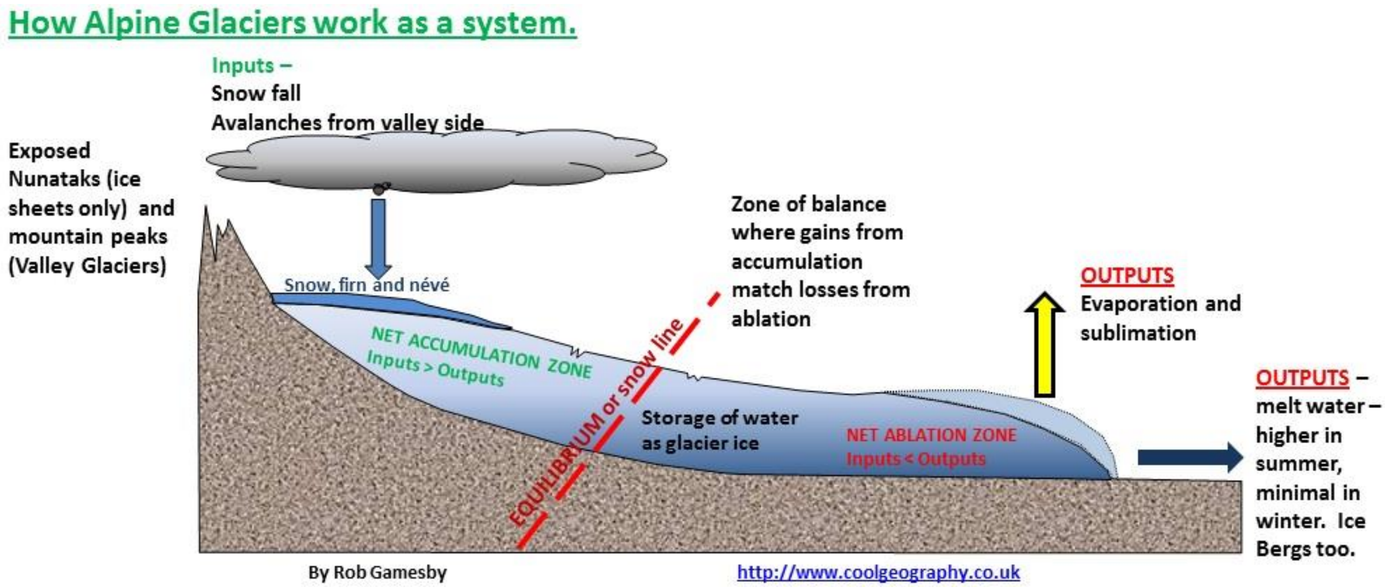
1. When accumulation is greater than ablation leading to growth in ice mass and potential glacial advance down the valley
2. When ablation is greater than accumulation leading to a loss of ice mass and the potential retreat of the glacier up valley.



Over a year accumulation tends to be within the colder months and ablation within the warmer months.

Ice movement

It is hard to understand that Ice moves given that it is a solid, but it can and does. Ice can move at extraordinary speeds, and glaciers in surge conditions are known to move at up to 300m a day. The Franz Joseph glacier in New Zealand has been known to surge in the past. Ice can move in many ways and this is determined by the glacial mass balance and the temperature and precipitation regime of the area the glacier is found within. The fact that ice moves is important. It shifts ice into more temperate zones where it can melt and become part of the atmosphere or hydrosphere via meltwater. It also moves ice to the edges of ice sheets by the sea where the ice can calve off to become ice bergs and melt into the oceans.



1 Source: Freeze, R.A. and Cherry, J.A, 1979. P.5, Groundwater, Prentice-Hall – available at http://hydrogeologistswithoutborders.org/wordpress/original-groundwater-by-freeze-and-cherry-1979-now-available-online/

2 https://www.britannica.com/science/hydrosphere/The-water-cycle#ref238299 accessed 7th October 2018

3 https://waterknowledge.colostate.edu/hydrology/water-cycle/ accessed 7th of October 2018

4 http://www.antarcticglaciers.org/glaciers-and-climate/estimating-glacier-contribution-to-sea-level-rise/ accessed 7th October 2018

5 https://en.wikipedia.org/wiki/Dew_point accessed 7th October 2018

6 https://en.wikipedia.org/wiki/Wegener%E2%80%93Bergeron%E2%80%93Findeisen_process Accessed 7th October 2018

7 https://scied.ucar.edu/webweather/clouds/cloud-types accessed 7th October 2018

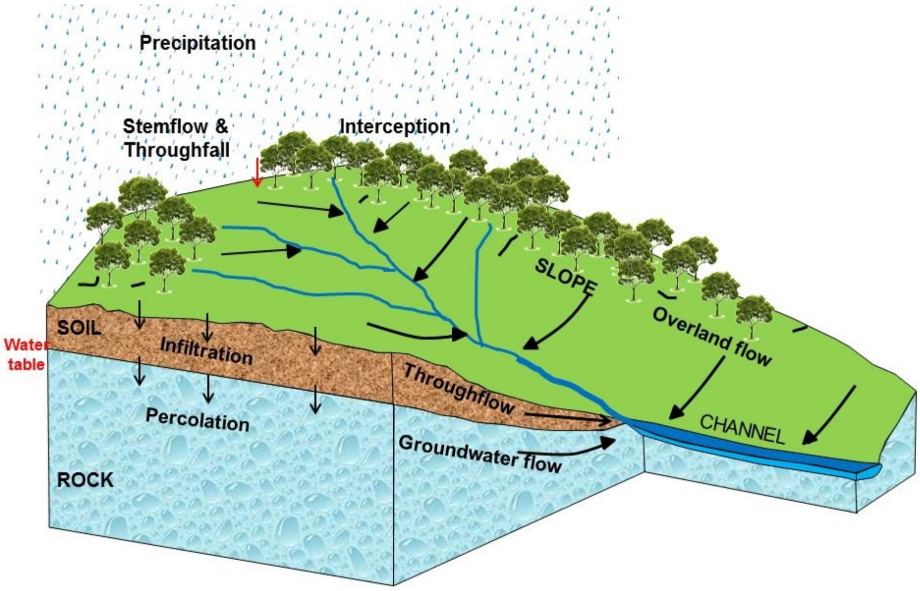
Drainage basins

The drainage basin is the area of land drained by a river system (a river and its tributaries). It includes the surface run-off in the water cycle, as well as the water found in the ground. Drainage basins are separated by **watersheds**. This is the area that separates on drainage basin from another, indeed, the water shed is the upper limit around the drainage basin.

A drainage basin is **an example of an open system** because it is open to inputs from outside, such as precipitation, and is responsible for outputs out of the system, such as output of water into the sea and evaporation of water into the atmosphere. It can also be seen as a **cascading system**, as the outputs from drainage basins become the inputs to other systems such as the coastal system.

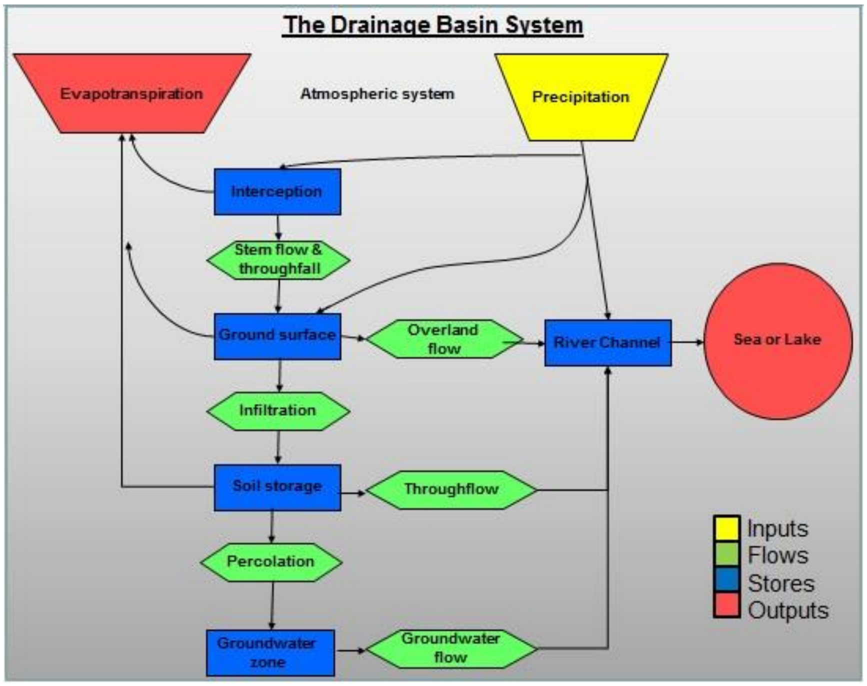
You can see a diagram of the drainage basin below. The North East of England has 3 major drainage basins, the Tyne, Tees and Wear, and several other smaller drainage basins. These are tiny compared to the world's largest drainage basins, such as the Nile, Amazon and Mississippi [1], which covers 3,225,000km^2.

The drainage basin – major flows and stores



The drainage basin as an open system

The drainage basin starts with an input from the water cycle – **precipitation**, after the processes of condensation and cloud formation. This precipitation can be stored on the surface as snow or ice (**surface storage**), or can be **intercepted** by trees and vegetation. On the trees or vegetation the water can be dripped off leaves, flow down the vegetation as **stem flow** or be taken up and lost as transpiration. Some water is stored in plants as vegetation storage (aka biospheric water). The combined losses of water through transpiration and evaporation are known as **EVAPOTRANSPIRATION**.



It could also fall straight into the ground where it can **infiltrate** (into the soil then **percolate** (the downward movement of water within the rock under the soil surface) into the rock underneath if the soil and rock are permeable. If the rock is not permeable or the soil stores are full then **surface runoff** will occur. This water will then work its way through the soil (**soil flow/throughflow**) or rock (groundwater flow - the slow movement of water through underlying rocks) or over the land as overland flow (the tendency of water to flow horizontally across land surfaces when rainfall has exceeded the infiltration capacity of the soil and all surface stores are full) and into streams and rivers. This is also known as **run-off** - all the water that enters a river channel and eventually flows out of the drainage basin. These small tributary streams join at confluences and the river will grow in size and strength.

These processes are true for hillslopes and larger scale drainage basins.

Factors affecting infiltration rate [3]

The infiltration capacity is the maximum rate at which water can be absorbed by a given soil per unit area under given conditions. There are several factors which affect how much water can be infiltrated by a soil;

1. Soil type (texture, structure, hydrodynamic characteristics) - the soil characteristics influence capillary forces (the ability of a liquid to flow in narrow spaces without the assistance of, or even in opposition to, external **forces** like gravity) and adsorption. This can be seen in the table below for uncompacted soils;

Infiltration rate (centimetres/hour)	Soil textures
4.14	silty gravels gravelly sands sand
2.03	sand loamy sand sandy loam
1.14	
0.76	loam, silt loam
0.51	Sandy clay loam
0.15	clay loam silty clay loam sandy clay silty clay clay

Source: Minnesota Pollution Control Agency [4]

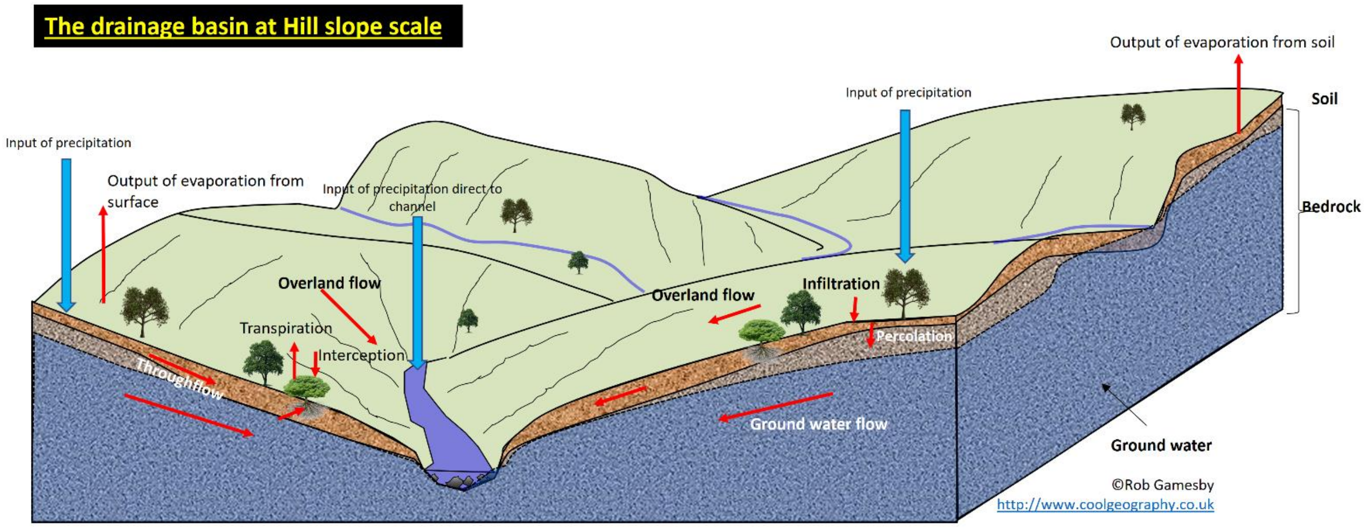
2. Soil coverage. Vegetation has positive influence on infiltration by increasing the time of water penetration in soil, this is because plant roots can create channels for the water to soak through.
3. The topography and morphology of slopes – it has been suggested that steeper slopes have lower infiltration rates and more surface runoff.
4. The flow supply (how intense is the rain? is there drainage?).
5. How humid are the soils already - this is an important factor of infiltration regime. The infiltration regime changes for dry or wet soils.
6. Soil compaction due to rain drop impact and other effects. The use of hard agricultural equipment can have consequences on the surface layer of soil.

In reality, infiltration rates are affected by a combination of these factors. These could be a potential NEA study. If the rainfall intensity is greater that the infiltration rate then water will remain at the surface of the soil as surface storage and overland flow can occur. Similarly, if soil pores are full no water can infiltrate and the soil is said to be **saturated**. In both cases there is the potential for localised flooding.

Factors affecting soil storage

Rain water can also be stored in the ground as soil storage. Soils consist of particles and pores. Those pores can be filled with air but also with water. The amount of pores is a soil is different for different types of soil. The pores in a clay soil account for 40% to 60% of the volume. In fine sand this can be 20%–45%

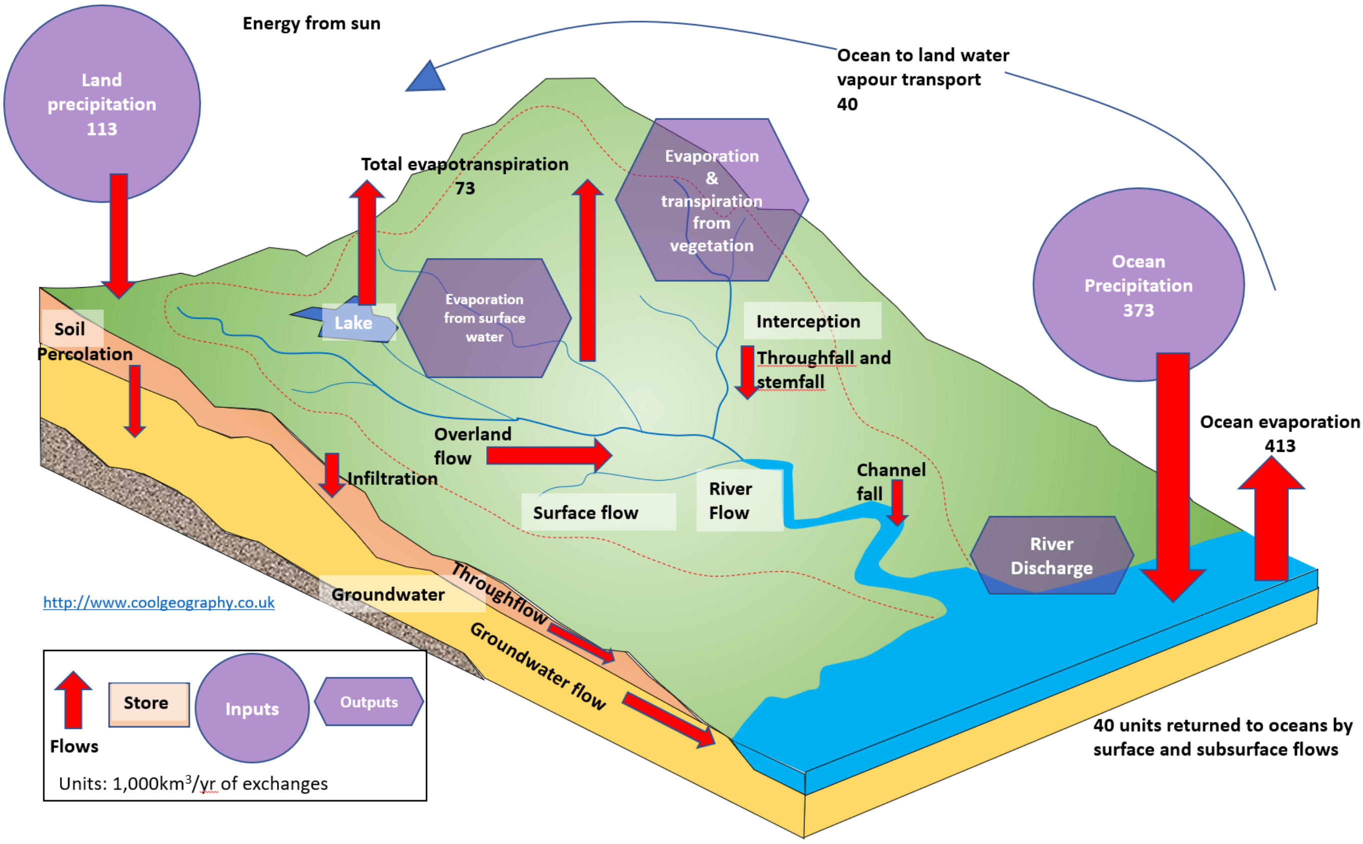
The soil particles have small pores in them where water can enter (soil water) and between the particles are larger pores that can be filled. The soil is filled with water up a certain level. This level goes up and down with changing weather conditions.[6] This water level is the ground water level also known as the water table. This can best be studied at local scale such as a valley or hill slope, as shown below.



Factors affecting interception rates

Interception is another important factor controlling flows and stores within the drainage basin. It is basically when plants trap water or stop it from reaching the ground during a rainfall event. The rates of interception are controlled by;

- The plant type and shape – for example coniferous trees intercept 25-35% of annual precipitation whilst deciduous trees intercept 15-25% of annual precipitation, but just as much as coniferous trees during the growing season. Grasses have high interception capacity during the growing but then either die (annual plants) or loose mass (perennial plants); also they are grazed and harvested (spring wheat intercepts 11-19% of precipitation before harvest).
- Plant density
- Plant structure in terms of size, flexibility, strength and pattern of branches. Leaves- their texture, surface area and orientation
- Plant community structure - secondary interception occurs in stratified forest communities where water drips from the canopy and is intercepted by lower plants
- Precipitation intensity - water can be delivered too quickly for the plants to intercept
- Precipitation duration - absolute interception storage increases with increasing storm duration
- Wind speed - promotes interception loss by evaporation
- Type of precipitation: rain versus snow [5]



All of this can be considered in the diagram above. Note that most ocean water evaporated is returned back the sea as ocean precipitation.

The water balance

The Water balance is the balance between inputs and outputs within a drainage basin. When the INPUTS and OUTPUTS of the drainage basin system are balanced over longer periods of time it is said to be in **dynamic equilibrium**. However, there will be periods were there is more rainfall than others leading to more erosion, or drier periods where there will be deposition occurring. All of this can be interpreted as a systems diagram. This can also be shown in a water budget, which is;

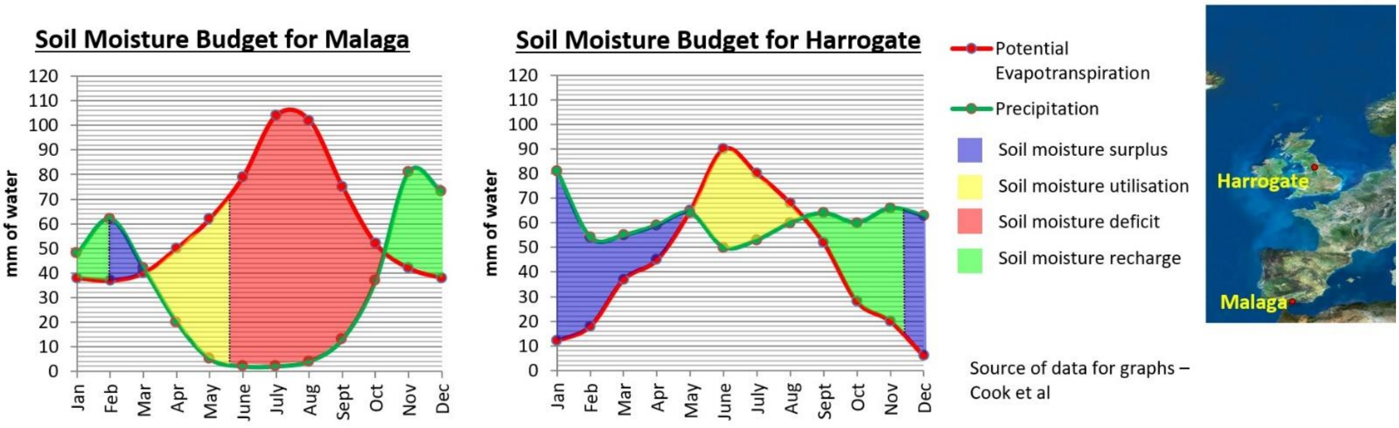
Change in storage (ΔS) = **Precipitation (P)** - Runoff (Q) **+ Evapotranspiration (E)**

A **positive balance** indicates that inputs are greater than outputs and **water will be stored in the system**.

A **negative balance** indicates that outputs are greater than inputs and **stores will deplete and be used up**.

This can be shown on a soil moisture budget graph, examples for Harrogate and Malaga are shown below. This graph comprises 3 basic sections. Where potential evapotranspiration (is a measure of the ability of the atmosphere to remove water from the surface through the processes of evaporation and transpiration assuming no control on water supply[2]) is above precipitation soil moisture utilisation will take place, that is, soil stores will be used and not replaced. This could continue until soil moisture depletion, where there is no water left in the soil and plants will begin to die. Once precipitation rises above evapotranspiration soil moisture recharge will occur, and soil stores will be replaced slowly. Once the field capacity of the soil is reached (the normal amount of water a soil can hold) then we reach a situation of soil moisture surplus.

Soil moisture budgets for Harrogate and Malaga



1 https://en.wikipedia.org/wiki/Mississippi_River accessed 13th October 2018

2 http://www.physicalgeography.net/fundamentals/8j.html accessed 8th October 2018

3 http://echo2.epfl.ch/VICAIRE/mod_1a/chapt_5/main.htm accessed 13th October 2018

4 https://stormwater.pca.state.mn.us/index.php?title=Design_infiltration_rates accessed 13th October 2018

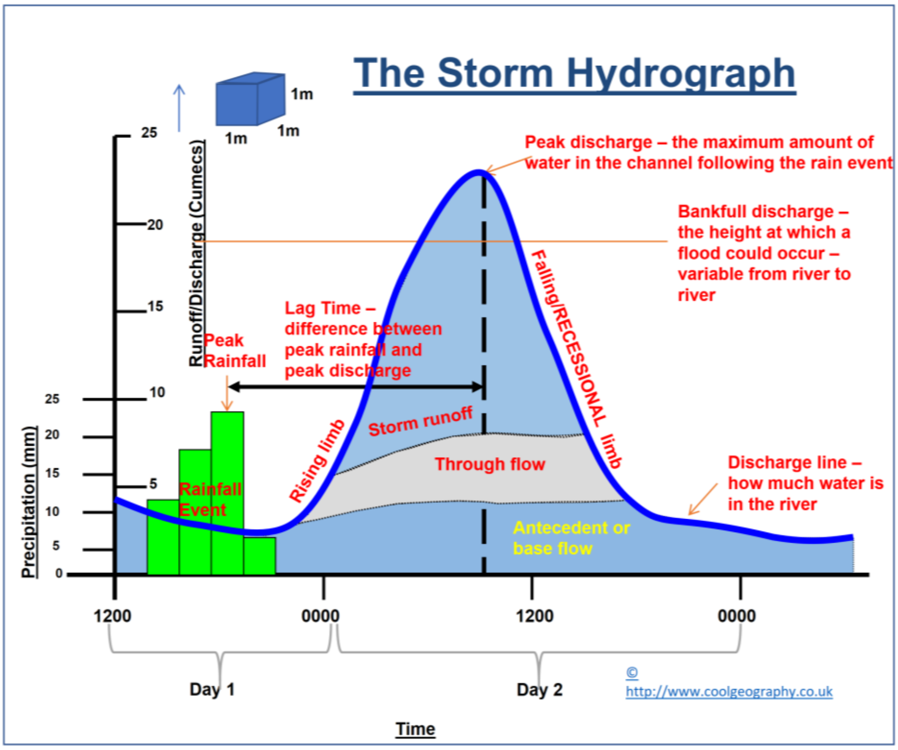
5 http://uregina.ca/~sauchyn/geog327/intercept.html accessed 13th October 2018

6 http://www.floodsite.net/juniorfloodsite/html/en/student/thingstoknow/hydrology/waterstorage2.html accessed 13th October 2018

Runoff variation and the flood hydrograph.

A storm hydrograph is a way of displaying how the discharge of a river can change over time in response to a rainfall event. [1] The **discharge of a river** is just the volume of water passing a certain point every second, and is calculated by multiplying the cross sectional area of the river by its velocity. Because the cross section is measured in metres^2 and the velocity is measured in metres per second the discharge is measured in metres^3 per second. These units are known as CUMECs (CUbic Metres per sECond).

These graphs are useful because the show us how variable runoff can be. They also reveal the contributions of water from the ground (as Antecedent or base flow) and from the soil.



The graph shows base flows and throughflow which are the contributions made to the river via soil and ground water flows. These will be ever present on the graph unless there is a long-extended period without any rainfall.

The runoff or storm flow is the water that arrives in the river via surface runoff or rapid throughflow through the rock.

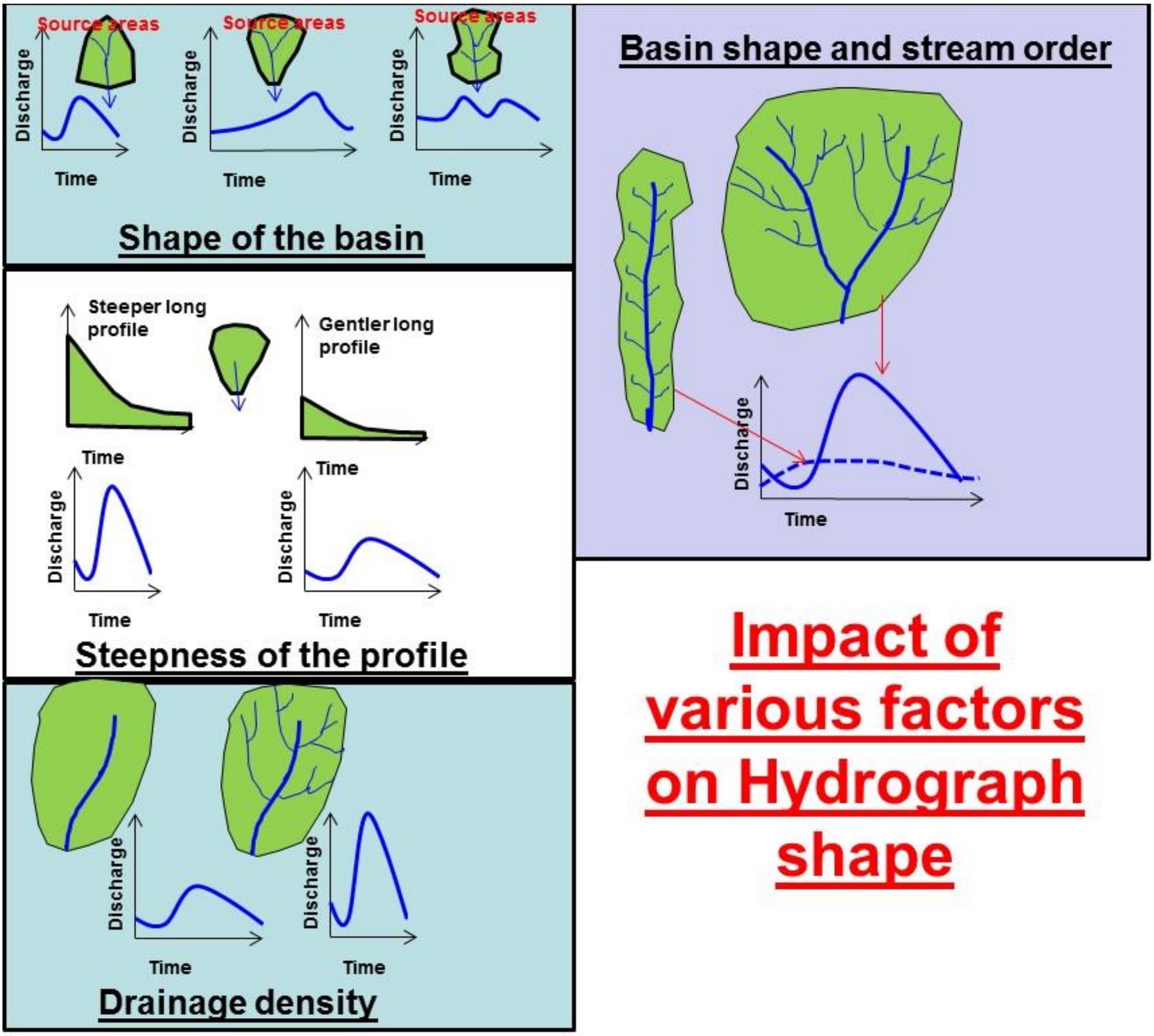
The **rising limb** gives an indication of how fast water is reaching the channel and represents the level of water rising in the channel. The steeper the rising limb the more likely a flood is to occur, this is vital knowledge for flood forecasters. This rising limb is also known as the approach segment.

The **falling limb** shows the river as its level falls. A long period for this falling or recessional limb can extend the period that the river is high. It could also be interrupted by another peak in discharge if there si a secondary rainfall event following the first event.

Peak discharge is the maximum amount of water in a river after a rainfall event, if this level surpasses the bankfull discharge then a flood will occur where the river overtops its banks.

The last item indicated on the hydrograph is the **lag time**, this is the amount of time between the peak amount of rainfall and the peak discharge in the river. Generally, the less the lag time the quicker the river rises, the more FLASHY the graph and the more likely a flood. Lag time is therefore a key feature of a river hydrograph, as it shows how much preparation time people have before a flood strikes.

Hydrographs can take different shapes dependent upon the characteristics of the drainage basin. The various flows and stores of the drainage basin are affected by these characteristics, and these in turn will affect the shape of the hydrograph and the volume of water in a river. This is shown on the diagram below and the characteristics are explained underneath.



Some of the factors (such as interception levels, soil types and infiltration rates) that affect hydrograph shape (and more importantly) river discharges are covered in the section on Drainage Basins. Other factors include;

1. Precipitation type, amount and duration are the most obvious reasons for river flooding. Long steady prolonged rainfall will produce rivers which rise slowly but can flood, these produce hydrographs with longer lag times and generally lower peak discharges.

   Heavy short showers can cause rivers to rise quickly and burst their banks, these would have a very short lag time and high peak discharge.

   Snowfall is another factor to take into account, river levels fall in the UK as precipitation is often stored as snow during cold snaps. However, when temperature warms and that snow melts many days' worth of precipitation can end up in rivers and cause flooding. The Hydrograph would have a high peak as a result of this but an extended lag time.

2. The **RELIEF or gradient of the river/drainage basin profile** can also have an impact. Steep slopes tend to reduce the amount of infiltration of water into the ground, this water can then flow quickly down to rivers as overland flow. In addition, steep slopes also cause more through flow within the soil. Both can raise river levels. Gentle slopes or flat land allow water to penetrate into the soil and increase lag times and reduce peak discharges
3. Vegetation type and coverage plays a big role, with forests intercepting more rainfall than grasses. This interception increases lag time and reduces the risk of a flood. Indeed, deforestation (the removal of trees) can increase soil erosion, reduce interception and increase flood risk. Afforestation, where trees are planted, can have the opposite effect.
4. **GEOLOGY - Soil and rock type** can also influence what happens to precipitation when it reaches the ground. Impermeable soils and rocks such as clay or shale do not allow water to infiltrate, this forces water to run off reducing river lag times and increasing flood risk. Permeable rocks allow water to infiltrate into them. If permeable rocks allow water in through cracks, fissures and bedding planes but not through their pores they are said to be pervious (such as limestone). Porous rocks allow water to penetrate into their pores such as sandstone.
5. **With more streams in an area or a higher drainage density** more water can collect quickly from within the basin. This reduces lag times and increases peak discharges**.**

Human reasons for river flooding

Humans cause changes in LAND USE which can impact upon river flooding.

1. **Urbanisation** can cause flooding because many of the surfaces in towns and cities are Impermeable. The whole urban system is designed to move water from the surface into underground pipes and away from urban areas which have value. This can lead to floods in other regions.

2. **Deforestation (the removal of trees)** can increase soil erosion, reduce interception and increase flood risk.

3. Increases in **population density** can also have an impact as it places more people in flood risk areas. It is for this reason that we are building on floodplains and flood risk areas in the UK, this just increases the likelihood of a flood.

4.**Agriculture** can also have a major impact. Ploughing of the soil breaks it up and allows more infiltration. This reduces peak discharges and increases lag times. Conversely, drainage channels and ditches designed to drain fields speed water into local rivers and increase peak discharges and reduce lag times. When fields are harvested that reduces interception, results in greater over land flow and decreases lag times.

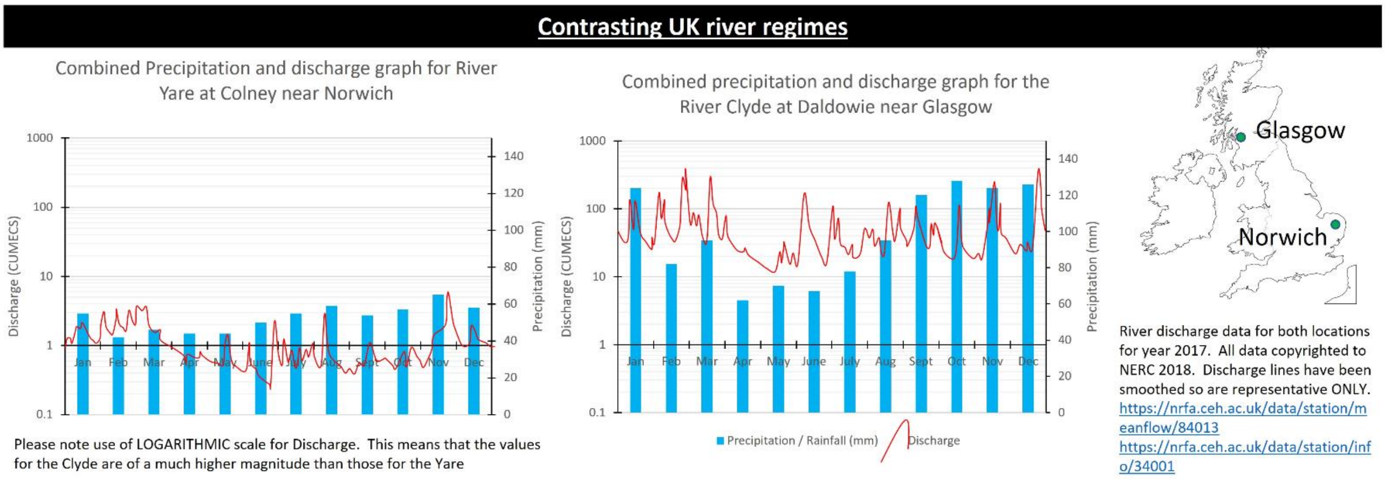
Other factors such as farming practices, deforestation and water abstraction are covered in detail in the next section.

River Regimes

When we consider discharge changes over a year we call this a River REGIME. The definition of river regime is
"*River regime* can describe one of two characteristics of a reach of an alluvial *river*: The variability in its discharge throughout the course of a year in response to precipitation, temperature, evapotranspiration and drainage basin characteristics" [2]

These changes and all of the factors mentioned above would have different consequences for the drainage basin and their river discharge at different times of the year. The river regime is also useful for us when considering how rivers change for different parts of the world.

The graphs below show 2 regimes for 2 rivers in different parts of the UK. The regime for the River Clyde near Glasgow contains discharges that are much higher than that of the River yare near Norwich. The Clyde is also more variable in its flow rates in winter too. This is because the North west of the British Isles is more affected by winter storms, which bring regular rainfall to the area and make the river more Flashy. The river Yare is in a drier part of the UK in the rain shadow of the East, hence the lower flows.



Source of data [3]

The river Nile

The River Nile is found in northeast Africa, and is known as the longest river in the world – stretching a massive 6,695km! The Nile River is often associated with Egypt, but it in fact flows through 11 countries: Tanzania, Uganda, the Democratic Republic of the Congo, Rwanda, Burundi, Ethiopia, Kenya, Eritrea, South Sudan, Sudan and Egypt.

Two main tributaries meet to form 'the Nile'. One tributary is called the White Nile, which starts in South Sudan, and the other is called the Blue Nile, which starts in Ethiopia. The Blue Nile and White Nile merge together in the city of Khartoum in Sudan. Another major tributary, the Atbara, joins just north of Khartoum. From there, the river continues to flow north through Egypt and, finally, into the Mediterranean Sea**.** [4]

Below you can see the river regime for the various rivers that make up the river Nile.

Essentially the following patterns are true of the Nile;

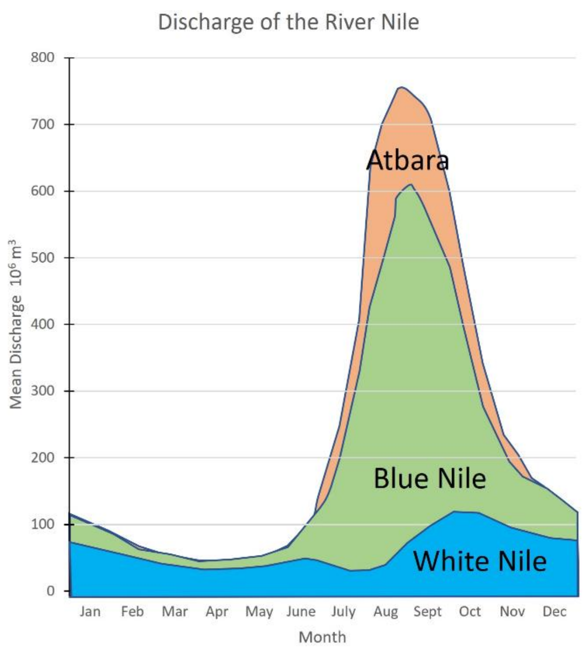
- the Nile's minimum flow is in winter
- the maximum flood occurred during summer

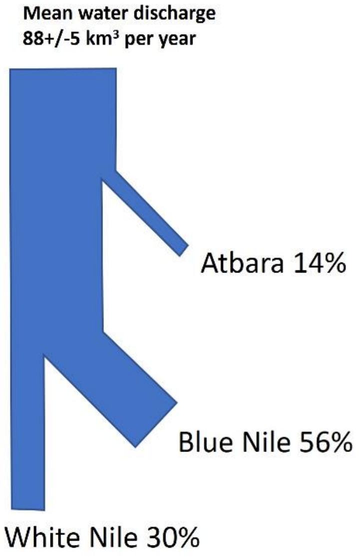
The White Nile coming from the South maintains a constant flow over the year. This is because its flow is affected and minimised by;

1. Storage in Central African lakes of Victoria and Albert and
2. The Sudd, the world's largest freshwater swamp, which slows the river and allows for lots of evaporation losses. The Sudd is very efficient in reducing annual variations in streamflow. In unusually wet years increase the area of the Sudd which leads to larger evaporative losses than during dry years, when the area of the Sudd is reduced. This steady stream keeps the Nile downstream from Khartoum flowing during the winter months, when the Blue Nile/Atbara system has dried up. [5]

The Blue Nile-Atbara system have a different hydraulic regime. They respond to the wet season/dry season variation of the Ethiopian highlands. In the winter, when little rain falls in the highlands, the Atbara and Blue Nile dry up. In the summer, when moist winds from the Indian Ocean cool as they climb up the Ethiopian highlands, bringing torrential rains to Ethiopia. This monsoonal rainfall fills the local rivers which flow into the Blue Nile and Atbara. Overall, these 3 river regimes keep the Nile flowing all year round but ensure a huge peak during the summer months.

River Regime of the River Nile





Map by Hel-hama [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)], from Wikimedia Commons

Changes in the water cycle over time Runoff variation and the flood hydrograph. Changes in the water cycle over time to include natural variation including storm events, seasonal changes and human impact including farming practices, land use change and water abstraction.

1 https://geology.com/articles/hydrograph.shtml accessed 14th October 2018

2 *Beckinsale* RP. *1969*. *River* regimes.

3 National River Flow Archive, https://nrfa.ceh.ac.uk/data/station/meanflow/84013 and https://nrfa.ceh.ac.uk/data/station/info/34001 , accessed 14th October 2018

4 https://www.natgeokids.com/uk/discover/geography/physical-geography/nile-river-facts/ accessed 16th October 2018

5 https://www.utdallas.edu/geosciences/nile/Hydromap.html accessed 16th October 2018

Human Impacts on the water cycle

Role of forests in the hydrological cycle

Forests play a very important role within the global and local hydrological cycles.

They transmit huge quantities of water into the atmosphere via the transpiration of plants (in which plants release water from their leaves during photosynthesis) and from evaporation from their leaves. These inputs replenish clouds and help produce the rain that sustains the rainforests. Indeed, much of the water that falls in tropical rainforests is recycled within the system if the forest is large enough. Some of this recycling is evaporation from lakes, rivers, or wet soil. However, a lot of it is fast-tracked by plants, and especially trees. Tree roots tap moisture from deep in the soil. This circulation system is driven by releases of moisture into the air through their leaves via transpiration.

In the Amazon, 50-80 percent of moisture remains in the ecosystem's water cycle. [1]

Deforestation and the hydrological cycle

When deforestation occurs, this cycle is interrupted. At a local level deforestation can have immediate effects on the hydrological cycle. In tropical forests;

1. Less plants means **less evapotranspiration.** Subsequently there is a decline in rainfall, subjecting the area to drought.
2. **Rainfall can be lost** from the area, permanent drying can occur and flood regimes of rivers are altered. [1] This can result in drought in former rainforest areas. Rainforests of Borneo and the Amazon have experienced very severe droughts.
3. The regular flow of clean water from forests and protecting communities from flood and drought can be affected.
4. **Interception rates are affected** – Tropical forests in particular are multi layered and catch huge volumes of rainfall falling from the sky. This is delivered to the forest floor via stemflow and through fall from leaves. This would stop and water would fall directly onto the forest floor.
5. **Infiltration and percolation would increase** but this would result in the water table being closer to the soil surface. Rainforests soak up rainfall brought by tropical storms Both by intercepting rainfall and allowing slow infiltration into the soil. This regulates floods and river levels. Without forest cover infiltration rates are affected and more overland flow occurs. This means more destructive flood and drought cycles can occur when forests are cleared.
6. **Overland flow increases** when forest cover is lost. Rainfall turns into runoff which rapidly flows into streams, raising river levels and creating potential flood risks during wetter periods. During the dry season areas downstream of deforestation can be prone to months-long droughts.
7. **Less water is stored in the biosphere as a result of deforestation**
8. Transpiration and shading from trees help to cool rainforests - this is lost from deforestation which can increase evaporative losses. In the Amazon, Michael Coe of the Woods Hole Research Center recently reported a difference of 3 degrees Celsius (5.4°F) between the cool of the forested Xingu indigenous park and surrounding croplands and pastures.

The global affects of deforestation

Our globe is connected by a global scale climate system. Moisture generated by rainforests travels around the world. According to Mongabay.com Scientists have discovered that rainfall in America's Midwest is affected by forests in the Congo. [2]

Whilst the UN's Food and Agriculture Organization (FAO) and the Center for International Forestry Research (CIFOR) say that deforestation does not cause more flooding, they have found that deforestation does have a role in small floods and topsoil erosion by eliminating the buffering and soil-anchoring effects of forests. In terms of climate change, the water that a single tree transpires daily has a cooling effect equivalent to two domestic air conditioners for a day. [14]

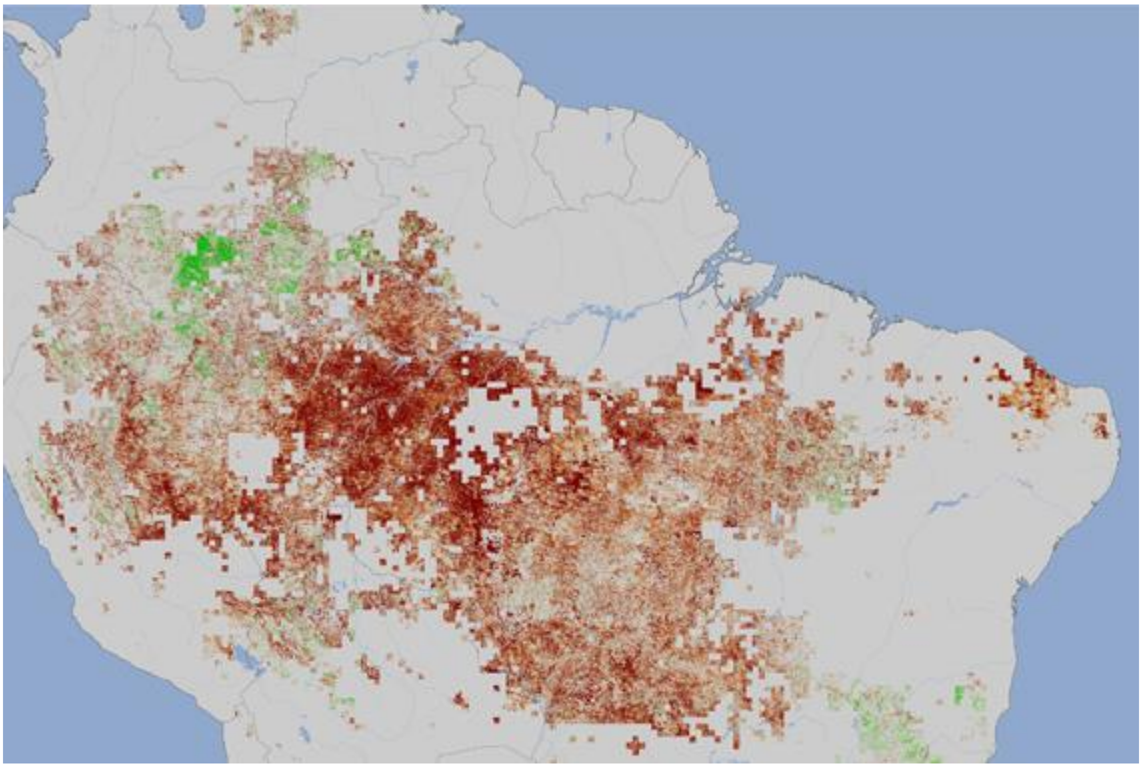
Links to the Carbon Cycle

A result of changes to the hydrological cycle caused by deforestation can have impacts upon the carbon cycle. The obvious link is that the loss of forest cover puts huge volumes of carbon into the atmosphere, replacing biospheric carbon with atmospheric carbon. However, increased drought risk increases fire risk for the scrublands and grasslands that replace the forest cover. These fires also release carbon into the atmosphere. According to Mongabay.com – "*The newly desiccated forest becomes prone to devastating fires. Such fires materialized in 1997 and 1998 in conjunction with the dry conditions created by el Niño. Millions of acres burned as fires swept through Indonesia, Brazil, Colombia, Central America, Florida, and other places. The Woods Hole*

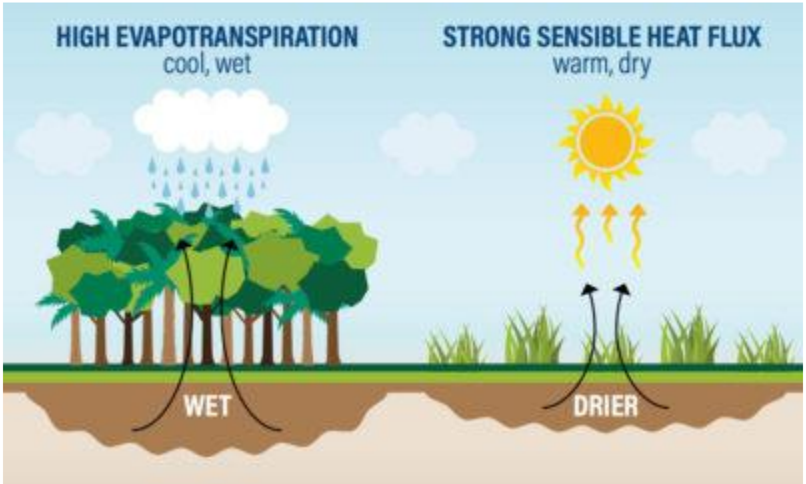
Research Center warned that more than 400,000 square kilometers of Brazilian Amazon were highly vulnerable to fire in 1998. That extent grew in 2005 and 2010 *when the Amazon was hit by even worse droughts*." [3]

It is also known that carbon dioxide emissions from deforestation add 10 percent or so to global warming by reducing the quantity of CO_2 that the world's forests pull from the atmosphere. [4]

In addition, forests release a range of volatile organic compounds that "have an overall cooling effect on our climate," mostly by blocking incoming solar energy, says Dominick Spracklen of Leeds University.[5] Removing forests eliminates this cooling effect and adds to warming.



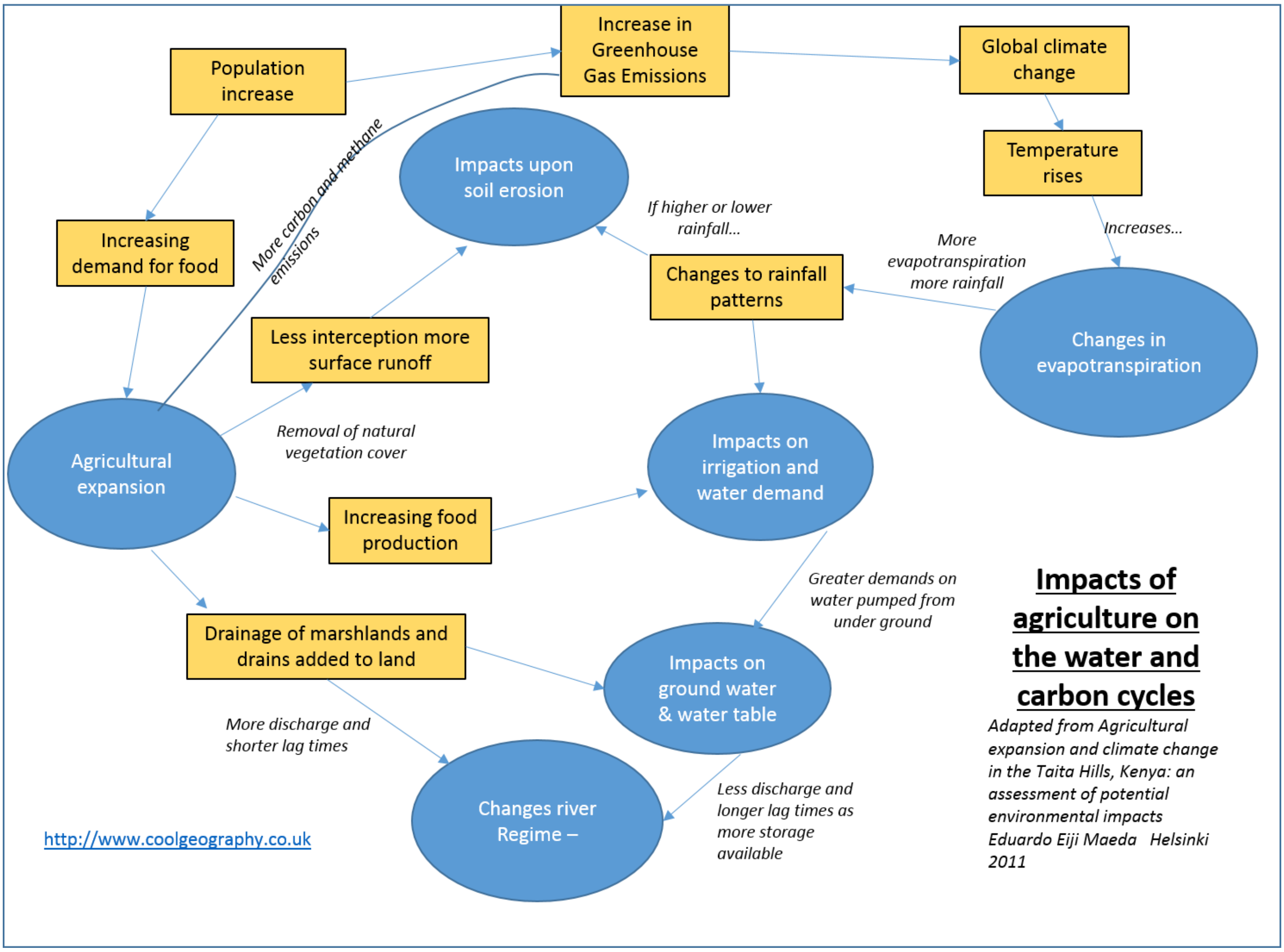
The image above shows vegetation 'greenness' during the 2010 drought, between July and September, compared to average conditions for the same period between 2000 and 2009. The redder the image the less 'green' the forest. Image from the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite, courtesy of NASA. [6]



Impact of Agriculture on the hydrological cycle

Modern agriculture has a large impact upon the hydrological cycle. In many parts of the world agriculture has replaced natural vegetation with crop cover and pasture, drastically altering the way that water moves through altered drainage basin systems. We need agriculture to feed the world's population but this has altered the water balance;

1. **Huge quantities of water are used in food production** – this water redistributes water away from its natural pathways. Precipitation is trapped and stored in surface reservoirs, groundwater and river water is extracted, then reused on fields to water crops during drier periods. The abstraction of river-water will reduce downstream flow.
2. Water is stored in biomass that is the plants and animals being farmed. In our global agriculture system much of this food enters world markets and thus the water is exported from one country to another.
3. The **evapotranspiration regime** of areas is affected, rather than natural annual plants cover of native ecosystems agriculture changes when plants are grown and in what quantities. This alters evapotranspiration rates, evapotranspiration from the crops may be reduced if the previous habitat was forest, or it may be increased if an arid area was cultivated and irrigated.
4. **Groundwater stores are affected** – wells are drilled into the ground and water pumped to the surface for use in irrigation. This can deplete groundwater levels under the ground and damage aquifer resources, this can also cause surface water features such as springs, rivers and marshland to dry up.
5. Surface runoff can increase as post-harvest fields are bare of vegetation. Farmed crops often intercept less precipitation than natural vegetation cover too. Subsequent precipitation can exceed infiltration capacities of the soil resulting in increased overland flow.
6. Drainage patterns are changed too. Farmers intentionally dig drainage ditches within and around their fields to prevent water logging of plants. This means that water moves initially via overland flow and then via small channels into rivers, affecting both the hydrograph and annual regimes of those rivers.
7. Agriculture often reduces vegetation cover and soil compaction from machinery can occur. Both of these can reduce the amount of water that infiltrates into the soil and therefore increase run off.



Source [7]

WATER ABSTRACTION

Rainfall doesn't only reach rivers by running off over the land surface. Much of the water that falls to earth as rain enters the soil and rock beneath our feet to become ground water. We often forget about this water because, unlike rivers and surface water, it is out of sight. The level beneath the ground at which the rock becomes saturated is called the water table. Water in this saturated zone will flow from where it has infiltrated to a point of discharge. This might be a spring, a river or the sea.

Whilst water can be found in many locations underground, some geological or rock formations are impermeable. This means that water can hardly flow through them, whilst others are permeable (they contain fine holes that allow water to flow). These permeable rocks that contain groundwater are known as aquifers. [12]

Groundwater abstraction is **the process of taking water from a ground source**. It is often pumped through boreholes and wells from underground aquifers, as a source of freshwater. [8] A lot of this water is used for irrigation for crops or to produce drinking water. As water is abstracted **the water table** (the upper limit of water in the soil or rock beneath the ground) is lowered around the borehole. If rates of abstraction exceed rates of groundwater recharge within an aquifer, the water table can fall across a wide area. Taking too much water, or over abstraction can lead to surface rivers drying up or the level of groundwater aquifers and the water table reducing.

Effects of over abstraction

Over abstracting ground water can have negative effects:

- Wells can dry up – this can occur as over abstraction lowers the water table (the upper limited of ground saturated with water). Unless the well owner can deepen the well or drill a new well, water shortages occur.
- Reduction of water in streams and lakes – Rivers often get a lot of their water from throughflow and groundwater flow from soil and groundwater sources. The amount or proportion of stream water that comes from groundwater inflow varies according to a region's geography, geology, and climate. Removing water from groundwater sources through abstraction reduces the amount available for rivers and streams on the surface. This can cause some surface rivers to dry up.
- **Deterioration of water quality –** this can occur in coastal regions where saline water can migrate inland and upward when freshwater is pumped out of the ground in these locations. This is known as saltwater intrusion and can contaminate the water supply.
- **Land subsidence** – This occurs as water is part of the subsurface support for the land above. When water is taken out of the soil and rock, the soil & rock collapses, compacts, and drops.[9]

Water Abstraction in Europe

Approximately 10 % of Europe's total freshwater resource is abstracted annually. Overall, the region abstracts a relatively small portion of its total renewable water resources each year, at around 350 km^3/year. As a continent, this means that much ground water abstraction is within sustainable levels as much of that water will be recharged from infiltrating rainwater. However, many regional differences exist. [10]

In many parts of Europe, groundwater is the main source of freshwater. In some parts of Europe water is being pumped from beneath the ground faster than it is being replenished through rainfall. The results are;

- Sinking water tables,
- Empty wells,
- Higher pumping costs and,
- The intrusion of saltwater from the sea which degrades the groundwater.

These issues are problematic in countries with lower precipitation totals and high potential evapotranspiration such as the Mediterranean coastlines of Italy, Spain, Malta and Turkey. These areas also have to cope where the demands of tourist resorts are the major cause of over-abstraction.

In addition, parts of Greece have to cope with ground water over exploitation as a result of irrigation. According to Europa.eu on the "*Greek Argolid plain of eastern Peloponnesus where it is common to find boreholes 400m deep contaminated by sea-water intrusion. In Italy, overexploitation of the Po River in the region of the Milan aquifer has led to a 25m (even up to 40 m) decrease in groundwater levels over the last 80 years*" [11]

Water in the London and the Thames Basin

The Geology of the London Basin in relation to water sources is dominated by Cretaceous chalk. This is the major aquifer, approximately 60m below the surface of central London trending approximately East to West. This chalk varies in depth due to the presence of numerous small faults which cross-cut basin.

AQUIFER

The aquifer of the London Basin is confined or kept in place in the Basin by the London Clay Formation. There are also Fluvial (river) muds and fine sands in many places between the clay and chalk.

The Aquifer is recharged anywhere where the Chalk sticks out at the surface, in places such as the Chilterns to the north and the North Downs to the south. The Chalk allows water to percolate rapidly through the aquifer to accumulate in large volumes beneath central London.

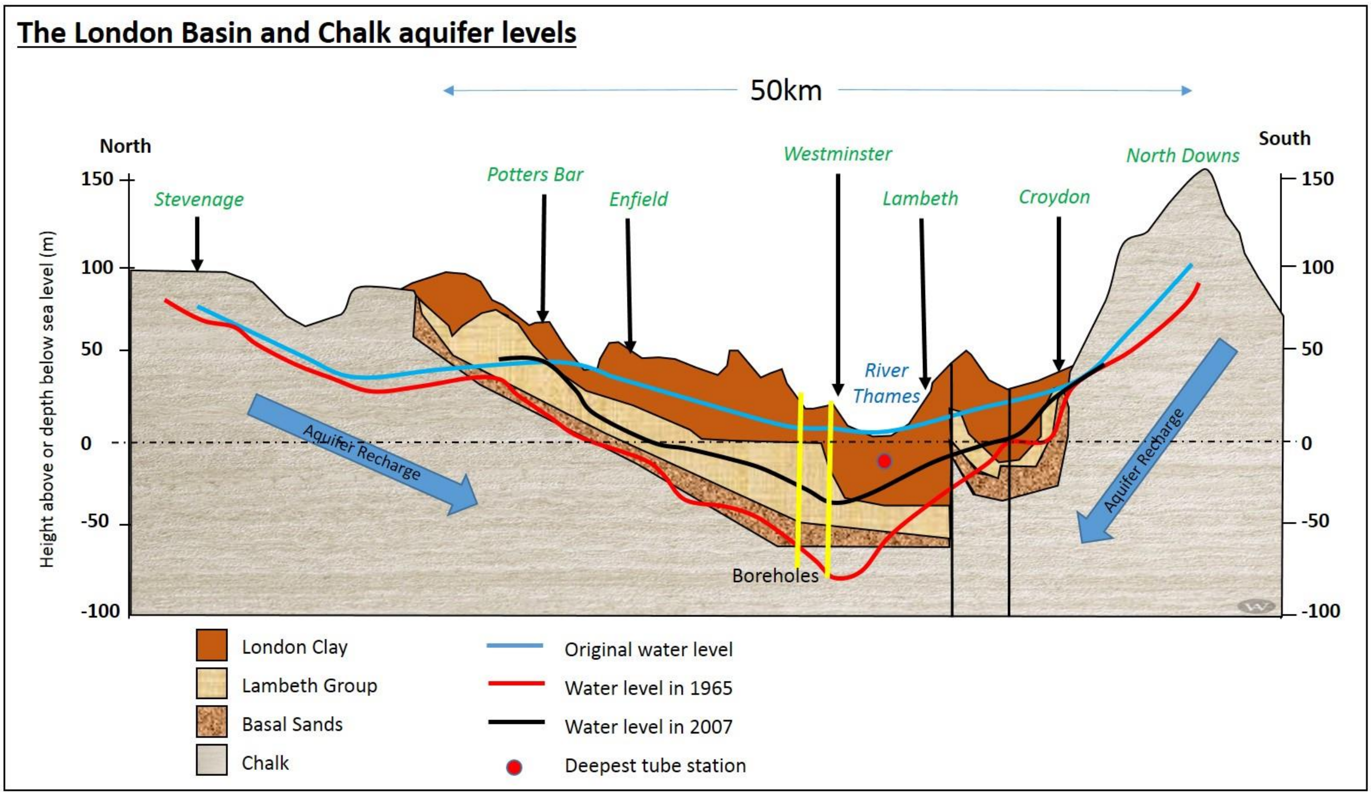
Water use in London

London has experienced periods of water shortage in the past and over abstraction of its ground water occurred because London grew expanded in the 19th century, and the industrial, commercial and public demand for water increased. This meant that groundwater was increasing exploited as a water source.

According to Groundwaterorg

"Progressive increases in abstraction from the confined Chalk in the late 19th century and early 20th century eventually became unsustainable, resulting in steady groundwater level decline. After WWII groundwater abstraction started to decrease, partly as a result of declining well yields and a consequential switch to river derived public supplies. Despite this, confined Chalk groundwater levels continued to fall until the mid 1960s when a dynamic equilibrium existed for several years. By this time, groundwater levels in the centre of the London Basin had fallen by about 65 m, from about 35 m below ground level (m bgl) in 1845 to almost 100 m bgl in 1967." [13]

This decline has been reversed with better management of water sources. The aquifer actually started recharging at a rate of 3m per year in parts of the basin posing a flooding risk to deeps tunnels, Underground escalators and the foundations of tall buildings.



1 http://www.3plearning.com/blog/deforestation-impacts-earths-water-cycle/ Accessed 19th October 2018
2 https://kids.mongabay.com/elementary/404.html Accessed 19th October 2018

3 https://rainforests.mongabay.com/0902.htm Accessed 19th October 2018

4 https://e360.yale.edu/features/how-deforestation-affecting-global-water-cycles-climate-change Accessed 19th October 2018

5 http://homepages.see.leeds.ac.uk/~eardvs/research_archive.html Accessed 19th October 2018

6 https://earthobservatory.nasa.gov/images/50136/2010-drought-in-the-amazon-forest Accessed 26th October 2018

7 Agricultural expansion and climate change in the Taita Hills, Kenya: an assessment of potential environmental impacts Eduardo Eiji Maeda Helsinki 2011. https://fennia.journal.fi/article/download/6813/5507/

8 http://www.oxfordreference.com/view/10.1093/oi/authority.20110803095909737 Accessed 26th October 2018

9 https://water.usgs.gov/edu/gwdepletion.html Accessed 26th October 2018

10 https://www.eea.europa.eu/themes/water/water-resources/water-abstraction Accessed 26th October 2018

11 https://www.eea.europa.eu/themes/water/water-resources/impacts-due-to-over-abstraction Accessed 26th October 2018

12 http://www.groundwateruk.org/What-is-Groundwater.aspx Accessed 26th October 2018

13 http://www.groundwateruk.org/Rising_Groundwater_in_Central_London.aspx

14 Forests and Floods - Drowning in fiction or thriving on facts?, FAO, 2005 - http://www.fao.org/forestry/11722-0aea9fb9406230267eaf9955570ec42f3.pdf

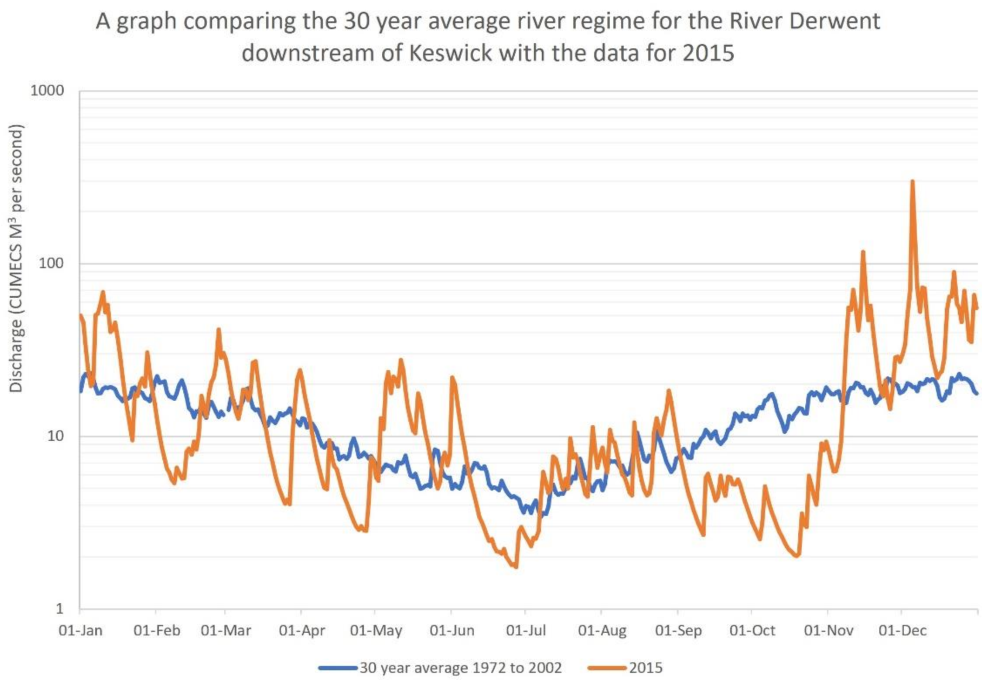
Not used as a source but interesting article on Mexico City and water abstraction - https://www.theguardian.com/science/2004/may/06/thisweekssciencequestions

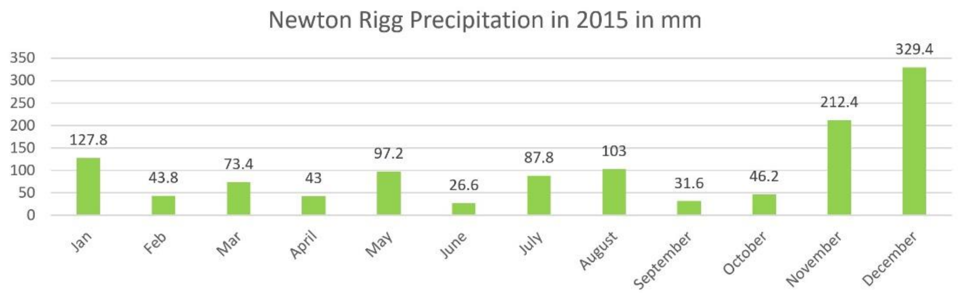
Example of a drainage basin on a local scale

The market town of Keswick is located immediately north of Derwentwater and is in the Lake District National Park. It is a popular tourist destination in Allerdale District and has a permanent resident population of 4821[1]. The population is greatly increased by several thousand by the tourist trade, with many camping/caravanning sites occupying low lying floodplain areas.

The River Greta flows through Keswick and is fed by the River Glenderamackin, Thirlmere via St. Johns Beck and the Glenderaterra Beck. There are many other smaller rivers that feed into the system and the River basin has a high drainage density.

Below the River Glenderamackin and St. Johns Beck confluence the river becomes relatively confined within a steep incised valley before opening out into the town, where it continues to fall relatively steeply before levelling out in the Greta Bridge area and entering the River Derwent. [2]





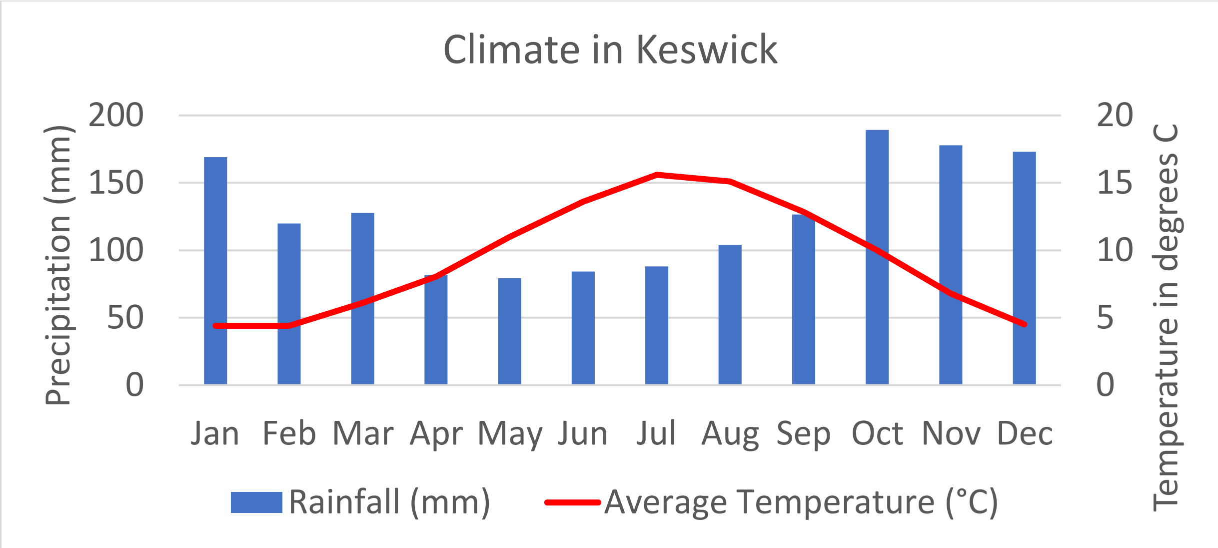
Lake levels can impede on the drainage of numerous watercourses in the catchment and the land between Derwentwater and Bassenthwaite Lake becomes inundated as a result of large floods. [2]

[3] Data source: https://nrfa.ceh.ac.uk/data/search

Physical Factor 1 – Climate and river regime

The graph below shows the regular river regime for the river Derwent downstream of Keswick averaged over a 30-year period. It is evident that this river has a peak of discharge throughout the winter and a drop in discharge in the summer. This links to the rainfall distribution of this part of the UK. Most rainfall falls in winter due to winter storms and relief rainfall hence the higher flow rates. Contrast this with the regime during the Storm Desmond event of 2015 (and be careful of the logarithmic scale on the graph). It is clear that 2015 had high rainfall totals and this resulted in higher than average discharge levels, which resulted in catastrophic flooding for the town of Keswick.

The climate is also mild, as shown on the climate graph below. This limits evapotranspiration across the basin. On the upland areas snow often falls and rests through the winter. This temporarily stores water that is then released as snow melt throughout the spring.

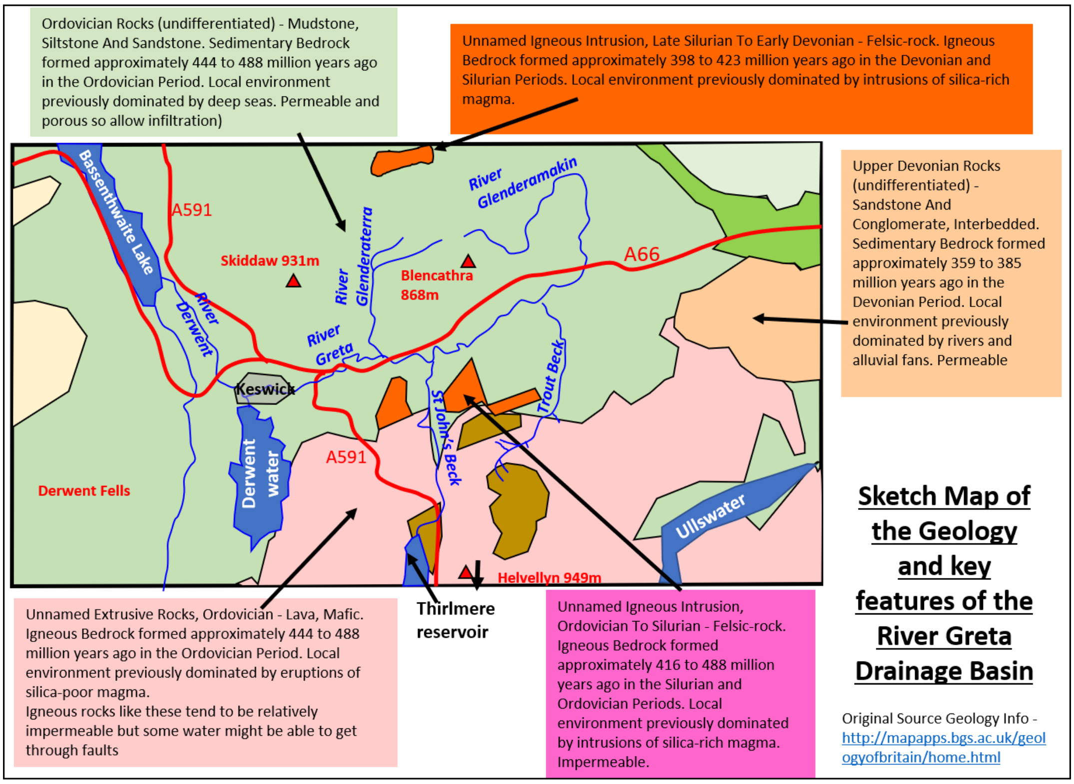


Physical factor 2 - Geological influences

The Drainage basin of the river covers a range of different geologies which can influence c=greatly if water is stored or transferred. These can be seen on the sketch map below, but in summary;

The Northern part of the basin is dominated by sedimentary rocks such as Mudstone, Siltstone and Sandstone formed approximately 444 to 488 million years ago in the Ordovician Period and interbedded Sandstone with Conglomerate formed 359 to 385 million years ago in the Devonian Period. There are also some small Igneous Intrusions. At the time of sedimentary rock formation the local environment was dominated by deep seas. Most of these rocks are Permeable and porous so allow infiltration.

The Southern part of the drainage basin has Igneous Intrusions (felsic rocks) from the Ordovician to Silurian periods (416 to 488 million years ago) and Igneous Extrusive Rocks such as Lava and Mafic. The local environment at that time previously dominated by eruptions of silica-poor magma.
These igneous rocks tend to be **relatively impermeable,** but some water might be able to get through faults. This limits ground water stores and encourages overland flow.



Physical Factor 3 - Vegetation and relief.

There are only sparse areas of forest in the river Greta drainage basin and many of the lowland areas are used for pasture for sheep and cattle. The upland areas are dominated by mosses and ferns. This allows for low interception rates across the drainage basin and lots of surface runoff. The basin is also very steep sided and has steep relief North and south of the valley in which the town of Keswick sits. This encourages a lot of surface runoff too.

December 2015 flood event

Causes

December 2015 was the wettest calendar month on record for the UK, with much of northern England receiving double the average December rainfall. This also followed a particularly wet November and as such, much of the ground within the Cumbria catchments was already saturated.

From the 4th to the 7th of December there was a period of prolonged, intense rainfall caused by Storm Desmond. Over this period, new 24 hour and 48 hour rainfall records were set for the UK. Both of these were within Cumbria and broke the previous records, also within Cumbria, set during the November 2009 floods. Table 2 shows the record levels of rainfall that fell during the flooding event. [2]

This rainfall fell on already saturated ground following three previous storms in November, which generated more than twice the monthly average rainfall for November. The wet conditions exacerbated the runoff from Storm Desmond and produced flood levels on the Rivers Greta and Derwent that were the highest ever recorded, breaking records set during the 2009 floods. The levels of Derwentwater and Bassenthwaite Lake also significantly exceeded previous record lake levels. [2]

Many locals blame the overfilling of Thirlmere reservoir for part of the flood damage, as water could not be stored in this lake, but was released.

Effects

515 residential properties and businesses were affected by flooding on the 5th and 6th December 2015. The majority of this flooding can be attributed to extreme river levels in the River Greta, following extensive rainfall over the preceeding 36-hour period. There was a huge amount of flooding both in Keswick and further upstream, with areas of significant erosion at Low Briery and high flood extent at the confluence of St John's Beck and the River Glenderamackin at New Bridge.

All bridges suffered damage to varying degrees. Knights Bridge was destroyed during the flood and Forge Bridge was severely damaged. The bridges contributed to the effects of the flooding by causing a constriction to the channel which affected flows under the structures. This constriction resulted in elevated river levels experienced immediately upstream and greater scour downstream. Elevated floodwater levels had a significant impact on the upstream areas above the Greta, Wivell, Calvert's and Forge bridges. [2]

Services were also affected with the mains water supply for parts of the town unavailable until approximately lunchtime on 8th December. Penrith Road, which forms one of the key access routes into the town, became inundated with flood water. This is all despite the fact that Keswick had improved flood defences put in place in 2012 in a £6m flood protection scheme. [5]

Sources

1 - UK National Statistics, Census 2011 data.

2 - Cumbria County Council, 2016, *Keswick Sec 19 Flood Investigation* Report. Accessible here - https://www.cumbria.gov.uk/eLibrary/Content/Internet/544/3887/6729/6730/4271394526.pdf

3 - National River Flow Archive, part of the Centre for Ecology and hydrology, retrieved May 2018 from https://nrfa.ceh.ac.uk/data/search

4 – British Geological Survey, Geology of Britain Viewer, retrieved May 2018, http://mapapps.bgs.ac.uk/geologyofbritain/home.html

5 – BBC news, 2012, *Keswick flood defence gates and barriers completed* – retrieved November 2018 from https://www.bbc.co.uk/news/uk-england-cumbria-19744736

Global distribution, and size of major stores of carbon – lithosphere, hydrosphere, cryosphere, biosphere, atmosphere.

Carbon on Earth

Carbon (**C**) is a hugely important element and can be found in many different compounds. The word Carbon comes from Latin word *carbo* which means "coal".[1]

Carbon is important because it is found in many different compounds. Carbon can be found;

- In the clothes you wear
- The food you eat
- In You!
- The cosmetics and sanitary products you use
- In building materials
- In hydrocarbons which power many of the appliances you use. [3]

Carbon is the sixth most abundant element in the Milky Way Galaxy[2] and the fourth most abundant element found on planet Earth. Carbon is essential as it is found in all living beings on Earth. It is the second most abundant element in the human body by mass after Oxygen.

Carbon comes in many different forms from the hardest substance known on Earth – diamonds, to other useful softer substances such as graphite (which is soft enough to use to write on paper).

Uses of Carbon

1. Diamond is used in jewellery and also in drills.
2. Carbon is used in the iron and steel industries
3. Graphite combined with clays form the 'lead' used in graphite pencils.
4. Carbon fibre is finding many uses as a very strong, yet lightweight, material. It is currently used in tennis rackets, skis, fishing rods, rockets and aeroplanes.
5. Graphite carbon in a powdered, caked form is used as charcoal for cooking, artwork and other uses.
6. Charcoal pills are used in medicine in pill or powder form to adsorb toxins or poisons from the digestive system.
7. Carbon is used for control rods in nuclear reactors.[3]

Carbon moves through the various "spheres" of the Earth in what is known as the Carbon Cycle. These spheres include the lithosphere, hydrosphere, cryosphere, biosphere, atmosphere. It moves through these spheres in many different forms but some important compounds of carbon include;

- **Methane (CH_4)** - is a gas - one molecule of methane contains one carbon atom, surrounded by four hydrogen atoms. Methane is found in rocks in the lithosphere, in the oceans, in soils but also in the atmosphere. Methane is a greenhouse gas, and is produced by cows and landfill sites. It is also being released from the cryosphere.
- **Carbon Dioxide (CO_2)** – is also a gas, found in the oceans, soils and the atmosphere and is released when we breath out.
- **Hydrocarbons** – these are any compounds of carbon that are found in sedimentary rocks in gas, solid or liquid form. Crude oil and natural gas are both hydrocarbons.
- **Calcium carbonate ($CaCO_3$)** is a common substance found in rocks as the minerals calcite and aragonite (most notably as limestone, which is a type of sedimentary rock consisting mainly of calcite) and is the main component of pearls and the shells of marine organisms, snails, and eggs.
- **Bio molecules in living things** – these organic macromolecules contain carbon and the four major classes of biological macromolecules include carbohydrates, lipids, proteins, and nucleic acids. [5] Together, all these forms of carbon account for approximately half of the total dry mass of living things.

The origin of Carbon

The primary source of carbon today comes from inside of the Earth and was stored there when the Earth formed. It is thought that this Carbon arrived here as the Earth formed and from subsequent meteorite strikes. [4] This carbon is held within the Earth's interior but escapes at constructive and destructive plate margins as well as at hot spot volcanoes.

The Carbon Cycle

The carbon cycle is another of those that works within the Earth's systems. Just like Water, Carbon moves between different SPHERES on planet Earth, these spheres include the atmosphere, the biosphere, the lithosphere, the hydrosphere and the cryosphere.

When carbon is held in these spheres we consider them to be **carbon pools** (also called **stocks or reservoirs**) because they act as storage houses for large amounts of carbon. Net Carbon sinks are those pools where more carbon is added than leaves. Net carbon sources are those pools where more carbon leaves than is added.

Carbon Sink = Inputs of carbon>Outputs of carbon

Carbon source = Inputs of carbon<Outputs of carbon

Any movement of carbon between the reservoirs is called a **flux**. [6] These fluxes vary in timescale from seconds to thousands of years. They can also result in feedback loops just like within the water cycle. If all sources are equal to all sinks, the carbon cycle can be said to be in **dynamic equilibrium** (or in balance) and there is no change in the size of the pools over time.

For example, over long periods of geologic time carbon dioxide returns to the atmosphere by decomposition of limestones subducted to the Earth's deep interior, releasing the carbon dioxide through gases dissolved in magmas that rise to the surface. Tectonic uplifting of carbonate rocks also causes them to be exposed to the atmosphere. Weathering processes release the trapped carbon, which can then pass into the oceans within precipitation. This carbon can then be taken up by sea creatures who use it in their shells. Their shells sink to the ocean bed upon death and are compressed into calcium carbonate rocks and the cycle begins again.

Major stores of carbon

The quantities of carbon in the Earth's major carbon pools can be enormous so it is inconvenient to use familiar units such as pounds or kilograms. The United Nations Intergovernmental Panel on Climate Change (IPCC) use Gigatonnes of carbon dioxide equivalent (GtC) to measure the stores of carbon. One GtC is a billion (1,000,000,000) tonnes and can also be referred to as a Petagram.

Store of Carbon	% of total carbon	Forms of carbon
Lithosphere	99.985	Sedimentary rocks like limestone Organic carbon Hydrocarbons such as fossil fuels Marine sediments
Hydrosphere	0.0076	Carbonate ions Bicarbonate ions Dissolved CO_2
Pedosphere (soils)	0.0031	Soil organisms Plant remains
Cryosphere	0.0018	Frozen mosses Methyl clathrates
Atmosphere	0.0015	Gaseous carbon
Biosphere	0.0012	Living plants and animals

[7]

The Lithosphere

The lithosphere includes the upper most part of Earth's mantle and the crust – together these make up the hard sections of our Earth's outer layer. The pedosphere is the outermost layer of the Earth that is composed of soil and subject to soil formation processes. It exists at the interface of the lithosphere, atmosphere, hydrosphere and biosphere. The lithosphere contains both inorganic carbon such as shale gas, coal, oil, gas and limestone, and organic carbon such as organic matter in soils and leaf litter.

The lithosphere contains by far the largest amount of carbon on Earth, much of which is stored in sedimentary rocks within the planet's crust. These carbon containing rocks are produced by;

1. The hardening of mud (containing organic matter) into shale over geological time or
2. The collection of calcium carbonate particles, from the shells and skeletons of marine organisms, into limestone and other carbon containing sedimentary rocks.

Together all sedimentary rocks on Earth store up to 100 million GtC, which represents a large mass of carbon!

Another 4,100 GtC is stored in the Earth's crust as **hydrocarbons** formed over millions of years from ancient living organisms under intense temperature and pressure. These hydrocarbons are commonly known as **fossil fuels such as coal, oil and gas**. [6]

The Hydrosphere & carbon

The hydrosphere consists of all of the water bodies on Earth. The Oceans are very important carbon source and store, there are many fluxes or exchanges or carbon between the ocean store and the atmosphere, and also with the deep oceans.
The Earth's oceans contain 38,000 GtC [6], which can split into;

- 900 GtC in the surface layers of the ocean. Here the sunlight can penetrate into the water allowing photosynthesis to happen. This carbon is exchanged rapidly with the atmosphere through both physical processes, such as CO_2 gas dissolving into the water, and biological processes, such as the growth, death and decay of plankton. Most of this surface carbon cycles rapidly, some of it can also be transferred by sinking to the deep ocean pool where it can be stored for a much longer time.

- 39,100GtC in the intermediate zone of the oceans – this makes up most of the carbon in the oceans and is in the form of dissolved inorganic carbon stored at great depths where it resides for long periods of time. [10]

When organisms such as Coccoliths die in the oceans their shells sink to the bottom. These shells are rich in Calcium Carbonate and are slowly compressed over time into layers of Chalk. This locks up hydrospheric carbon in the lithosphere

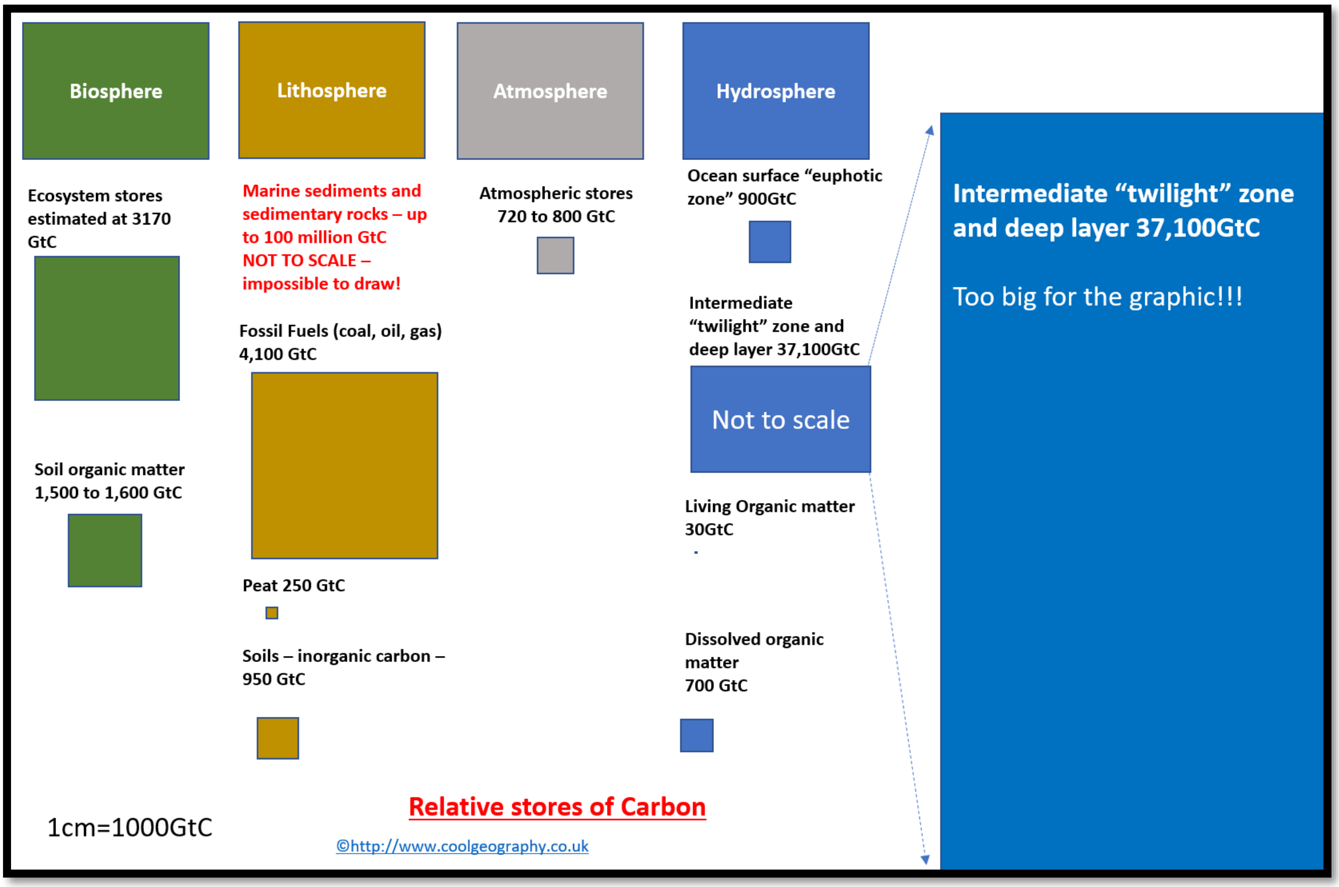
The Cryosphere and carbon

The cold parts of our globe store a lot of carbon. The are 2 potential sources of carbon in the form of methane in the cryosphere;

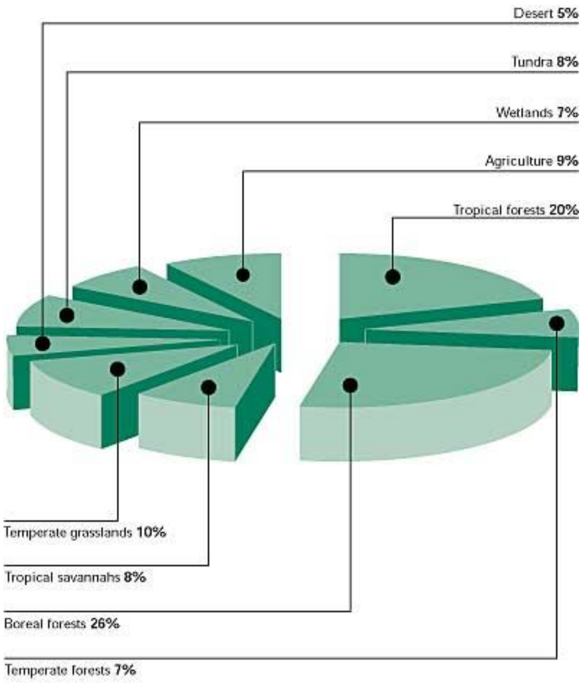
1. **Methyl clathrates** are molecules of methane that are frozen into ice crystals. These molecules form under high pressure and low temperatures deep in the Earth or underwater. These are special conditions, and if the temperature rises or pressure changes, the ice that imprisons the methane will break apart, and the methane will escape.
2. **Organic matter frozen in permafrost**. Permafrost is permanently frozen ground, and it contains a lot of frozen organic matter. This organic matter is made of dead plants and animals that have been frozen deep in permafrost for thousands of years. The carbon in this organic matter is locked up because it is frozen. With global warming, if this permafrost melts the organic matter will decay, and this will release carbon dioxide or methane into the atmosphere.

Both of these sources are problematic as it traps heat about twenty times as efficiently as carbon dioxide (however, there is much less methane in the atmosphere than carbon dioxide).

It is estimated that there are about 1,400 gigatons of carbon frozen in permafrost.[12]



[Biospheric carbon](#)

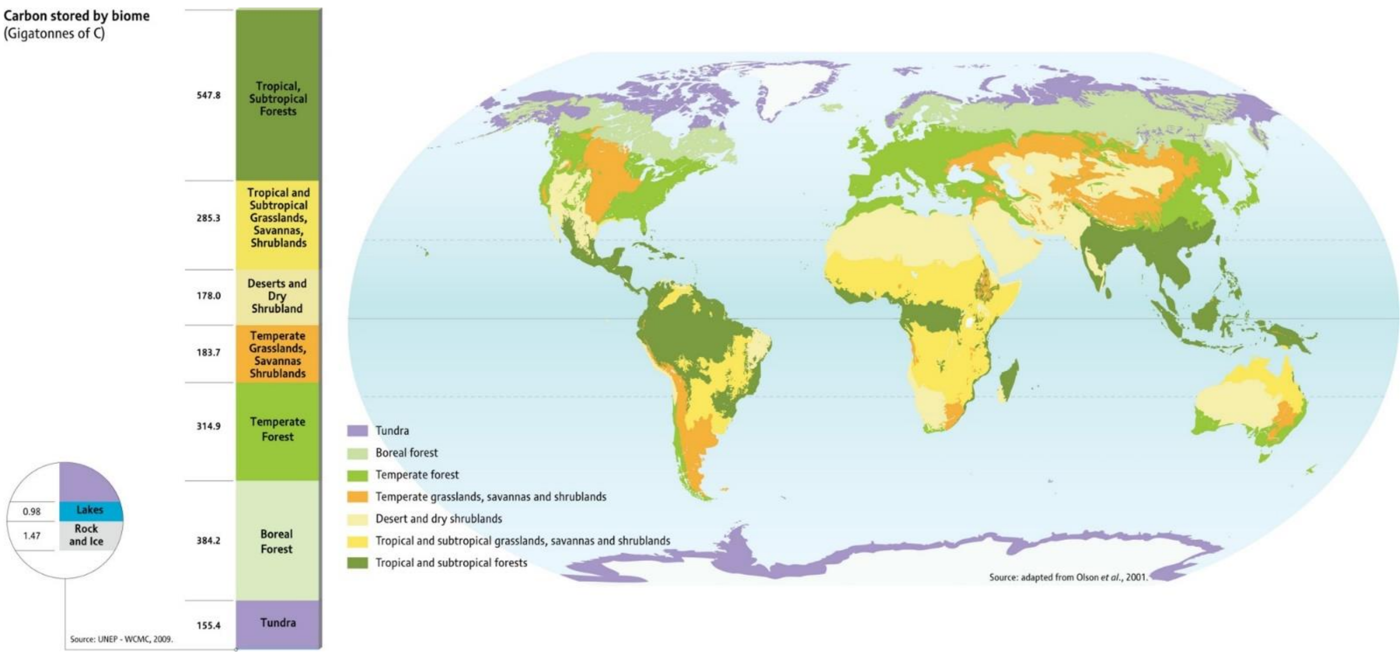


Source[11]

The biosphere includes the regions of the surface and atmosphere of the earth or another planet occupied by living organisms. It contains all of the world's ecosystems and is thought to contain 3170GtC. On Earth, the terrestrial ecosystems contain carbon in the form of plants, animals, soils and microorganisms (bacteria and fungi). Of these, plants and soils are by far the largest and, when dealing with the entire globe, the smaller pools are often ignored. Most of the carbon in terrestrial ecosystems exists in organic forms, unlike in the lithosphere and hydrosphere. The term "organic" refers to compounds produced by living things, including leaves, wood, roots, dead plant material and the brown organic matter in soils (which is the decomposed remains of formerly living tissues). [6]

Within the biosphere;

1. The Earth's plants store approximately 560 GtC, with the wood in trees being the largest fraction (woody stems have the greatest ability to store large amounts of carbon, because wood is dense and trees can be large). The pie chart shows the various percentages of the carbon that the world's ecosystems have. This shows that forests do indeed store the most carbon.
2. The world's soils carbon content is estimated to be 1500 GtC.
3. Peat contains over 250GtC. Peat is an accumulation of partially decayed vegetation or organic matter. It is unique to natural areas called peatlands, bogs, mires and moors. It is created in anaerobic conditions and keeps carbon locked up.
4. Litter – the decaying remains of plants, contain carbon, and this can be released over time via decomposition.



Credit - Riccardo Pravettoni, UNEP/GRID-Arendal sourced at http://www.grida.no/resources/7554

The Atmosphere and carbon

The atmosphere is a small store of carbon relative to the other stores. It contains approximately 750 GtC [6], the majority of which is in the form of CO_2, with much smaller amounts of methane (CH_4) and various other compounds.

Despite the small size of the store, carbon in the atmosphere is of great importance because of its influence on the greenhouse effect and climate. The relatively small size of the atmospheric C pool also makes it more sensitive to disruptions caused by an increase in sources or sinks of C from the Earth's other pools.

Carbon in the atmosphere is measured in parts per million. Deforestation and fossil fuel combustion have added to this store which has been monitored at the Mauna Loa Observatory (MLO) atmospheric research facility. It has been continuously monitoring and collecting data related to atmospheric change since the 1950's. The station has measured CO2 concentrations over 400ppm despite pre industrial revolution levels of less than 280ppm.

Summary

Store of Carbon	Sub Store	Amount of Carbon in GtC
Lithosphere	Marine sediments and sedimentary rocks Soil organic matter Fossil fuels Peat	100 million GtC 1,500 to 1,600 GtC 4,100 GtC 250 GtC
Hydrosphere	Surface zone of oceans (Euphotic zone Intermediate zone of oceans (twilight zone) Living organic matter Dissolved organic matter	900 GtC 37,100 GtC 30 GtC 700 GtC
Pedosphere (soils)	Soils Peat	1,500 GtC 250 GtC
Cryosphere	Permafrost soils	~1700 GtC [8]
Atmosphere	Total Atmospheric carbon	720 to 800 GtC
Biosphere	Total Biospheric carbon	3,170 GtC

Source [9]

1 – Wikipedia, 2018, *Carbon* – retrieved 23rd November 2018 from https://en.wikipedia.org/wiki/Carbon

2 - Education for the Information Age, 1999, *The Carbon Atom* – retrieved 23rd November 2018 from http://www.edinformatics.com/math_science/c_atom.htm

3 – Royal Society of Chemistry, 2018, *Periodic Table: Carbon* – retrieved 23rd November 2018 from http://www.rsc.org/periodic-table/element/6/carbon

4 – George Shaw, 2006, A (Not So) Brief History of Carbon on Earth, NASA Astrobiology Institute. Retrieved 23rd November 2018 from https://nai.nasa.gov/seminars/featured-seminar-channels/university-of-washington-seminars/2006/10/24/a-not-so-brief-history-of-carbon-on-earth/

5 - Charles Molnar and Jane Gair, Concepts of Biology-1st Canadian Edition, retrieved 2nd December 2018 from https://opentextbc.ca/biology/chapter/2-3-biological-molecules/

6 – The University of New Hampshire, 2008, An introduction to the global carbon cycle - retrieved 2nd December 2018 from http://globecarboncycle.unh.edu/CarbonCycleBackground.shtml

7 – Andy Day & Tutor2U, Introduction to Carbon and Carbon Stores, retrieved 2nd December 2018 from https://www.tutor2u.net/geography/reference/carbon-and-carbon-stores-explained

8 - Kevin Schaefer, Hugues Lantuit, Vladimir E Romanovsky, Edward A G Schuur and Ronald Witt, 2014, The impact of the permafrost carbon feedback on global climate retrieved 2nd December 2018 from http://iopscience.iop.org/article/10.1088/1748-9326/9/8/085003/pdf

9 - "Geography for A-level and AS", pages 27 to 29, Skinner et al, Hodder Education, 2016

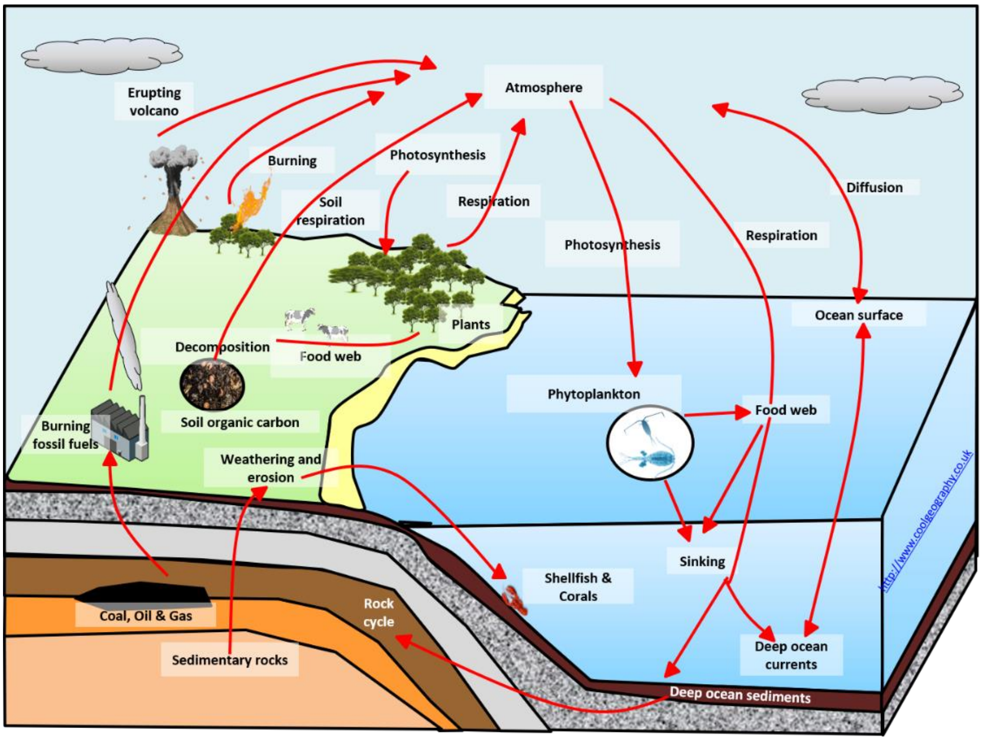
10 - National Center for Atmospheric Research Staff (Eds). Last modified 31 Jan 2014. "The Climate Data Guide: GLODAP: GLobal Ocean Data Analysis Project for Carbon." Retrieved from https://climatedataguide.ucar.edu/climate-data/glodap-global-ocean-data-analysis-project-carbon

11 – Food and Agriculture Organisation, Climate change and forests, Retrieved from http://www.fao.org/docrep/003/y0900e/y0900e06.htm

12 - Kevin Schaefer of National Snow and Ice Data Center, 2018. Methane and Frozen Ground. Retrieved from **https://nsidc.org/cryosphere/frozenground/methane.html**

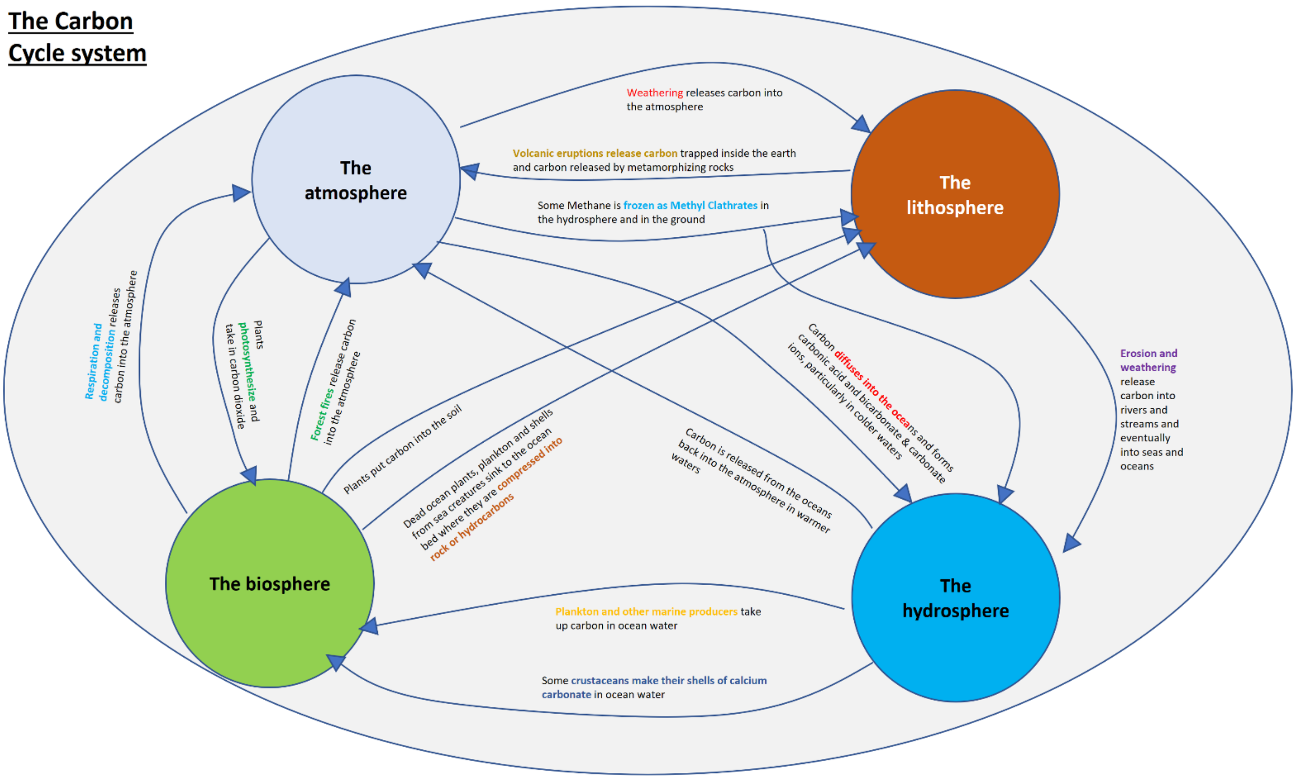
Factors driving change in the magnitude of these stores over time and space, including flows and transfers at plant, sere and continental scales. Photosynthesis, respiration, decomposition, combustion, carbon sequestration in oceans and sediments, weathering.

The Carbon Cycle and the movement of Carbon



The carbon cycle describes the movement of carbon in its various forms between the different spheres – between the Atmosphere, Hydrosphere, Biosphere and lithosphere. It is described in the diagram above. Carbon can take many pathways through the stores and moves over different timescales. According to NASA's Earth observatory "Through a series of chemical reactions and tectonic activity, carbon takes between 100-200 million years to move between rocks, soil, ocean, and atmosphere in the slow carbon cycle. On average, 10–100 million metric tons of carbon move through the slow carbon cycle every year."[1] The pathways and processes are described in detail below.
For example, carbon can end up in the atmosphere from many other sources. Carbon can arrive from erupting volcanoes, decaying vegetative matter, respiration from the biosphere and oceans, weathering of rocks and the burning of fossil fuels. However, carbon can leave the atmosphere in many ways too. It can enter the oceans via diffusion and the plants in the biosphere by photosynthesis.

The Carbon Cycle system

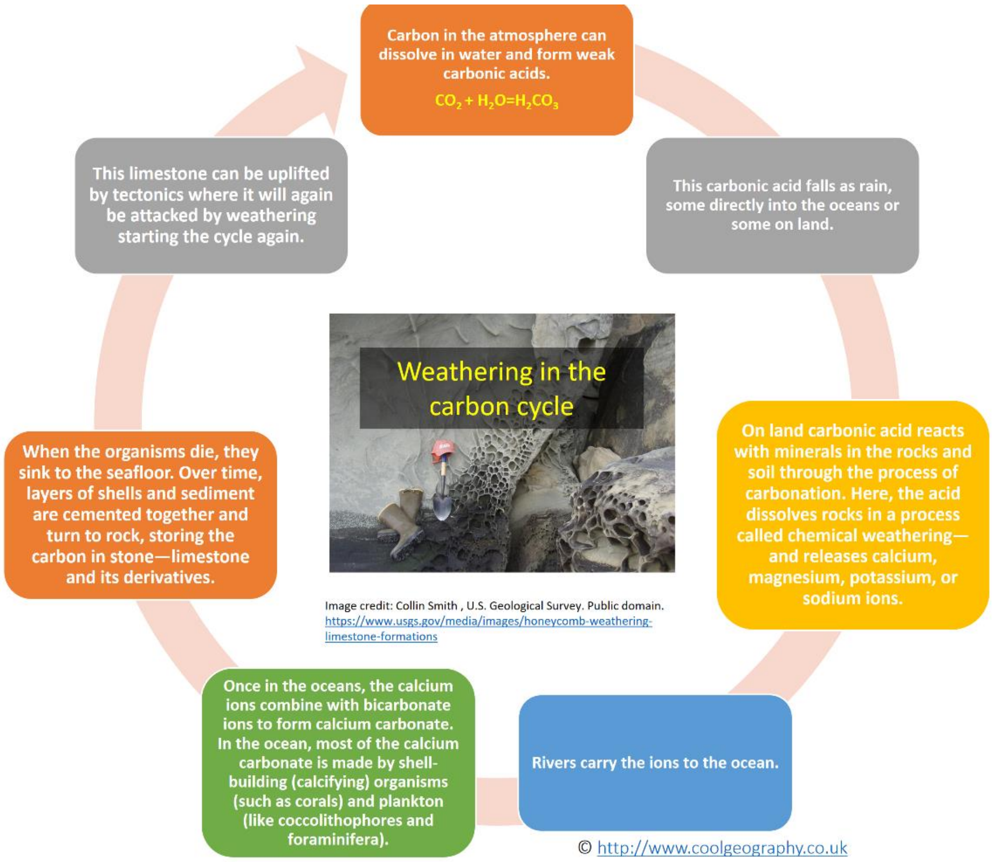


Weathering

Weathering is hugely important part of the rock cycle and links directly to how carbon is transferred through the lithosphere. Other lithospheric or geologic components include burial and compression of sediments rich in carbon, subduction of carbon rich rocks at subduction zones along destructive plate margins and volcanic eruptions. Carbon in the atmosphere can dissolve in water and form weak carbonic acids. The formula for the formation of carbonic acids is;

$$CO_2 + H_2O = H_2CO_3$$

This carbonic acid falls as rain and thus the carbon is transferred out of the atmosphere into water stores such as the oceans. If the carbonic acid falls onto land, it can react with minerals in the rocks and soil through the process of carbonation. Here, the acid dissolves rocks in a process called chemical weathering—and releases calcium, magnesium, potassium, or sodium ions. When carbonic acid comes into contact with limestone and passes through joints and bedding planes, it reacts with the rock to form calcium bicarbonate. The calcium bicarbonate is soluble and is carried away in solution, gradually weathering the limestone. Rivers carry the ions to the ocean. [1]



Carbon sequestration in oceans and sediments

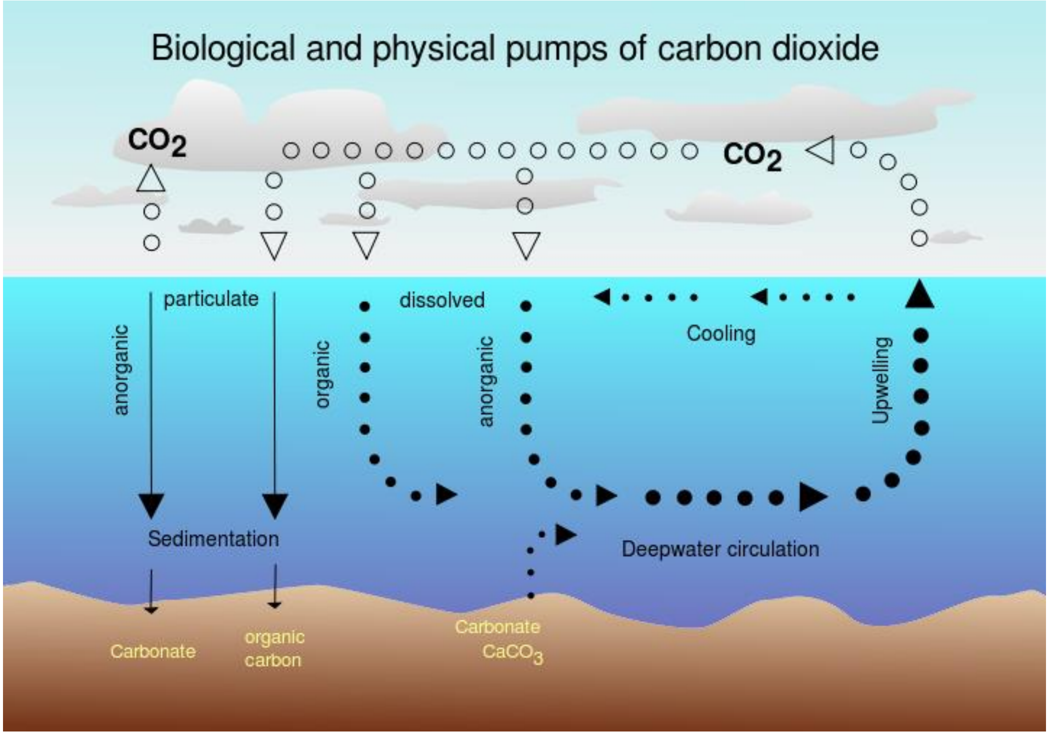
Once in the oceans, the calcium ions combine with bicarbonate ions to form calcium carbonate. In the ocean, most of the calcium carbonate is made by shell-building (calcifying) organisms (such as corals) and plankton (like coccolithophores and foraminifera).[1] When the organisms die, they sink to the seafloor. Over time, layers of shells and sediment are cemented together and turn to rock, storing the carbon in stone—limestone and its derivatives. This limestone can be uplifted by tectonics where it will again be attacked by weathering starting the cycle again. The rock could also become part of the slow cycle - returning carbon to the atmosphere through volcanoes. Earth's land and ocean surfaces sit on several moving crustal plates. When the plates collide, one sinks beneath the other, and the rock it carries melts under the extreme heat and pressure. The heated rock recombines into silicate minerals, releasing carbon dioxide. [1]

When volcanoes erupt, they vent the gas to the atmosphere and cover the land with fresh silicate rock to begin the cycle again.

Ocean carbon pumps

The ocean contains 50 times more carbon than the atmosphere[5] and exchanges large amounts of CO_2 with the atmosphere every year. In the past decades, the ocean has slowed down the rate of climate change by absorbing about 30% of human emissions. [5]

CO_2 moves between the atmosphere and the ocean by molecular diffusion when there is a difference between CO_2 gas pressure between the atmosphere and oceans. For example, when the pressure of atmospheric CO_2 is higher than the surface ocean, CO_2 diffuses across the air-sea boundary into the sea water.



Source: Derivative work: McSush (talk)CO2_pump_hg.png: Hannes Grobe 21:52, 12 August 2006 (UTC), Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany [CC BY-SA 2.5 (https://creativecommons.org/licenses/by-sa/2.5)], via Wikimedia Commons

The oceans are able to hold much more carbon than the atmosphere because of 2 pumps;

How the Physical pump of carbon dioxide works;

1. Cold Polar ocean waters can dissolve more than twice as much CO_2 than in the warm equatorial waters.
2. This means that as major ocean currents (e.g., the Gulf Stream) move waters from the tropics to the poles, they are cooled and can take up more CO_2 from the atmosphere.
3. As the waters are cooled as they head to the high latitudes, they become denser and sink into the deep ocean's taking with them the CO_2 accumulated at the surface.
4. The water returns along the ocean bed to the tropics, where it upwells, warms and releases some CO_2 back into the atmosphere.
5. The cycle then repeats.

The Biological Carbon Dioxide Pump

The biological pump is another process that moves CO_2 away from the surface ocean. The growth of marine plants such as phytoplankton takes CO_2 and other chemicals from sea water to make plant tissue. This happens in the upper layers of the ocean as photosynthesis requires light.

Most of the CO_2 taken up by phytoplankton is recycled near the surface, a substantial fraction, perhaps 30 percent, sinks into the deeper waters before being converted back into CO_2 by marine bacteria. Only about 0.1 percent reaches the seafloor to be buried in the sediments. [6]

Photosynthesis

Photosynthesis is the process used by plants, algae and certain bacteria to harness energy from sunlight and turn it into chemical energy. It takes place both on land and within the oceans by tiny marine plants known as phytoplankton. It is important to the carbon cycle as plants take in carbon and convert it to organic matter during the process. The process is a s follows;

Carbon Dioxide + water + sunlight = carbohydrate + Oxygen

$$6CO_2 + 6H_2O + \text{light energy} = C_6H_{12}O_6 + 6O_2.$$

Basically, plants use sunlight, water and carbon dioxide in the process to produce carbohydrates and oxygen is given off as a biproduct.

Indeed, the process is much more rapid than that mentioned for weathering and the lithosphere. The plants exchange carbon with the atmosphere relatively rapidly through photosynthesis, in which CO_2 is absorbed and converted into new plant tissues, and **respiration**, where some fraction of the previously captured CO_2 is released back to the atmosphere as a product of metabolism.

Respiration

Photosynthesis provides plants with the energy they need to carry out essential life functions. In respiration, Oxygen from the atmosphere is used alongside carbohydrates and this frees up the stored energy. The biproducts are water and carbon dioxide. Plant cells respire, just as animal cells do. The equation for respiration is;

Carbohydrate + Oxygen = Carbon Dioxide + water + energy

$$C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6H_2O + \text{Energy}$$

Animals depend on plants for food, energy and oxygen. Once those plants are consumed, carbon dioxide is released into the atmosphere because of cells respiration. In turn, this CO_2 produced from respiring cells can be used in photosynthesis again.

Essentially, photosynthesis and respiration are the opposite of one another.

The exchange of carbon dioxide and oxygen thorough photosynthesis or cellular respiration worldwide helps to keep atmospheric oxygen and carbon dioxide at stable levels. This balance can be affected by other factors however and not all stored carbon from photosynthesis is released by respiration as some is stored in biomass and some is stored in soils. As some of the carbon gets stored in rocks over time, Oxygen has become enriched in the atmosphere.

Decomposition

Decomposition is very important in returning carbon from the biosphere to the atmosphere. Some of the carbon from decomposition can also end up in the pedosphere (soils) and lithosphere (rocks). Decomposition includes physical, chemical and biological mechanisms and processes that break down organic matter. **Decomposers** break down the dead organisms and return the carbon in their bodies to the atmosphere as carbon dioxide by respiration. Indeed, decomposers are organisms that break down dead plants or animals into the substances that plants need for growth.

Think of all of the dead and decaying leaf matter that falls from deciduous trees in the UK in Autumn or the contents of a compost bin. It is the work of decomposers such as slugs, worms and woodlice that break down that leaf litter or waste organic matter. In some conditions, decomposition can be blocked, if the organic matter is frozen for example, or if it is buried in anaerobic environments such as in peat bogs.

There are many kinds of decomposer. Each helps recycle food in its own way.

1. Fungi release chemicals to break down dead plants or animals into simple substances. They absorb some of these substances for growth, but others enter the soil.

2. Earthworms digest rotting plant and animal matter as they swallow soil. The waste that comes out of their bodies at the other end contains the important minerals, all ready for plants to take up again.

3. Bacteria are tiny, microscopic organisms. Some kinds live on other living things – for instance, there are millions inside your gut helping you to digest your food. Others live on dead things, and help break them down into the minerals in the soil. [2]

Chemical processes can help to decompose animal bodies and plant remains too, via processes such as proteolysis and hydrolysis. The process of decomposition is a part of the nutrient cycle and is essential for recycling the finite matter that occupies physical space in the biosphere. It ensures that the important elements of life, such as nitrogen, phosphorous, oxygen and carbon, are continually cycled.

Combustion

Combustion is basically the **burning of material**. It occurs when any organic material is reacted (burned) in the presence of oxygen to give off the products of carbon dioxide and water and energy. The organic material can be any fossil fuel or hydrocarbon such as natural gas (methane), oil, or coal. However, many other types of organic matter are combustible including wood, paper, plastics, and cloth. Organic materials contain at least carbon and hydrogen and may include oxygen. If other elements are present, they also ultimately combine with oxygen to form a variety of pollutant molecules such as sulphur oxides and nitrogen oxides. [3]

Combustion occurs because of a range of human and natural factors. People can deliberately set fire to natural vegetation and natural wild fires can occur where leaf litter builds up and is ignited by lightning strikes. Combustion occurs in biomes across the globe including;

1. Tropical forests as found in Indonesia, the Amazon, and central Africa. Burning can be natural but more often than not is caused by forest clearance which is accompanied by burning of vegetation

2. Savannah grasslands in Africa, where seasonal dry periods result in large quantities of dry organic matter available to burn.
3. Mediterranean areas such as southern Europe and parts of California (including the devastating fires of November 2018)
4. Coniferous or boreal forests across Northern Europe and North America
5. Farming areas, as wastes are burnt off at the end of growing seasons.

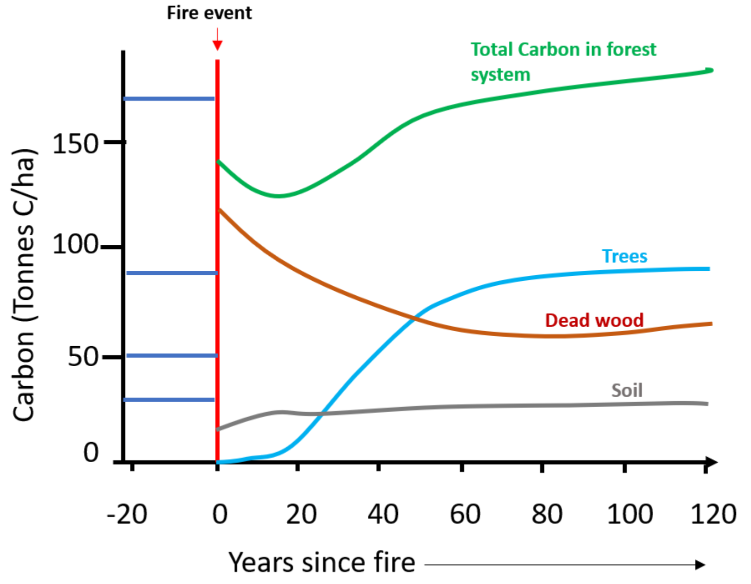
Forest fires and the carbon cycle

Immediately after a fire, carbon is released in huge quantities into the atmosphere through combustion. Wild fires in forests kill living biomass in forests and reduce carbon gains to near zero.

In the longer term the balance between carbon lost through subsequent decomposition and simultaneous carbon gains through growth of new vegetation is changed. The decomposition of dead biomass that lasts for several decades post-fire can release up to three times as much carbon as that lost in the initial combustion.

Eventually many decades later, as the forest continues to regrow and decomposition tapers off, carbon storage in trees eventually "catches up," and the carbon balance equalises. [4]

Hypothetical pattern of forest carbon through a fire cycle with tree regeneration, including carbon in dead wood, in soil, and in live trees



Adapted from - Christina Frame: Sink or Source? Fire and the forest carbon cycle, Fire Science Brief, Issue 86, January 2010 – retrieved 10th December 2018 from http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1043&context=jfspbriefs

1 – NASA Earth Observatory, 2011 , The Slow Carbon Cycle - retrieved 9th December 2018 from https://earthobservatory.nasa.gov/features/CarbonCycle/page2.php

2 – RSPB, 2018, Decomposers – retrieved 10th December 2018 from https://www.rspb.org.uk/birds-and-wildlife/natures-home-magazine/birds-and-wildlife-articles/food-chains/decomposers/

3 – Charles E Ophardt, Virtual Chembook, 2003, Carbon Cycle – retrieved 10th December 2018 from http://chemistry.elmhurst.edu/vchembook/306carbon.html

4 – Christina Frame, Sink or Source? Fire and the forest carbon cycle, Fire Science Brief, Issue 86, January 2010 – retrieved 10th December 2018 from http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1043&context=jfspbriefs

5 – Laurent Bopp, 2002, The Ocean: a Carbon Pump – retrieved 10th December 2018 from http://www.ocean-climate.org/wp-content/uploads/2015/03/ocean-carbon-pump_ScientificItems_BD-2.pdf

6 – *Christopher L. Sabine* , Water encyclopaedia, Carbon Dioxide in the Ocean and Atmosphere – retrieved 10th December 2018 from http://www.waterencyclopedia.com/Bi-Ca/Carbon-Dioxide-in-the-Ocean-and-Atmosphere.html#ixzz5YqOy6ksY

Changes in the carbon cycle over time, to include natural variation (including wild fires, volcanic activity) and human impact (including hydrocarbon fuel extraction and burning, farming practices, deforestation, land use changes).

The Carbon cycle and the location of carbon has changed over cast periods of time. For example, with regards to concentrations of CO_2 in the atmosphere;

- They were as high as 4,000 parts per million (ppm) during the Cambrian period about 500 million years ago and;
- As low as 180 ppm during the Quaternary glaciation of the last two million years.

Current concentrations are over 400 ppm and on the 15th of December 2018 the concentration was 409 ppm [2]. This is despite the fact that for the 400,000 years prior to the industrial revolution CO_2 never went above 300ppm.

Carbon can change locations from other stores too, as climate changes the amount of vegetation can change which either locks up carbon in the biosphere or releases it. Some carbon can be locked up over long periods of time during **Geological sequestration** as hydrocarbons and sedimentary rocks are formed on the sea bed only for that carbon to be released later by weathering after tectonic uplift of those rocks.

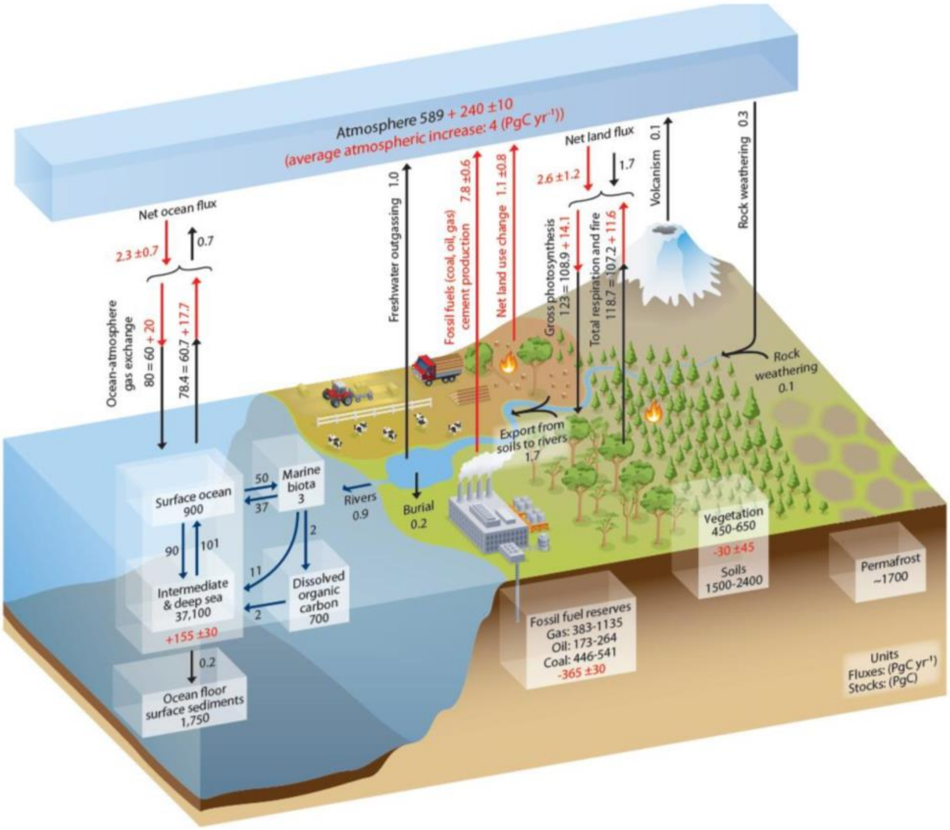
The exam board would like you to consider change in the carbon cycle because of 2 major broad groups of factors;

- **Variation in natural factors** that influence the stores of carbon including **wild fires and volcanic activity** and
- **Human factors** (such as **hydrocarbon fuel extraction and burning, farming practices, deforestation and land use changes**) that are increasingly changing the balance within the Carbon Budget.

A summary of the size of these changes can be seen in the table below. Many of these are human induced or Anthropogenic changes resulting from human activity since the industrial revolution.

Fluxes	Flux of carbon PgC yr^{-1} (into atmosphere unless stated)
Ocean – atmosphere gas exchange (Net)	20 (into ocean) 17.7 (Out) = Oceans gain 2.3±0.7
Fossil fuel burning and cement production	7.8±0.6
Fires	11.6
Photosynthesis	14.1 into biosphere
Net Land use change	1.1 ±0.8
Volcanism	0.1
Rock weathering	0.3
Average Atmospheric increase as a result	4

n.b. not all fluxes considered, figures are to illustrate changes. Source – IPCC[3]

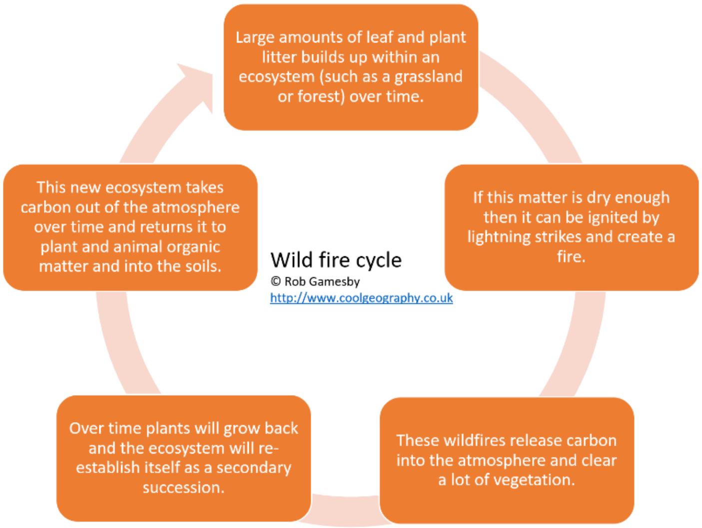


Natural Variation

Feedback loops

Wild fires

Wild fires link to combustion from the previous section. Wildfires play a significant natural role within the carbon cycle and our natural systems. Wild fires tend to occur when large amounts of leaf and plant litter builds up within an ecosystem (such as a grassland or forest) over time. If this matter is dry enough then it can be ignited by lightning strikes and create a fire. In this context wild fires are natural, but people can set fires deliberately or by accident too. These wildfires release carbon into the atmosphere and clear a lot of vegetation. However, over time plants will grow back and the ecosystem will re-establish itself as a secondary succession. This new ecosystem takes carbon out of the atmosphere over time and returns it to plant and animal organic matter and into the soils.



It has been noted that wildfires in vary ecosystems across the world are increasing in intensity, duration and frequency. The wild fire season in many places is also increasing. Recent major events include;
2015 - Unusually large wildfires ravaged Alaska and Indonesia
2016 - Canada, California and Spain were devastated by uncontrolled flames.
2017 - massive fires devastated regions of Chile and in Portugal a blaze claimed dozens of lives. [4]
2018 -Huge and devastating wildfires hit California [5]

The Rim Fire in the Stanislaus National Forest near in California began on Aug. 17, 2013. [7]

With reference to change over time, over the past few decades;

1. The number of wildfires has indeed increased, especially in the western United States. According to the Union of Concerned Scientists (UCS), every state in the western US has experienced an increase in the average annual number of large wildfires over past decades.
2. Some studies have found that large forest fires in the western US have been occurring nearly five times more often since the 1970s and 80s. Such fires are burning more than six times the land area as before, and lasting almost five times longer. [4]
3. Forest fires are also occurring in areas that used to rarely get them, like Siberia

The reasons for the increase in wildfires are linked to global warming;

- Warmer local and global temperatures increase evaporation, which means the atmosphere draws more moisture from soils, making the land drier.
- A warmer climate also leads to earlier snowmelt, which causes soils to be drier for longer. And dry soils become more susceptible to fire.

This means that for the Carbon Budget:

Wildfires emitted about 8 billion tons of CO_2 per year for the past 20 years. In 2017, total global CO_2 emissions reached 32.5 billion tons, according to the International Energy Agency.[6]

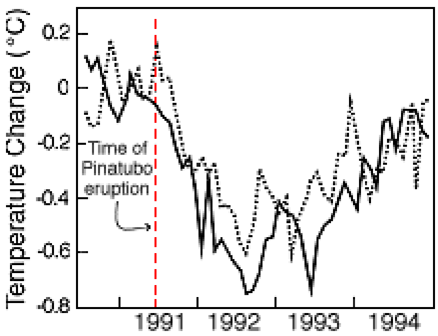
Not all of wildfire emissions as net emissions, though, because some of the CO_2 is offset by renewed forest growth in the burned areas. As a result, they estimate that wildfires make up 5 to 10 percent of annual global CO_2 emissions each year. [6]

Volcanic activity

Carbon can be transferred from the lithosphere to the atmosphere through volcanoes. The Earth's land and ocean surfaces sit on several moving crustal plates. When the plates collide, one sinks beneath the other, and the rock it carries melts under the extreme heat and pressure. The heated rock recombines into silicate minerals, releasing carbon dioxide.

When volcanoes erupt, they vent the gas to the atmosphere and cover the land with fresh silicate rock to begin the cycle again. According to Earth Observatory "*At present, volcanoes emit between 130 and 380 million metric tons of carbon dioxide per year. For comparison, humans emit about 30 billion tons of carbon dioxide per year—100–300 times more than volcanoes—by burning fossil fuels*." [8] This means that the amount of carbon emitted by volcanoes is minimal, and under normal natural conditions would follow the slow carbon cycle and slowly be sequestered back into rocks at the bottom of oceans.

In addition, volcanoes can ironically cause COOLING of temperatures despite emitting carbon. This is because during volcanic eruptions Sulphur Dioxide and huge quantities of dust are also emitted. The Sulphur Dioxide combines with water in the atmosphere to create sulphuric acid. This acid, together with the dust, act to reflect radiation from the sun back to space and actually cool the Earth. Following the eruption of Mount Pinatubo in 1991, temperatures dropped by 0.6°C. [9]



Impact of Mount Pinatubo on global climate. Source NASA [9]

Human Impacts on the Carbon Cycle

Farming

Agriculture or farming can have a significant impact upon the carbon budget. Farming is essential for life on earth as it provides people with the food they need, but with increasing numbers of people on the planet and modern agricultural methods the impact upon the environment can be large. Farming impacts upon the carbon budget in the following ways;

1. **People have cleared vast areas of natural biomes** and replaced them with crops and pasture. Although farmed plants do take in carbon seasonally, it tends to be far less that the storage in a natural biome. In Tropical forests the process of slash and burn releases huge amounts of stored carbon, and the replacement farming of soya and pasture for cattle takes in small amounts. Palm oil plantations take in more carbon than soya, but not as much as tropical forests. In the UK, the same can be said of our clearing of vast areas of deciduous forest to make way for our farms.
2. **Peat lands and wetlands have been drained** and used for farmland. In doing so, methane is released as organic matter that was previously stored and in anaerobic conditions can now decay.
3. There has been **a huge increase in stock densities of animals such as cattle and chickens** as global demand for animal products increases. These animals produce huge amounts of methane during their digestive processes and this is released into the atmosphere. Up to 60% of all agricultural emissions of carbon come from this pastoral farming. Researchers at the University of Oxford found that cutting meat and dairy products from your diet could reduce an individual's carbon footprint from food by up to 73 per cent. [10]
4. **Rice paddies produce methane**. This potent greenhouse gas is emitted from flooded rice fields as bacteria in the waterlogged soil produce it in large quantities. Nitrous oxide, commonly known as laughing gas, is also produced by soil microbes in rice fields. This can also have a harmful climate effect.
5. **Ploughing of fields**

According to the United Nations Food and Agriculture Organisation;

- Carbon emissions from agriculture have increased from 4.6 to 5.0 Gt CO^2 eq. yr^{-1} in 1990s and 2000s to 5.3 Gt CO^2 eq. yr^{-1} in 2011)[11]
- Agriculture, forestry and other land uses emitted 10Gt CO^2 eq. yr^{-1} in 2010 but only stored 2Gt CO^2 eq. yr^{-1} [12]

Hydrocarbon fuel extraction and burning

Hydrocarbons are a compound of hydrogen and carbon, for example any of those which are the chief components of petroleum and natural gas. Fossil fuels are types of hydrocarbon and are created from the compressed remains of organic matter (plant or animal) at the bottom of oceans over millions of years. They effectively lock up carbon within the lithosphere over long periods of time as carbon enters the oceans from the atmosphere and enters into phytoplankton or animal life. Those living things die and sink to the oceans where they are compressed into oil and gas.

Humans have been extracting hydrocarbons to produce energy and heat for centuries. The rate of extraction and burning has increased over time shifting carbon stores from the lithosphere to the atmosphere and this poses significant problems for the delicate climate balance of our planet. This is because carbon dioxide is released in the burning of hydrocarbons which contributes to climate change and global warming. The extra carbon dioxide in the air acts as a greenhouse gas and effectively traps heat within the Earth's atmosphere. Human activities are responsible for almost all of the increase in greenhouse gases in the atmosphere over the last 150 years. [13]

Global carbon (C) emissions from fossil fuel use were 9.795 gigatonnes (Gt) in 2014 (or 35.9 $GtCO_2$ of carbon dioxide). [14] Fossil fuel emissions (including cement production) accounted for about 91% of total CO_2 emissions from human sources in 2014. This portion of emissions originates from coal (42%), oil (33%), gas (19%), cement (6%) and gas flaring (1%). [14] Countries such as China and the USA dominate CO2 emissions from these sources.

Cement manufacture

Cement is a vital material used to bind building materials together. China alone makes and uses 45 percent of worldwide output. In places like Ukraine, production is doubling every four years. [15]

However, the manufacture of cement creates greenhouse gases both directly through the production of carbon dioxide when calcium carbonate is thermally decomposed, producing lime and carbon dioxide, and also through the use of the energy needed to make cement, particularly from the combustion of fossil fuels. Cement plants account for 5 percent of global emissions of carbon dioxide, the main cause of global warming.

Land use changes

Changes in land use are responsible for about 9% of all global CO_2 emissions. [14]

Deforestation

Deforestation is the widespread removal of forest cover for other land uses. This happens globally and much attention is currently on tropical forests, but deciduous and boreal forests also store a lot of carbon and are used as a wood stock. In tropical regions there is particular focus because of the rates of forest clearance and the abundance of carbon stored per hectare. For example, the Amazon helps a Newly Emerging Economy(NEE), Brazil, to make money. They build roads into the forest, logging firms then go in and take out valuable hard woods such as mahogany and cedar, worth thousands of pounds in richer economies like Europe. Then farmers, often cattle ranchers from big companies, burn the rest to make way for cattle pasture. 75% of cleared areas are used in this way.

Similarly, small scale farmers can use a process known as slash and burn to remove an area of forest to create a small holding to be farmed by themselves and their family.

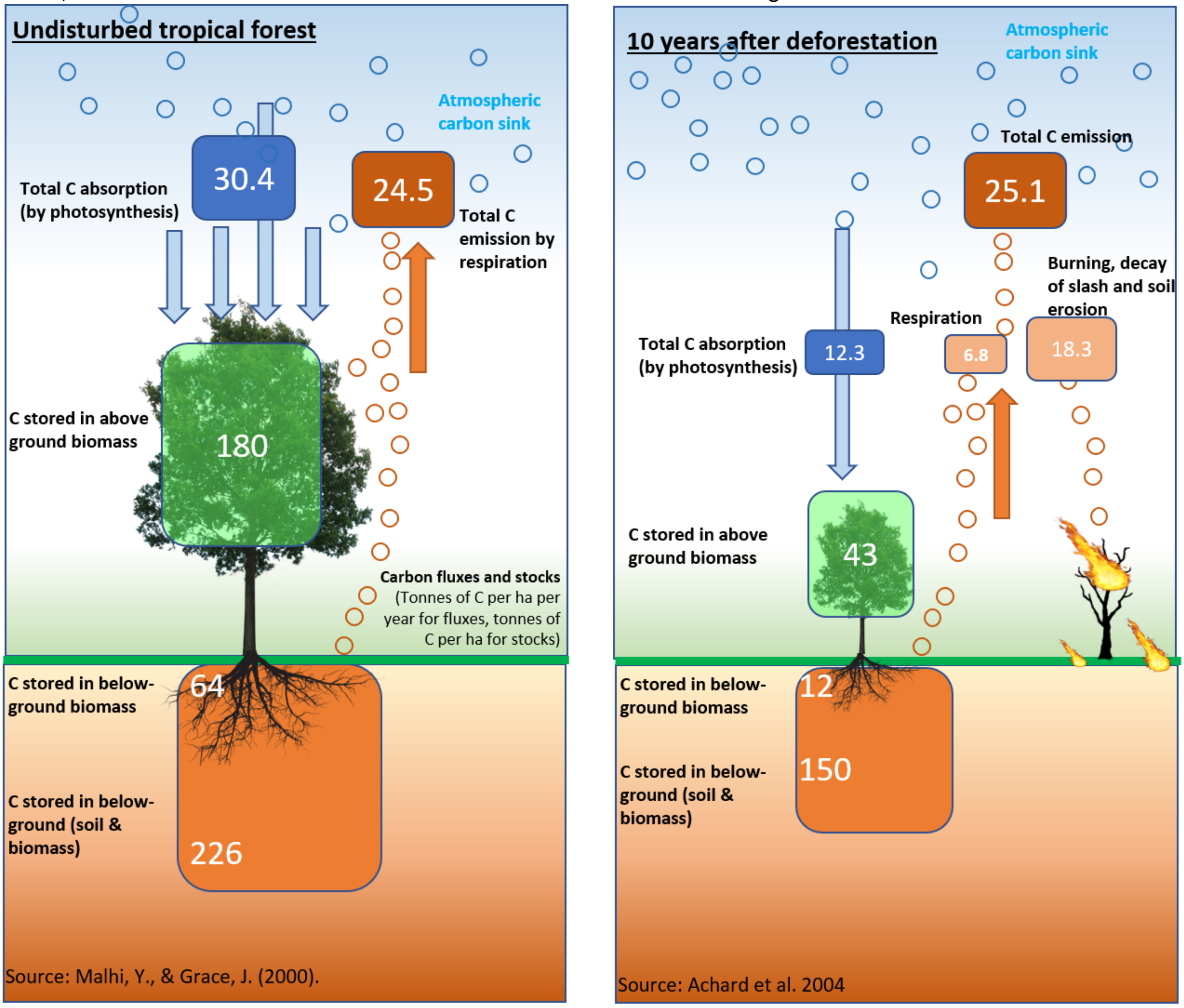
Deforestation impacts the carbon budget because;

1. The biomass store of trees and plants is removed and replaced by something inferior in terms of carbon storage
2. Waste from the deforestation process such as any woods not valuable enough to sell, small plants etc. are burned, this releases Carbon directly into the atmosphere as part of the combustion process.
3. Clearing forests speeds up the decay of leaf litter on the forest floor, releasing even more carbon to the atmosphere
4. Soil carbon is exposed to the atmosphere, speeding up soil erosion, removal of carbon into the hydrosphere by rainwater and rivers and even the release of stored soil carbon through decomposition into the atmosphere.

Recall from the water cycle that this deforestation process also damages the forest water cycle and can result in these environments being significantly damaged. Some dry out so much that they are more at risk of wild fires which alters the carbon budget further.

According to carbonfootprint.com "Around 13 Million hectares of forests lost per annum between 2000 and 2010 and as well as the ecological impact, rainforest deforestation jeopardises people's livelihoods." Deforestation accounts for a staggering 15% of Global Greenhouse Gas (GHG) emissions plus there is the loss of the carbon sink in the biosphere. [15]

In 1990 forests made up 31.6 percent of the word's land areas, or some 4 128 million hectares, this has changed to 30.6 percent in 2015, or some 3 999 million hectares. [17] The rate of forest destruction is slowing down however.



Sourced from https://ees.kuleuven.be/klimos/papers/wp3reddfinal.pdf

Urban growth

"We are increasingly interconnected—no city can wall itself off from the consequences of climate change, and no city can prevent catastrophic climate change on its own."
—KEN LIVINGSTONE Former Mayor of London (2007)

More and more people are living in the World's urban areas. Half of the world's population lives in cities, a share that is likely to reach 70 percent in 2050. [18] Cities are major contributors to greenhouse gas emissions. This is because;

1. Cities consume as much as 80 percent of energy production worldwide, due to the many industrial activities that take place within them.
2. As development proceeds, greenhouse gas emissions are driven less by industrial activities and more by the energy services required for lighting, heating, and cooling.
3. A lot of the cement produced creates greenhouse gasses

It is not surprising that rich cities use more energy than poor cities and therefore emit more greenhouse gas emissions.

- The International Energy Agency (IEA) estimates that cities in 2006 emitted 19.8 gigatonnes of CO_2e ($GtCO_2e$) from energy use, which was 71 percent of global energy-related GHG emissions.
- By 2030, this number is expected to increase to 30.8 $GtCO_2e$, or 76 percent of global energy-related emissions.
- The 50 largest cities, with more than 500 million urban citizens, generate about 2.6 GtC of CO_2 equivalent GHG emissions, more than all countries apart from the United States and China.

The table below signifies the importance of cities to carbon emissions compared to countries. Note, C40 cities belong to a network of the world's megacities committed to addressing climate change and Top 10 GHG cities means the top 10 greenhouse gas emitting cities in the world combined.

Top 10 Cities, Countries, C40 Cities (Combined), and the 50 Largest Cities (Combined), in Terms of Population Size, GHG Emissions, and GDP

Population (millions)	GHG emissions (million tCO_2e)	GDP (billion US$ PPP)
1. China: 1,192 2. India: 916 3. 50 Largest Cities: 500 4. C40 Cities: 393 5. United States: 301 6. Indonesia: 190 7. Brazil: 159 8. Russian Federation: 142 9. Top 10 GHG Cities: 136 10. Japan: 128	1. United States: 7,107 2. China: 4,058 3. 50 Largest Cities: 2,606 4. C40 Cities: 2,364 5. Russian Federation: 2,193 6. Japan: 1,374 7. Top 10 GHG Cities: 1,367 8. India: 1,214 9. Germany: 956 10. Canada: 747	1. United States: 14,202 2. 50 Largest Cities: 9,564 3. C40 Cities: 8,781 4. China: 7,903 5. Japan: 4,354 6. Top 10 GHG Cities: 4,313 7. India: 3,388 8. Germany: 2,925 9. Russian Federation: 2,288 10. United Kingdom: 2,176
Source: World Bank 2010. Note: This table is for indicative purposes only. The years of data sources vary across countries and are determined by the last available UNFCCC reported country data. All China data refer to 1994, the last year when China reported its GHG emissions to UNFCCC. [19]		

1 - *Eggleton, Tony (2013). A Short Introduction to Climate Change. Cambridge University Press. p. 52. Accessed the 15th December 2018*

2 – NOAA, 2018, Trends in Atmospheric Carbon Dioxide, *accessed the 15th December 2018 retrieved from* https://www.esrl.noaa.gov/gmd/ccgg/trends/monthly.html

3 – IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp. *accessed the 15th December 2018 retrieved from* https://www.ipcc.ch/report/ar5/wg1/

4 - Anne-Sophie Brändlin (2017). How climate change is increasing forest fires around the world, Deutsche Welle. *Accessed the 15th December 2018 retrieved from* https://www.dw.com/en/how-climate-change-is-increasing-forest-fires-around-the-world/a-19465490

5 – BBC special report (2018). Wildfires - *Accessed the 15th December 2018 retrieved from* https://www.bbc.co.uk/news/topics/cjyq4rd3x3zt/california-wildfires

6 – International Energy Agency (2017). Global Energy & CO_2 Status Report 2017. *Accessed the 15th December 2018 retrieved from* https://www.iea.org/publications/freepublications/publication/GECO2017.pdf

7 – *Image from* https://commons.wikimedia.org/wiki/File:The_Rim_Fire_in_the_Stanislaus_National_Forest_near_in_California_began_on_Aug._17,_2013-0004.jpg

8 - NASA Earth Observatory, 2011 , The Slow Carbon Cycle - retrieved 9th December 2018 from https://earthobservatory.nasa.gov/features/CarbonCycle/page2.php

9 - Hansen, J., et al. 1996. A Pinatubo climate modeling investigation. In *The Mount Pinatubo Eruption: Effects on the Atmosphere and Climate* (G. Fiocco, D. Fua, and G. Visconti, Ed.). NATO ASI Series Vol. I 42, pp. 233-272. Springer-Verlag. Heidelberg, Germany. *Accessed the 15th December 2018 retrieved from* https://www.giss.nasa.gov/research/briefs/hansen_02/

10 - J. Poore, T. Nemecek (2018). Reducing food's environmental impacts through producers and consumers. Science, 01 Jun 2018 : 987-992. *Accessed the 15th December 2018 retrieved from* http://science.sciencemag.org/content/360/6392/987/tab-article-info

11 - F.N. Tubiello, M. Salvatore, R.D. Cóndor Golec, A. Ferrara, S. Rossi, R. Biancalani, S. Federici, H. Jacobs, A. Flammini (2014). Agriculture, Forestry and Other Land Use Emissions by Sources and Removals by Sinks 1990 – 2011 Analysis.

Climate, Energy and Tenure Division, FAO *Accessed the 15th December 2018 retrieved from* http://www.fao.org/3/a-i3671e.pdf

12 – FAO (2014). Greenhouse Gas Emissions from Agriculture, Forestry and Other Land Use. *Accessed the 15th December 2018 retrieved from* http://www.fao.org/resources/infographics/infographics-details/en/c/218650/

13 - IPCC (2007). Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

14 – CO2.earth (2018), *Annual Global Carbon Emissions. Accessed the 16th December 2018 retrieved from* https://www.co2.earth/global-co2-emissions

15 - ELISABETH ROSENTHAL (2007), *Cement Industry Is at Center of Climate Change Debate*. New York Times. *Accessed the 16th December 2018 retrieved from* https://www.nytimes.com/2007/10/26/business/worldbusiness/26cement.html

16 – Carbon footprint ltd (2018) *Deforestation*. *Accessed the 16th December 2018 retrieved from* https://www.carbonfootprint.com/deforestation.html

17 – FAO (2015). *World deforestation slows down as more forests are better managed* http://www.fao.org/news/story/en/item/326911/icode/

18 - World Bank (2015) *Cities and climate change: an urgent agenda* http://siteresources.worldbank.org/INTUWM/Resources/340232-1205330656272/4768406-1291309208465/PartIII.pdf

19 - Axel Baeumler, Ede Ijjasz-Vasquez, Shomik Mehndiratta, Editors (2012). Sustainable Low-Carbon City Development in China. World Bank group. Retrieved 9th December 2018 from http://documents.worldbank.org/curated/en/576131468261265617/pdf/672260PUB0EPI0067848B09780821389874.pdf

The carbon budget and the impact of the carbon cycle upon land, ocean and atmosphere, including global climate.

The Carbon Budget

A budget takes into account what goes into a system and what goes out. In terms of a carbon budget this would include how much carbon is emitted by various processes (such as combusting fossil fuels) compared to what can be absorbed by nature or captured by people. This can be calculated using a carbon footprint calculator, as found at https://www.carbonfootprint.com/calculator.aspx . Your carbon footprint is defined as the total amount of greenhouse gases produced to directly and indirectly support human activities, usually expressed in equivalent tons of carbon dioxide (CO_2).

We could consider the carbon budget at various scales;

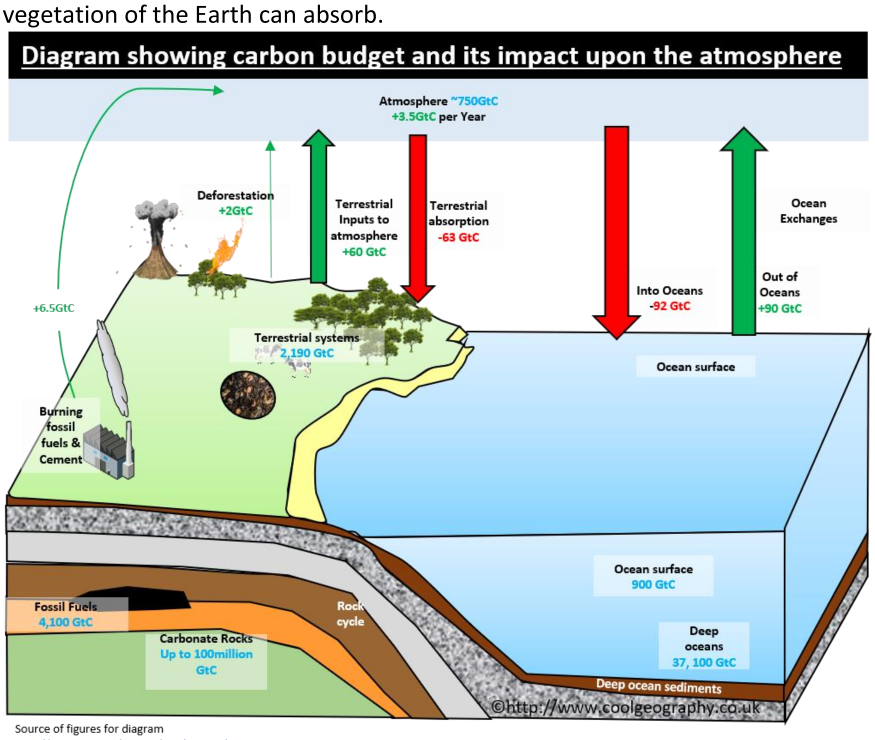
1. **Individually** – how much carbon is produced by our activities such as heating our home, the food we eat, how we get around, less how much carbon is absorbed by the plants in our gardens, our use of renewable energy like solar etc.
2. **Businesses** – how much carbon is produced to run the business, is it offset in any way? The cool Geography website is hosted by Ecohosting, who "Provide Carbon Neutral Web Hosting Based Entirely In The UK, Powered By Renewable Energy" [1]
3. **Nations** – as part of international agreements countries must consider how much carbon is produced in their country compared to how much is absorbed in biological and geologic sequestration, ort captured using technology.
4. **Globally** – this is the scale we need to address, as the carbon system is interconnected and global, so changes to the budget in one part of the world will have impacts upon other parts of the world. Since many of the carbon emissions have occurred in wealthier countries they have a bigger impact on other countries.

A summary of the size of these changes to the Carbon Budget can be seen in the table below. Many of these are human induced or Anthropogenic changes resulting from human activity since the industrial revolution.

Fluxes	Flux of carbon PgC yr^{-1} (into atmosphere unless stated)
Ocean – atmosphere gas exchange (Net)	20 (into ocean) 17.7 (Out) = Oceans gain 2.3±0.7
Fossil fuel burning and cement production	7.8±0.6
Fires	11.6
Photosynthesis	14.1 into biosphere
Net Land use change	1.1 ±0.8
Volcanism	0.1
Rock weathering	0.3
Average Atmospheric increase as a result	4

n.b. not all fluxes considered, figures are to illustrate changes. Source – IPCC[3]

The diagram below shows some of these exchanges (n.b. not all fluxes are shown on the diagram and the 2 sources are different hence some of the differences in figures). It is clear from the diagram that it is land use changes like deforestation and the burning of fossil fuels that is increasing the amount of carbon in the atmosphere, at rates faster than the oceans, rocks and vegetation of the Earth can absorb.



Source of figures for diagram
http://www.fao.org/docrep/003/y0900e/y0900e06.htm

The global carbon budget and climate change.

In 2015, the countries that signed the UN Framework Convention on Climate Change adopted a target to stop the average global temperature from rising before it reaches 2°C above pre-industrial levels.

This goal can be met if cumulative emissions of carbon do not exceed 1 trillion tonnes of carbon (GtC) [2]

However, of that 1 trillion tonnes of carbon 535 GtC have already been emitted during industrial times. This leaves only 465 GtC to stay within the agreed limits.

Many developing countries also support a reduction in the target to keep global average temperature increases below 1.5°C above pre-industrial levels.

Impact of the changing carbon budget on THE LAND

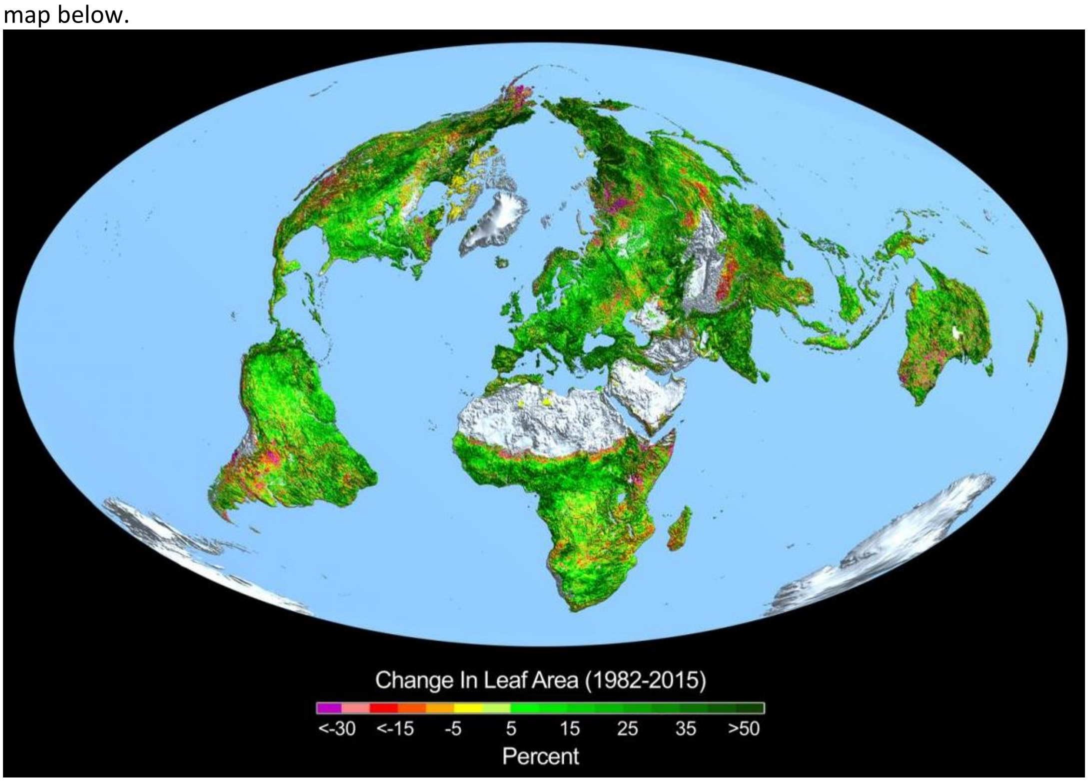
The changing carbon budget can have significant impacts upon the land.

Carbon fertilization

It is thought that plants on land have taken up approximately 25 percent of the carbon dioxide that humans have put into the atmosphere. [3]

Overall, the world's plants have increased the amount of carbon dioxide they absorb since 1960 although the amount they absorb varies from year to year. Only some of this increase occurred as a direct result of fossil fuel emissions.

NASA have found that increased amounts of atmospheric carbon dioxide means more carbon is available to convert to plant matter in photosynthesis. This means that plants were able to grow more. This extra growth is referred to as **carbon fertilization**. This extra growth is not boundless however, as plants also need water, sunlight, and nutrients, especially nitrogen. If a plant doesn't have one of these things, it won't grow regardless of how abundant the other necessities are. This means that the amount of extra carbon taken in from place to place on earth varies according not just to how much extra carbon there is but also factors such as water and nitrogen availability. You can see how much extra carbon fertilization is taking place on the map below.



Source: Boston University/R. Myneni
https://www.youtube.com/watch?time_continue=29&v=zOwHT8yS1XI

Land use decisions.

Agriculture has become much more intensive, so we can grow more food on less land.

In high and mid-latitudes, some abandoned farmland is reverting to forest, and these forests store much more carbon, both in wood and soil, than crops would.

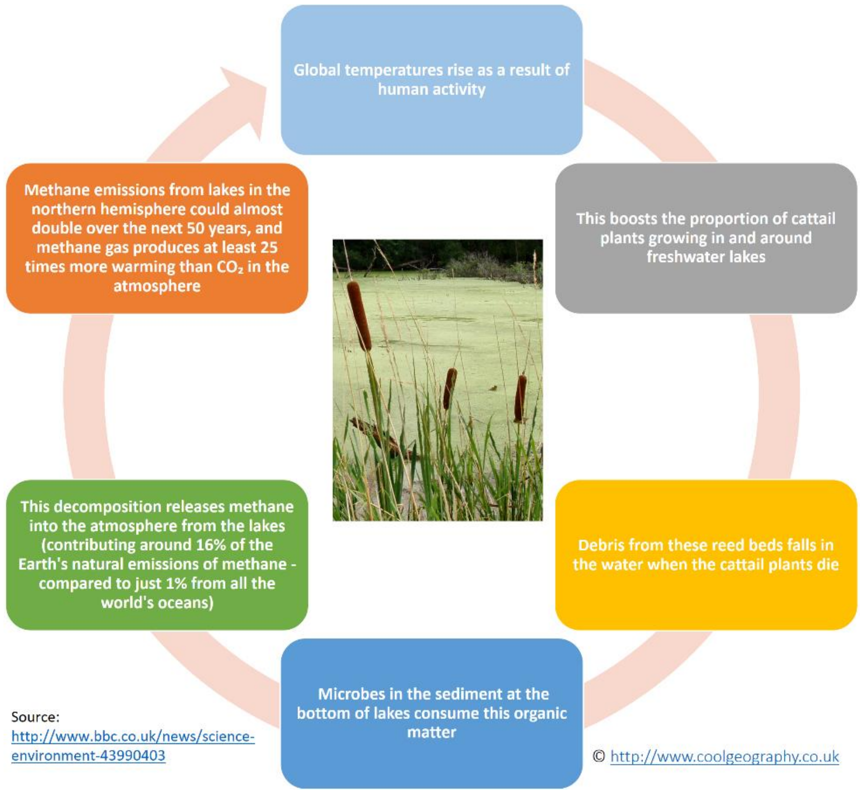
In many places, we prevent plant carbon from entering the atmosphere by extinguishing wildfires. This allows leaf litter and woody material (which stores carbon) to build up. All of these land use decisions are helping plants absorb human-released carbon in the Northern Hemisphere.
However, this balance could be changing as more forest fires appear to be occurring releasing this stored carbon. According to NASA "In the far north, where an increase in temperature has the greatest impact, the forests have already started to burn more, releasing carbon from the plants and the soil into the atmosphere. Tropical forests may also be extremely susceptible to drying. With less water, tropical trees slow their growth and take up less carbon, or die and release their stored carbon to the atmosphere." [3]

In the tropics forests are being removed, often through fire via slash and burn, and this releases carbon dioxide.

Global warming and the land

Other impacts of the global warming element of changing carbon budgets can occur and impact upon the terrestrial environment.

1. Carbon dioxide increases temperatures, extending the growing season and increasing humidity. This has led to some additional plant growth. However, warmer temperatures also stress plants. With a longer, warmer growing season, plants need more water to survive. Scientists are already seeing evidence that plants in the Northern Hemisphere slow their growth in the summer because of warm temperatures and water shortages. [3]
2. Higher temperatures can "bake" the soil, this allows the rate at which carbon seeps out to increase in some places.
3. The permanently frozen soil, the permafrost—is thawing. Permafrost contains rich deposits of carbon from plant matter that has accumulated for thousands of years because the cold slows decay. When the soil warms, the organic matter decays and carbon—in the form of methane and carbon dioxide—seeps into the atmosphere. [3]
4. There is increasing evidence of complex feedback loops emerging too, an example of cattail plants can be seen in the diagram.



Impact of changes to the carbon budget in THE OCEANS

The oceans are a very important sink and source of carbon, and changes to the carbon budget can have profound impacts upon the oceans. NASA calculate that about 30 percent of the carbon dioxide that people have put into the atmosphere has diffused into the ocean through the direct chemical exchange (recall the **physical carbon pump**). [3]

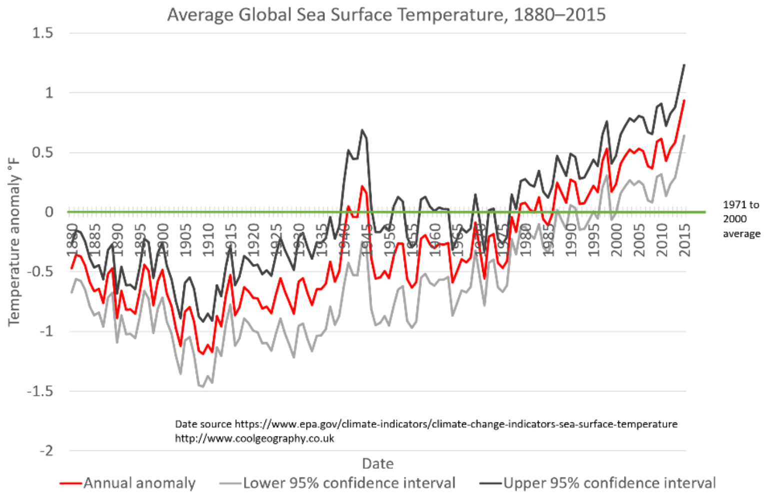
Ocean acidification

As carbon dioxide dissolves into the ocean it creates carbonic acid, and this increases the acidity of the water. This is a slight change and the ocean remains alkaline (the pH has dropped from 8.2 to 8.1[4]), NASA state that "Since 1750, the pH of the ocean's surface has dropped by 0.1, a 30 percent change in acidity."

This ocean acidification is bad for many marine organisms as the carbonic acid reacts with carbonate ions that shell building creatures use to create calcium carbonate shells. This is bad for shell-based creatures making their shells thinner and more fragile, and damaging things like coral. An effect called coral bleaching can be seen on the Great Barrier Reef in Australia, where ocean acidification's effects are already taking place. Coral bleaching is when unicellular organisms that help make up the coral begin to die off and leave the coral giving it a white appearance. [5]

A benefit of this acidification of the oceans are that in the long term because the more acidic seawater will dissolve calcium carbonate rocks more which will release more carbonate ions and increase the ocean's capacity to absorb CO_2.

Ocean warming



Phytoplankton grown better in cooler nutrient rich waters, an increase in ocean temperatures could also decrease the abundance of phytoplankton. This would reduce the amount of carbon held in the oceans. A few species of phytoplankton and ocean plants might benefit from more carbon in the oceans, but most are not.

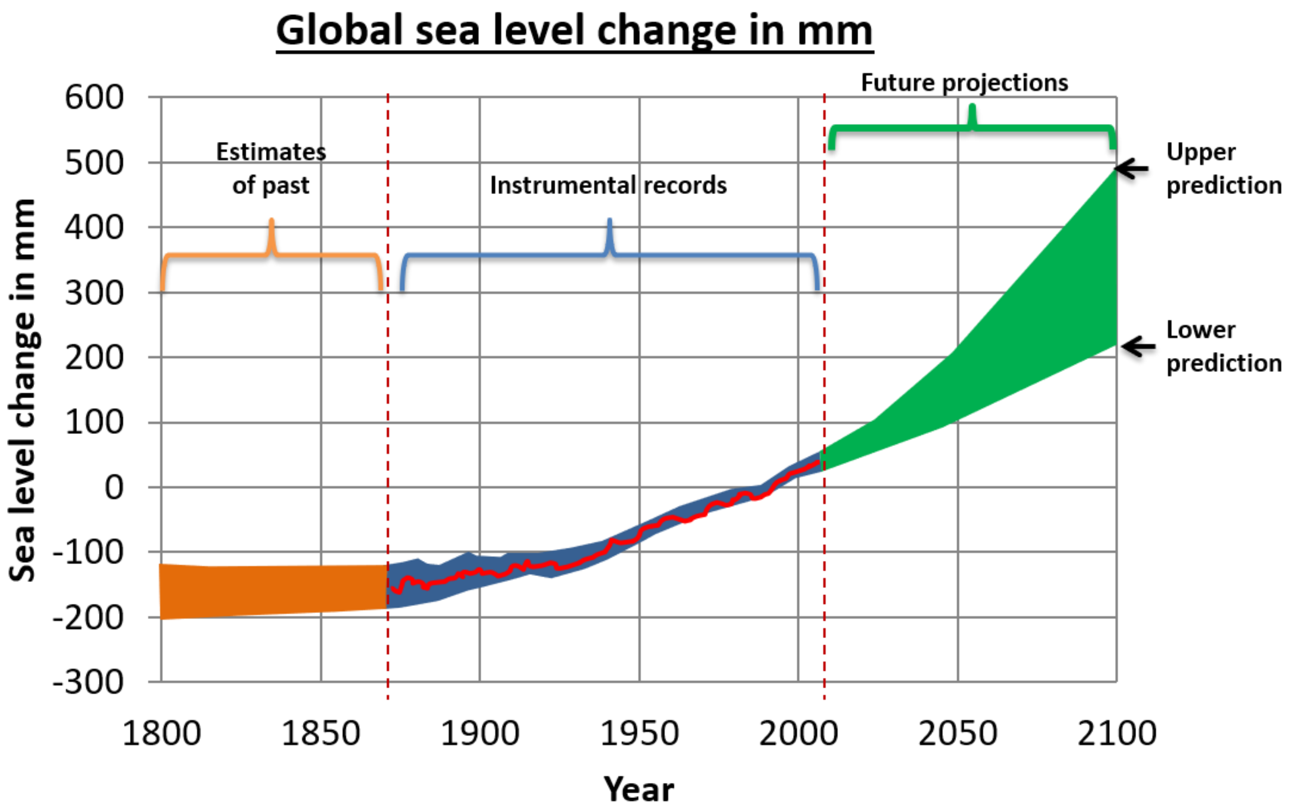
A study by Roxy (2016)[6] shows that marine ecosystems are suffering because of increasing ocean temperatures. The study on phytoplankton changes in the Indian Ocean shows a decline of up to 20% in marine phytoplankton during the past six decades.

Warmer ocean water also absorbs less carbon dioxide from the atmosphere than cooler water.

Changes in sea level

Long-term measurements of tide gauges and recent satellite data show that global sea level is rising, with best estimates of the global-average rise over the last two decades centred on 3.2 mm per year. The overall observed rise since 1901 is about 20 cm. [8]

The graph below derived from the IPCC shows that sea levels are predicted to continue to rise;



Since the start of the industrial revolution the burning of fossil fuels and other human and natural activities has released enormous amounts of heat-trapping gases such as methane and carbon dioxide into the atmosphere. These emissions have caused the Earth's surface temperature to rise, and the oceans absorb about 80 percent of this additional heat. [7]

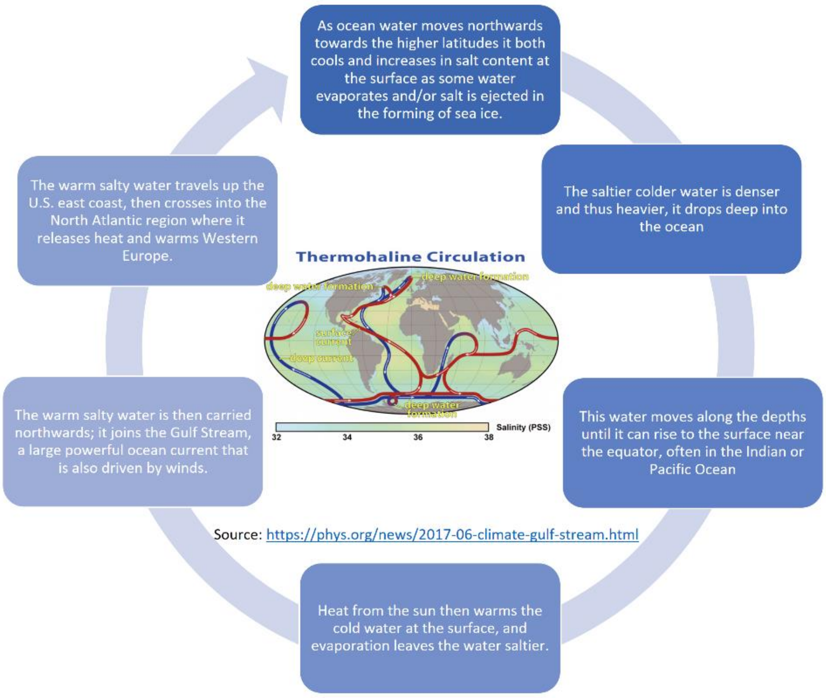
The rise in sea levels is caused by 3 factors, all linked to rising global temperatures

1. As water heats up, it expands, this is known as **Thermal Expansion**. It is calculated that about half of the past century's rise in sea level is caused by warmer oceans occupying more space.
2. Ice on land such as Glaciers and Polar Ice Caps have had a negative mass balance for decades now. More water is lost to ablation (melting) than is gained by accumulation of new snow and ice. This means more runoff to the oceans causing sea levels to rise.

3. Increased temperatures in the atmosphere and ocean is causing the massive ice sheets that cover Greenland and Antarctica to melt at an accelerated pace. Scientists also believe meltwater from above and seawater from below is seeping beneath Greenland's and West Antarctica's ice sheets, effectively lubricating ice streams and causing them to move more quickly into the sea. Higher sea temperatures are causing the massive ice shelves that extend out from Antarctica to melt from below, weaken, and break off. [7] In 2002 the Larsen B Ice Shelf covering 3,250 square kilometers splintered and collapsed in just over one month.

Ocean salinity and the thermohaline conveyor

The Earth has ocean currents and wind systems that move heat from the equator northwards towards the poles then transport the cold water back towards the equator. The oceanic part of this is known as the **thermohaline circulation**. “Thermo” refers to temperature, “haline” refers to the salt content of the water. It works like this;



1. As ocean water moves northwards towards the higher latitudes it both cools and increases in salt content at the surface as some water evaporates and/or salt is ejected in the forming of sea ice.
2. The saltier colder water is denser and thus heavier, it drops deep into the ocean a
3. This water moves along the depths until it can rise to the surface near the equator, often in the Indian or Pacific Ocean
4. Heat from the sun then warms the cold water at the surface, and evaporation leaves the water saltier.
5. The warm salty water is then carried northwards; it joins the Gulf Stream, a large powerful ocean current that is also driven by winds.
6. The warm salty water travels up the U.S. east coast, then crosses into the North Atlantic region where it releases heat and warms Western Europe. [9]

With Global warming, it is a concern that large amounts of melting ice in Greenland could dilute the salty water and weaken or even shut down this circulation. This would cool large parts of western Europe.

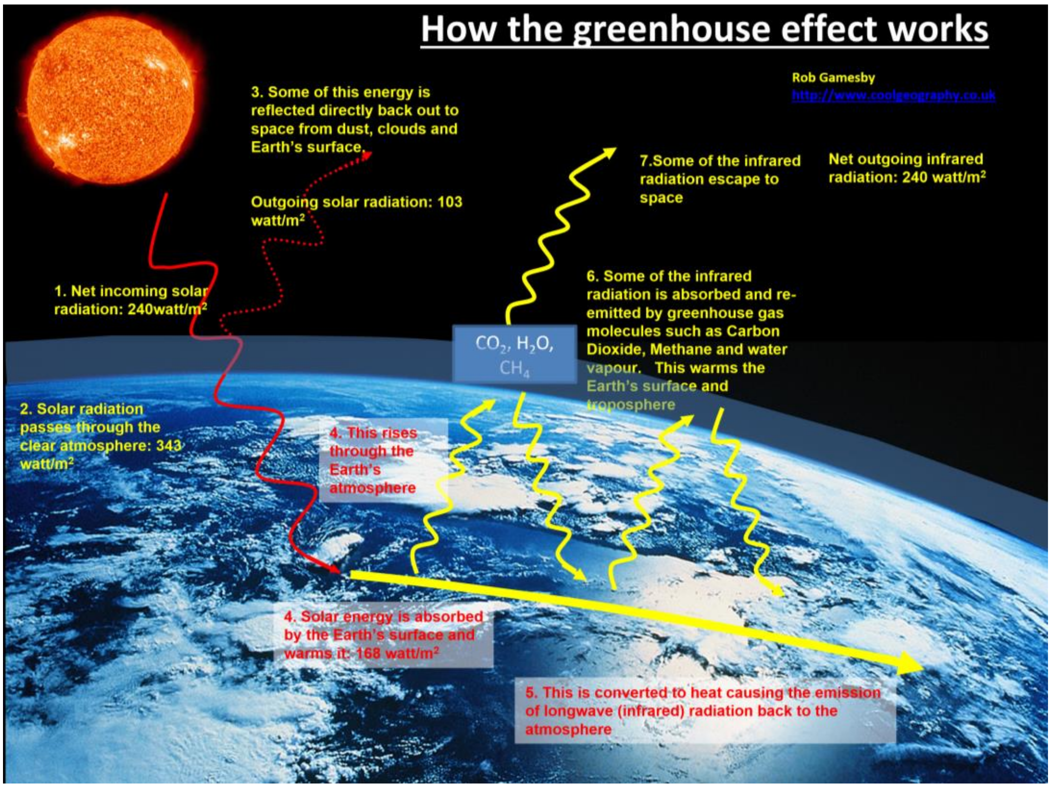
Impact of the carbon cycle upon THE ATMOSPHERE, with particular reference to global climate

Key words

Radiative forcing - also known as climate forcing and is the difference between insolation (sunlight) absorbed by the Earth and energy radiated back to space.

Climate forcing – the influences that cause changes to the Earth's climate system altering Earth's radiative equilibrium, forcing temperatures to rise or fall.

Enhanced greenhouse effect – The impact on global climate of additional heat retained in the atmosphere due to the additional greenhouse gasses such as Carbon dioxide that humans have emitted into the atmosphere.



The greenhouse effect describes the natural balance between incoming and outgoing solar radiation in our atmosphere. The various greenhouse gasses in our atmosphere such as carbon dioxide, methane, and halocarbons absorb a wide range of energy—including infrared energy (heat) emitted by the Earth—and then re-emit it. The re-emitted energy travels out in all directions, but some returns to Earth, where it heats the surface. Without these greenhouse gases, Earth would be a frozen planet with an average temperature of around -18 degrees Celsius. With too many greenhouse gases, Earth would be like Venus, where the greenhouse atmosphere keeps temperatures around 400 degrees Celsius. [3]

The enhanced greenhouse effect includes the impact of people. Indeed, it is the impact on global climate of additional heat retained in the atmosphere due to the additional greenhouse gasses such as Carbon dioxide that humans have emitted into the atmosphere. The extra greenhouse gasses cause what is known as radiative forcing, changes to the Earth's climate system altering Earth's radiative equilibrium, forcing temperatures to rise or fall.

Energy is constantly flowing into the atmosphere in the form of sunlight that always shines on half of the Earth’s surface. Some of this sunlight (about 30 percent) is reflected back to space and the rest is absorbed by the planet. And like any warm object sitting in cold surroundings — and space is a very cold place — some energy is always radiating back out into space as invisible infrared light. Subtract the energy flowing out from the energy flowing in, and if the number is anything other than zero, there has to be some warming (or cooling, if the number is negative) going on.

There are a couple of theories that relate to climate change and why it happens, but the finger points overwhelmingly towards human enhanced global warming given the current evidence collected by scientists. The International Panel for Climate Change (IPCC) is an independent body of thousands of scientists from all over the globe and they agree that human industrial activity is to blame for the current upward trend in temperatures. This is because more of the incoming solar energy is trapped and retained by the extra greenhouse gasses.

These extra greenhouse gasses pose a long term problem, as according to NASA, to date “land plants and the ocean have taken up about 55 percent of the extra carbon people have put into the atmosphere while about 45 percent has stayed in the atmosphere. Eventually, the land and oceans will take up most of the extra carbon dioxide, but as much as 20 percent may remain in the atmosphere for many thousands of years.”[3]

The current level of radiative forcing, according to the IPCC AR4, is 1.6 watts per square meter (with a range of uncertainty from 0.6 to 2.4). That gives a total warming effect of about 800 terawatts — more than 50 times the world’s average rate of energy consumption, which is currently about 15 terawatts. [10]

The changes in the carbon cycle can impact upon each reservoir of carbon. Excess carbon in the atmosphere warms the planet and helps plants on land grow more. Excess carbon in the ocean makes the water more acidic, putting marine life in danger.

The cause of changes to the Earth’s climate are extra greenhouse gasses. The Keeling Curve (named after scientist Charles David Keeling) is a graph of the accumulation of carbon dioxide in the Earth's atmosphere based on continuous measurements taken at the Mauna Loa Observatory on the island of Hawaii from 1958 to the present day. The graph shows rapidly increasing carbon dioxide levels in the atmosphere.

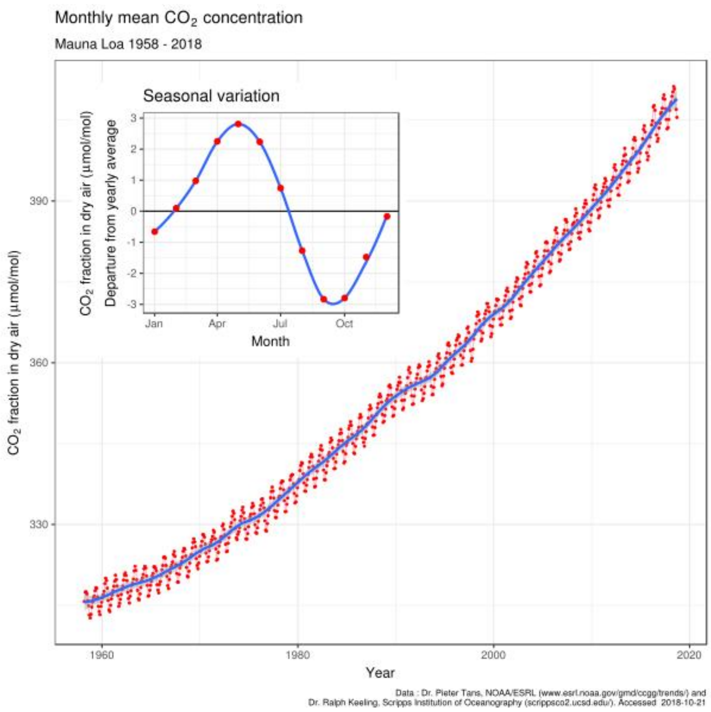
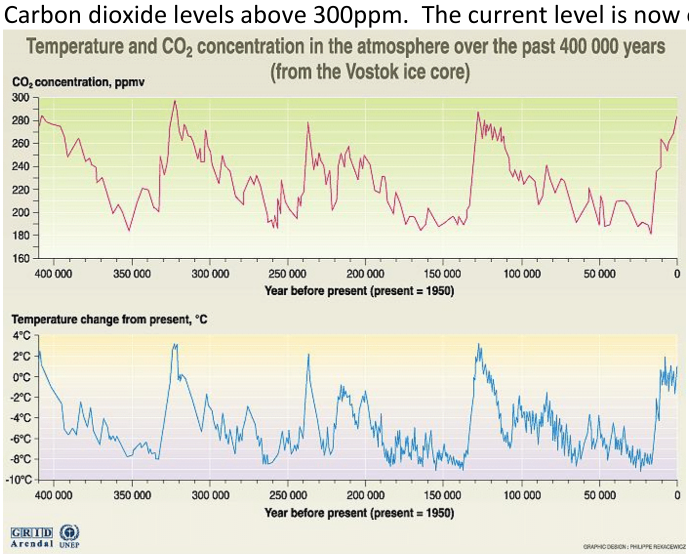


Image credit: Delorme [CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0)], from Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Mauna_Loa_CO2_monthly_mean_concentration.svg

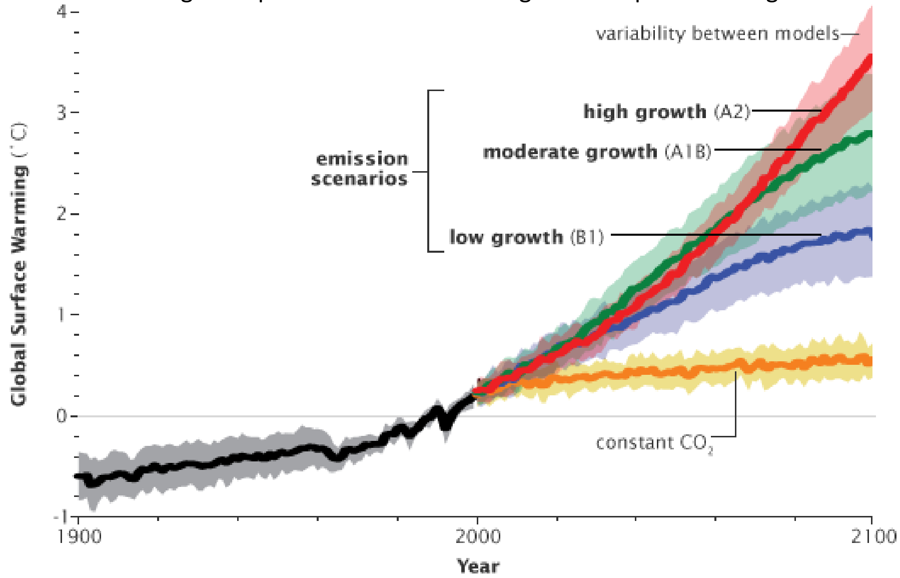
Over longer periods of time scientists have had to use other data sources. Scientists have drilled out a huge core of ice in Antarctica. The air trapped in bubbles in the ice can be analysed and this has shown that the Earth is normally cooler than it is now and that Ice ages are common. It also shows a very strong link between CO_2 concentrations and temperature. Consider now that the graph never shows Carbon dioxide levels above 300ppm. The current level is now over 400ppm and is rising.



Source: J.R. Petit, J. Jouzel, et al. Climate and atmospheric history of the past 420 000 years from the Vostok ice core in Antarctica, Nature 399 (3June), pp 429-436, 1999.

This has resulted in rising temperatures. We have already seen temperatures rise 1°C above preindustrial levels by 2015. Even if greenhouse gas concentrations stabilized today, the planet would continue to warm by about 0.6°C over the next century because of greenhouses gases already in the atmosphere. [11]

Predictions by the IPCC show continued warming over a range of scenarios, from a low amount of carbon emissions to higher amounts. This is shown on the graph below. Model simulations by the Intergovernmental Panel on Climate Change estimate that Earth will warm between two and six degrees Celsius over the next century, depending on how fast carbon dioxide emissions grow. Scenarios that assume that people will burn more and more fossil fuel provide the estimates in the top end of the temperature range, while scenarios that assume that greenhouse gas emissions will grow slowly give lower temperature predictions. The orange line provides an estimate of global temperatures if greenhouse gases stayed at year 2000 levels.



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Sources

1 – Ecohosting , 2018. *Accessed the 30th December 2018 retrieved from* https://ecohosting.co.uk/

2 – IPCC, 2014. *AR5 Synthesis Report: Climate Change 2014*. Accessed the 30th December 2018 retrieved from https://www.ipcc.ch/report/ar5/syr/

3 – NASA Earth observatory, 2011. *Effects of Changing the Carbon Cycle*. Accessed the 30th December 2018 retrieved from https://earthobservatory.nasa.gov/features/CarbonCycle/page5.php

4 - National Geographic, 2017. *Ocean Acidification.* Accessed the 30th December 2018 retrieved from https://www.nationalgeographic.com/environment/oceans/critical-issues-ocean-acidification/

5 – Wikipedia, 2018. *Effects of global warming on oceans.* Accessed the 30th December 2018 retrieved from https://en.wikipedia.org/wiki/Effects_of_global_warming_on_oceans#cite_note-35

6 - Roxy, M.K. (2016). "*A reduction in marine primary productivity driven by rapid warming over the tropical Indian Ocean*". Geophysical Research Letters. Accessed the 30th December 2018 retrieved from https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2015GL066979

7- National Geographic, 2017. Sea level rise. Accessed 1st of January 2019 retrieved from https://www.nationalgeographic.com/environment/global-warming/sea-level-rise/

8 - Shum, C.K. & Kuo, C.Y. (2011). Observation and Geophysical Causes of Present-Day Sea-Level Rise. 10.1007/978-90-481-9516-9_7.

9 - Renee Cho, 2017. *Could climate change shut down the Gulf Stream?* Earth Institute, Columbia University. Accessed 1st of January 2019 retrieved from https://phys.org/news/2017-06-climate-gulf-stream.html

10 - David L. Chandle, 2010. *Explained: Radiative forcing.* MIT News. Accessed 2nd of January 2019 retrieved from http://news.mit.edu/2010/explained-radforce-0309

11 – NASA Earth bservatory, 2010. How Much More Will Earth Warm? Accessed 2nd of January 2019 retrieved from https://earthobservatory.nasa.gov/features/GlobalWarming/page5.php

3.1.1.4 Water, carbon, climate and life on Earth

The key role of the carbon and water stores and cycles in supporting life on Earth with particular reference to climate.

The relationship between the water cycle and carbon cycle in the atmosphere.

This section has been covered continuously throughout the previous pages. The section below is simply a summary of much of that information. The Carbon and Water cycles are linked together in many ways such as;

1. Ocean-atmosphere interchange – physical and biological pumps
2. Volcanic outgassing of both water and carbon transfer them from the lithosphere to the atmosphere
3. Thermohaline circulation – the movement of the Earth's ocean currents transfers heat energy and organic matter around the globe. It also allows carbon to be diffused into the water when it cools in the northern hemisphere and be dragged down to the depths of our oceans.
4. Ocean warming – the increasing impact of the enhanced greenhouse effect is forcing the oceans to warm.
5. Permafrost melting – the changes in the carbon cycle are melting parts of the cryosphere, releasing more carbon dioxide and methane from methyl clathrates
6. Photosynthesis and respiration transfer carbon and water between the biosphere and the atmosphere
7. Weathering releases carbon from the lithosphere and transfers it into the atmosphere and oceans
8. Ocean acidification – where ocean water is made less alkaline by rising carbon levels in the water

Therefore, the links between the global water cycle and the global carbon cycle are strong. Both are key ingredients to all life on the planet.

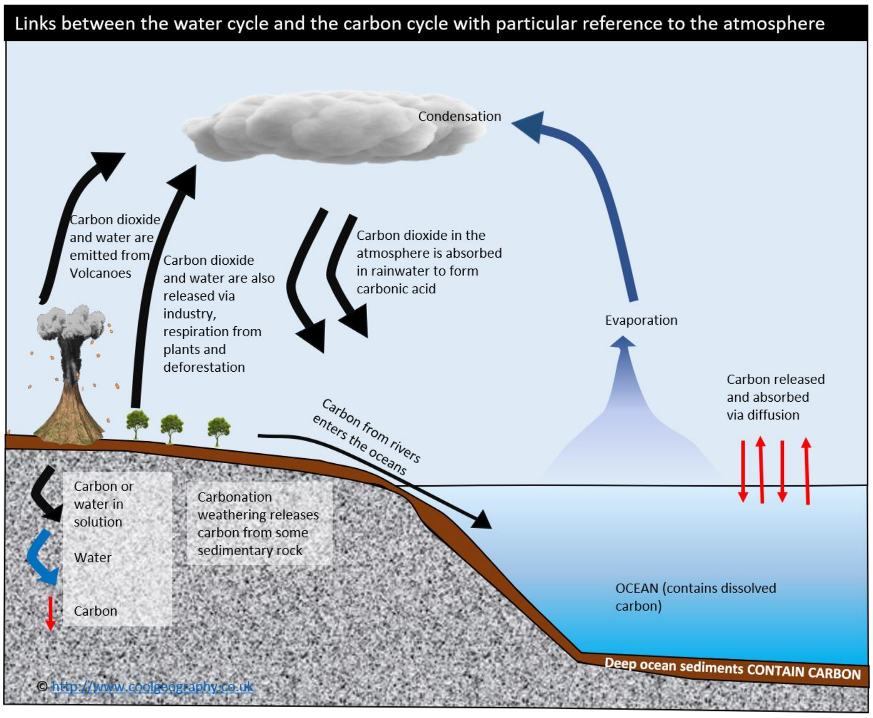
Interrelationships between the water and carbon cycles.

Energy from the sun sets in motion both the carbon and water cycles. Recall that sunlight plus water plus carbon dioxide are combined by photosynthesis in green plants to create carbohydrates.

However, changes to the carbon cycle can have an impact upon the water cycle. Through enhanced global warming via increasing levels of carbon in the atmosphere the impact has been to ***super-charge both cycles****.*

For example, we have seen greater evaporation in parts of the world that creates heavier rainfall in some areas and deeper droughts in others. This shows that the water cycle has been altered by the greater amount of carbon in the air. Similarly, plant growth is accelerated by greater carbon levels in the atmosphere. This accelerated plant growth also contributes more water vapor to the atmosphere during transpiration, which likewise leads to heavier downpours during rain events.

So, both water and carbon are cycling faster and differently as our climate changes.



The role of feedbacks within and between cycles and their link to climate change and implications for life on Earth.

Whilst the burning of fossil fuels, deforestation, and land use changes have altered the carbon budget, this is only the first or **PRIMARY stage** in the story. It is being increasingly acknowledged that changes in one part of the carbon and water cycles can cause additional unexpected consequences. Changes to one part of the climate system can cause additional changes to the way the planet absorbs or reflects energy. These are known as SECONDARY CHANGES and are also called CLIMATE FEEDBACKS. The worry scientists have is that they could FURTHER increase the amount of warming caused by carbon dioxide alone.

Snow and ice

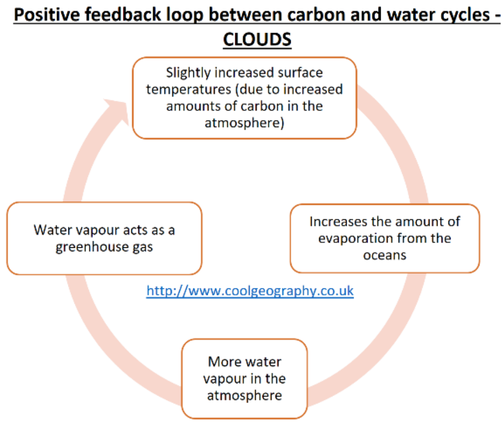
Snow and ice is melting in the Northern Hemisphere and it has been seen that warming temperatures are already melting a growing percentage of Arctic sea ice. This exposes dark ocean water during the summer. Snow cover on land is also declining in many areas. This changes the ALBEDO of these areas. The albedo is the proportion of the incident light or radiation that is reflected by a surface, and it is highest for white surfaces and less for darker surfaces (more energy is absorbed). As snow and ice cover decreases these areas go from having bright, sunlight-reflecting surfaces that cool the planet to having dark, sunlight-absorbing surfaces that bring more energy into the Earth system. This is causing more warming and is hence a positive feedback loop.

Water Vapour

Water vapour is a strong greenhouse gas and according to NASA is the largest feedback factor.[1] The relative abundance of water in the atmosphere means it causes about two-thirds of greenhouse warming. As temperatures warm, more water vapour evaporates from the surface into the atmosphere, where it can cause temperatures to climb further.

Clouds

With more water vapour in the atmosphere we are seeing more clouds. Clouds can both cool the planet (by reflecting visible light from the sun) and warm the planet (by absorbing heat radiation emitted by the surface, see diagram opposite). According to NASA, in our current climate, clouds have a cooling effect overall, but that could change in a warmer environment. [1]



This can also vary by cloud type and how high they are in the atmosphere. For example, low, warm clouds emit more energy than high, cold clouds. Read more by visiting the NASA website.

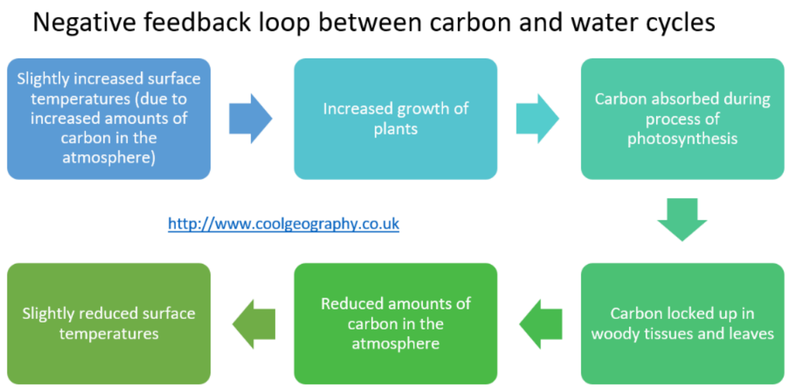
The carbon cycle and the oceans

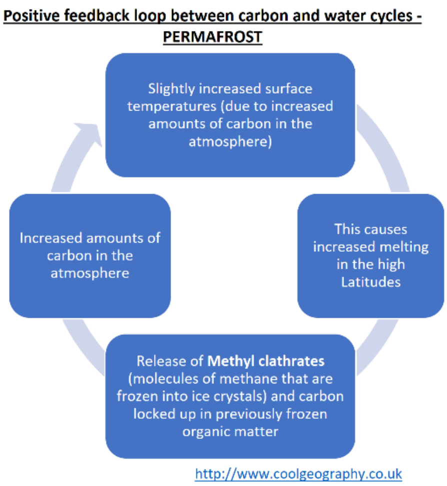
At present increased atmospheric carbon dioxide concentrations and warming temperatures are causing changes in the Earth's natural carbon cycle. Much of the carbon emitted by human activity has been absorbed by the oceans, causing the oceans to become less alkaline. This helps to slows global warming by removing some carbon dioxide from the atmosphere. However, in the future as warmer ocean waters can hold less dissolved carbon, it will leave more in the atmosphere.

Carbon cycle feedback and the cryosphere

As climate warms, we are seeing the thawing Arctic tundra and permafrost, which can release trapped carbon dioxide or methane to the atmosphere. This is shown opposite, and is a positive feedback loop.

However, extra carbon dioxide can stimulate plant growth and these plants to take additional carbon out of the atmosphere. The limiter to this is when plant growth is limited by water, nitrogen, and temperature. This is a negative feedback loop, as it diminishes the impact of the original change.





Sources
1 – NASA:Earth Observatory, 2010. *How Much More Will Earth warm?* - https://earthobservatory.nasa.gov/features/GlobalWarming/page5.php

Consequences of changes to the carbon cycle for life on earth

Enhanced climate change is already happening and is set to get worse. The consequences for people could be very significant. In the latest report from the Intergovernmental Panel on Climate Change released in 2018 major issues for people globally are discussed. The report has taken over two years to produce and included the assessment of more than 6,000 scientific studies. The report was commissioned after the Paris Agreement of 2015 and looked at 2 major scenarios, warming of 1.5°C and warming of 2°C.

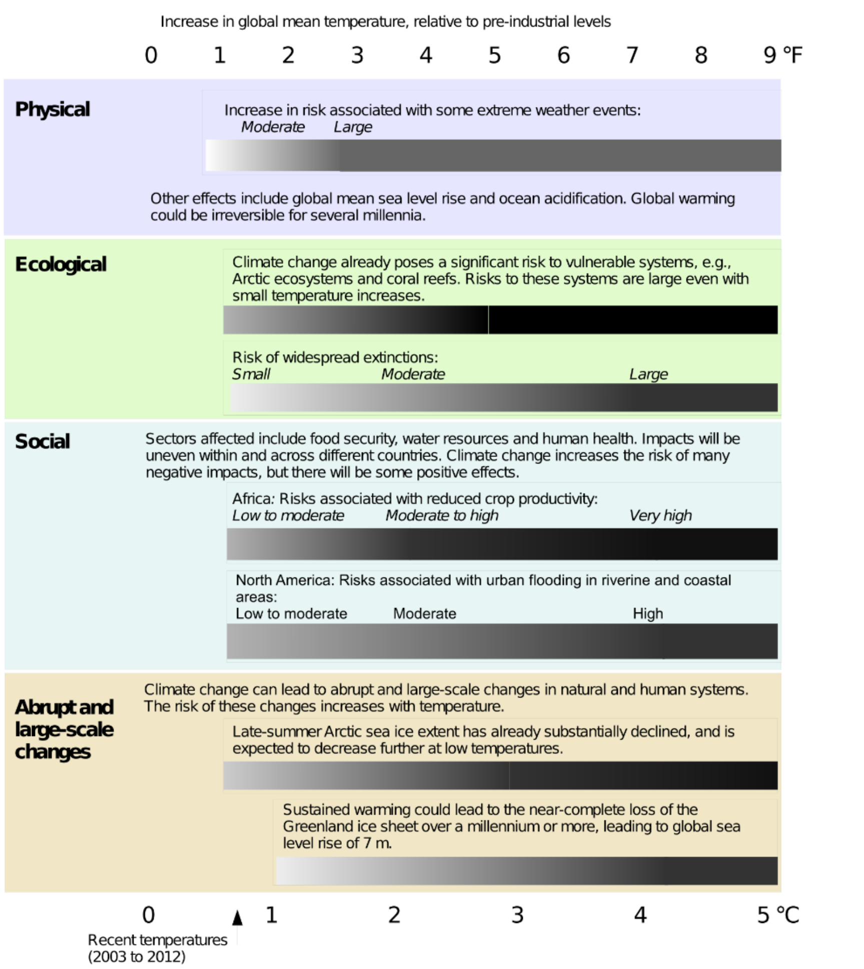
The main conclusions are;

We will not achieve the limits we set to global warming agreed in Paris. We are on track to reach 1.5°C between 2030 and 2052 if temperatures continues to increase at the current rate, and 3°C by the end of the century.

At 2°C warming, major changes take place;

1. There will be almost no coral reefs remaining
2. The Arctic will be completely devoid of ice during summer at least once a decade
3. Huge numbers of animals and plants will become extinct as their habitat becomes smaller.
4. Vulnerable areas such as the low-lying coastal regions of Bangladesh and Vietnam, and island territories like Kiribati and the Maldives will see sea level rise. This will drive millions from their homes
5. There will be more human health risks such as malaria
6. Crop yields will fall dramatically in sub-Saharan Africa, Southeast Asia, and Central and South America. [1]

We have already seen more extreme weather over past decades and 2018 was a particularly hazardous year with major big freezes, forest fires, floods and droughts. [2] Christian Aid issued a report that identified ten events that cost more than $1bn each, with four costing more than $7bn each. [3]



By Enescot - Own work, CC0, https://commons.wikimedia.org/w/index.php?curid=35955459

To meet these challenges of climate change we need mitigation and adaptation.

Human interventions in the carbon cycle designed to influence carbon transfers and mitigate the impacts of climate change.

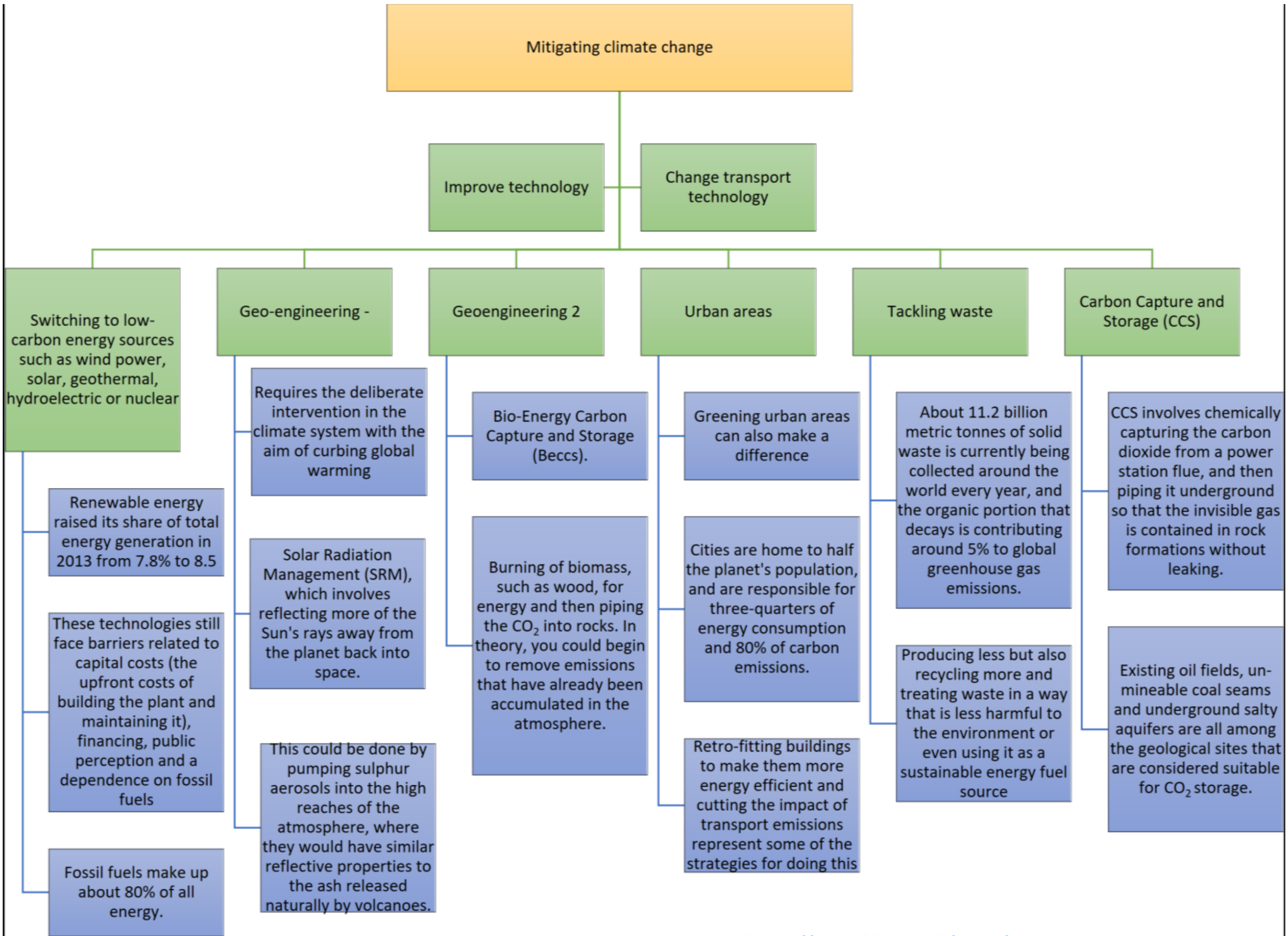
Mitigation

Mitigation refers to efforts to cut or prevent the emission of greenhouse gases – this would limit the magnitude of future warming. Mitigation can also include new attempts to actually remove carbon currently in the atmosphere.

Climate change adaptation is different, this is how people can manage unavoidable impacts of climate change.

Mitigation involves;

1. Using new technologies
2. Using clean energy sources
3. Changing people's behaviour
4. Making older technology more energy efficient



Source: https://www.bbc.co.uk/news/science-environment-26980837

Carbon Capture and Storage (CCS)

Carbon Capture and Storage (CCS) is a technology that can capture up to 90% of the carbon dioxide (CO_2) emissions produced in electricity generation and industrial processes from the use of fossil fuels. This prevents the carbon dioxide from entering the atmosphere.

CCS involves;

1. Capture technologies allow the separation of carbon dioxide from gases produced in electricity generation and industrial processes by one of three methods: pre-combustion capture, post-combustion capture and oxyfuel combustion.
2. Transport the CO_2 by pipeline or by ship for safe storage. Millions of tonnes of carbon dioxide are already transported annually for commercial purposes by road tanker, ship and pipelines

3. The carbon dioxide is then stored in carefully selected geological rock formation that are typically located several kilometres below the earth's surface. [4]

Geological sequestration

New technologies are emerging to fix carbon deep under the ground in a process known as Geologic sequestration. In Iceland a new process is taking place to fix carbon in the abundant Basalt rocks there. It starts with the capture of waste CO_2 from the steam used in the geothermal power plant there, which is then dissolved into large volumes of water. The fizzy liquid is then piped to the injection site2km away. Then it is pumped 1,000m beneath the surface. Here, chemical reactions will solidify the CO_2 into rock in a matter of months - thus preventing it from escaping back into the atmosphere for millions of years. The carbon forms calcites within the pores of the basalt rock. [5]

Other schemes involve actually removing carbon currently in the atmosphere, using Carbon dioxide removal (CDR) technologies. These include bio-energy with carbon capture and storage, biochar, ocean fertilization, enhanced weathering, and direct air capture when combined with storage.

Biological sequestration

Biological sequestration involves the net removal of CO_2 from the atmosphere by plants and micro-organisms and its storage in vegetative biomass and in soils.

This offers many potential advantages:

1. could sequester relatively large volumes of carbon at comparatively low cost
2. protecting or improving soils, water resources, habitat, and biodiversity
3. generate rural income
4. promotes more sustainable agriculture and forestry practices

This means new sinks can be created, for example, afforestation in the UK can capture carbon.

International Policy

There is a long history of trying to resolve climate change and human impact upon the carbon and water cycles. Climate change is a global issue, and so needs global agreements and solutions. These take place at huge conferences. A history of these is outlined below;

Date	Location and events
1978	Brandt Report, in which the greenhouse effect was dealt with in the energy section
1987	the Montreal Protocol established clear rules and priorities to restrict ozone layer-damaging CFCs.
1988	IPCC (Intergovernmental Panel on Climate Change) was established to coordinate scientific research, by two United Nations organizations, the World Meteorological Organization and the United Nations Environment Program (UNEP) to assess the "risk of human-induced climate change".
1992	Earth summit in Rio de Janeiro set up the United Nations Framework Convention on Climate Change. The objective of the UNFCCC was to stabilise greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous human interference with the climate system. Treaty itself set no mandatory limits on greenhouse gas emissions for individual countries and contains no enforcement mechanisms. In that sense, the treaty is considered legally non-binding. Instead, the treaty provides for updates (called "protocols") that would set mandatory emission limits.
1994	UNFCC enters into force, European Union set a target of a maximum 2°C rise in average global temperature.
1997	Earth summit agreement was then followed by Kyoto Protocol of 1997. This was agreed by nearly every country in the world except the USA (plus 4 others), who wanted developing nations to have to cut their emissions as well. The protocol demanded that 37 countries including the UK ("Annex I countries") commit themselves to a reduction of four greenhouse gases (GHG) (carbon dioxide, methane, nitrous oxide, sulphur hexafluoride) and all member countries give general commitments.
2011	UN climate talks were held in Durban. It was agreed that the EU would put its current emission-cutting pledges inside the legally-binding Kyoto Protocol, a key demand of developing countries
2015	The Paris Protocol agreed. The key elements were; • To keep global temperatures "well below" 2.0C (3.6F) above pre-industrial times and "endeavour to limit" them even more, to 1.5C • To limit the amount of greenhouse gases emitted by human activity to the same levels that trees, soil and oceans can absorb naturally, beginning at some point between 2050 and 2100 • To review each country's contribution to cutting emissions every five years so they scale up to the challenge • For rich countries to help poorer nations by providing "climate finance" to adapt to climate change and switch to renewable energy.
2018	Katowice Climate Change Conference. Paris Protocol and the details of how it is to be achieved agreed in this conference.

Sources

1 - Ove Hoegh-Guldberg, Daniela Jacob, Michael Taylor, 2018. Special Report: Global Warming of 1.5 ºC - Summary for Policymakers. Chapter 1 and 3, IPCC. Accessed 3rd of January 2019 retrieved from https://www.ipcc.ch/sr15/

2 - Damian Carrington, 2018. Extreme global weather is 'the face of climate change' says leading scientist. The Guardian. Accessed 3rd of January 2019 retrieved from https://www.theguardian.com/environment/2018/jul/27/extreme-global-weather-climate-change-michael-mann

3 – Christian Aid, 2018. *Counting The Cost: A Year of Climate Breakdown*. Accessed 3rd of January 2019 retrieved from https://mediacentre.christianaid.org.uk/download?id=4170&pn...pdf

4 – Carbon Capture and Storage Association, *What is CCS?* http://www.ccsassociation.org/what-is-ccs/

5 - Valeria Perasso, 2018. Turning carbon dioxide into rock – forever. BBC. Accessed 3rd of January 2019 retrieved from https://www.bbc.co.uk/news/world-43789527

Case study of a tropical rainforest setting to illustrate and analyse key themes in water and carbon cycles and their relationship to environmental change and human activity.

Amazon Forest

The Amazon is the largest tropical rainforest on Earth. It sits within the Amazon River basin, covers some 40% of the South American continent and as you can see on the map below includes parts of eight South American countries: Brazil, Bolivia, Peru, Ecuador, Colombia, Venezuela, Guyana, and Suriname. The actual word "Amazon" comes from river.

Amazing Amazon facts;

- It is home to 1000 species of bird and 60,000 species of plants
- 10 million species of insects live in the Amazon
- It is home to 20 million people, who use the wood, cut down trees for farms and for cattle.
- It covers 2.1 million square miles of land
- The Amazon is home to almost 20% of species on Earth
- The UK and Ireland would fit into the Amazon 17 times!

The Amazon caught the public's attention in the 1980s when a series of shocking news reports said that an area of rainforest the size of Belgium was being cut down and subsequently burnt every year. This deforestation has continued to the present day according to the Sao Paulo Space Research Centre. In 2005 they had lost 17% of Amazon rainforest or 650,000 square kilometres. Their satellite data is also showing increased deforestation in parts of the Amazon.

Carbon

Tropical forests are very important stores of carbon, and in their untouched state act as carbon sinks. It is thought that there are approximately 100 PgC in aboveground biomass (AGB) in Amazonia. [1] The Amazon forest covers an estimated 5.3 million sq km and holds 17% of the global terrestrial vegetation carbon stock.[5]

A study by Fauset (2015) showed that around 1% of all the tree species in the Amazon account for half of the carbon locked in the vast South American rainforest. Despite the fact that the region is home to an estimated 16,000 tree species, just 182 species dominated the carbon storage process. [6]

Untouched Amazon forests take in more carbon dioxide than they put back into the atmosphere. This shows that the Amazon forests help reduce global warming by lowering the planet's greenhouse gas levels.

Dead Amazonian trees (which account for around 20% of above ground biomass[5]) emit an estimated 1.9 billion tons (1.7 billion metric tons) of carbon to the atmosphere each year. In a normal year, the Amazon rainforest absorbs about 2.2 billion tons (2 billion metric tons) of carbon dioxide. This means that untouched tropical forests act as a SINK for carbon. [2]

However, a study from 2015 confirms that Amazon forests have acted as a long-term net biomass sink, but also found a long-term decreasing trend of carbon accumulation. Rates of net increase in above-ground biomass declined by one-third during the past decade compared to the 1990s. This means tropical forests are becoming less efficient at trapping carbon. [7]

Water

The water cycle is very active within the Amazon rainforest and it interlinks the lithosphere, atmosphere and biosphere. The basin is drained by the Amazon River and its tributaries. The average discharge of water into the Atlantic Ocean by the Amazon is approximately 175,000 m^3 per second, or between 1/5th and 1/6th of the total discharge into the oceans of all of the world's rivers. [3]

The Rio Negro, a tributary of the Amazon, is the second largest river in the world in terms of water flow, and is 100 meters deep and 14 kilometres wide near its mouth at Manaus, Brazil.

Rainfall across the Amazon is very high. Average rainfall across the whole Amazon basin is approximately 2300 mm annually. In some areas of the northwest portion of the Amazon basin, yearly rainfall can exceed 6000 mm. [3]

Only around 1/3 of the rain that falls in the Amazon basin is discharged into the Atlantic Ocean. It is thought that;

1. Up to half of the rainfall in some areas may never reach the ground, being intercepted by the forest and re-evaporated into the atmosphere.
2. Additional evaporation occurs from ground and river surfaces, or is released into the atmosphere by transpiration from plant leaves (in which plants release water from their leaves during photosynthesis)
3. This moisture contributes to the formation of rain clouds, which release the water back onto the rainforest. In the Amazon, 50-80 percent of moisture remains in the ecosystem's water cycle. [4]

This means that much of the rainfall re-enters the water cycling system of the Amazon, and a given molecule of water may be "re-cycled" many times between the time that it leaves the surface of the Atlantic Ocean and is carried by the prevailing westerly winds into the Amazon basin, to the time that it is carried back to the ocean by the Amazon River. [4]

It is thought that the water cycle of the Amazon has global effects. The moisture created by rainforests travels around the world. Moisture created in the Amazon ends up falling as rain as far away as Texas, and forests in Southeast Asia influence rain patterns in south Eastern Europe and China. [4]

When forests are cut down, less moisture goes into the atmosphere and rainfall declines, sometimes leading to drought.

In recent years, the rainforests of Borneo and the Amazon have experienced very severe droughts. These have been made worse by deforestation. [4]

Change to the water and carbon cycles in the Amazon

The main change to the Amazon rainforest is deforestation. Deforestation in the Amazon is generally the result of land clearances for;

1. **Agriculture** (to grow crops like Soya or Palm oil) or for pasture land for cattle grazing
2. **Logging** – This involves cutting down trees for sale as timber or pulp. The timber is used to build homes, furniture, etc. and the pulp is used to make paper and paper products. Logging can be either selective or clear cutting. Selective logging is selective because loggers choose only wood that is highly valued, such as mahogany. Clear-cutting is not selective. Loggers are interested in all types of wood and therefore cut all of the trees down, thus clearing the forest, hence the name- clear-cutting.
3. **Road building –** trees are also clear for roads. Roads are an essential way for the Brazilian government to allow development of the Amazon rainforest. However, unless they are paved many of the roads are unusable during the wettest periods of the year. The Trans Amazonian Highway has already opened up large parts of the forest and now a new road is going to be paved, the BR163 is a road that runs 1700km from Cuiaba to Santarem. The government planned to tarmac it making it a superhighway. This would make the untouched forest along the route more accessible and under threat from development.
4. **Mineral extraction** – forests are also cleared to make way for huge mines. The Brazilian part of the Amazon has mines that extract iron, manganese, nickel, tin, bauxite, beryllium, copper, lead, tungsten, zinc and gold!
5. **Energy development** – This has focussed mainly on using Hydro Electric Power, and there are 150 new dams planned for the Amazon alone. The dams create electricity as water is passed through huge pipes within them, where it turns a turbine which helps to generate the electricity. The power in the Amazon is often used for mining. Dams displace many people and the reservoirs they create flood large area of land, which would previously have been forest. They also alter the hydrological cycle and trap huge quantities of sediment behind them. The huge Belo Monte dam started operating in April 2016 and will generate over 11,000 Mw of power. A new scheme the 8,000-megawatt São Luiz do Tapajós dam has been held up because of the concerns over the impacts on the local Munduruku people.
6. **Settlement & population growth** – populations are growing within the Amazon forest and along with them settlements. Many people are migrating to the forest looking for work associated with the natural wealth of this environment. Settlements like Parauapebas, an iron ore mining town, have grown rapidly, destroying forest and replacing it with a swath of shanty towns. The population has grown from 154,000 in 2010 to 220,000 in 2012. The Brazilian Amazon's population grew by a massive 23% between 2000 and 2010, 11% above the national average.

The WWF estimates that 27 per cent, more than a quarter, of the Amazon biome will be without trees by 2030 if the current rate of deforestation continues. They also state that Forest losses in the Amazon biome averaged **1.4 million hectares** per year between 2001 and 2012, resulting in a total loss of **17.7 million hectares**, mostly in Brazil, Peru and Bolivia. [12]

The impacts of deforestation

Atmospheric impacts

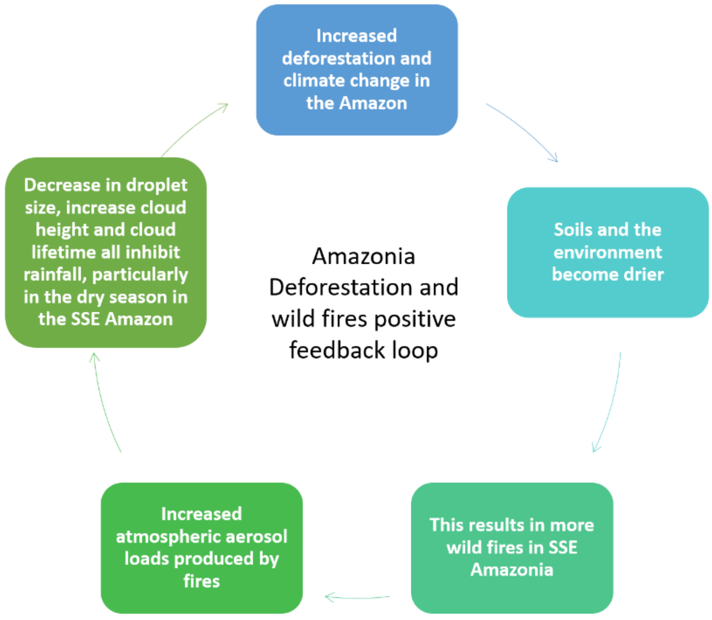
Deforestation causes important changes in the energy and water balance of the Amazon. Pasturelands and croplands (e.g. soya beans and corn) have a higher albedo and decreased water demand, evapotranspiration and canopy interception compared with the forests they replace. [9] Lathuillière et al. [10] found that forests in the state of Mato Grosso;

- Contributed about 50 km^3 per year of evapotranspiration to the atmosphere in the year 2000.
- Deforestation reduced that forest flux rate by approximately 1 km^3 per year throughout the decade.
- As a result, by 2009, forests were contributing about 40 km^3 per year of evapotranspiration in Mato Grosso.

Differences such as these can affect atmospheric circulation and rainfall in proportion to the scale of deforestation

The agriculture that replaces forest cover also decreases precipitation. In Rondônia, Brazil, one of the most heavily deforested areas of Brazil, daily rainfall data suggest that deforestation since the 1970s has caused an 18-day delay in the onset of the rainy season.[11]

SE Amazon also has many wild fires, which are closely associated with deforestation, forest fragmentation and drought intensity. According to Coe et al (2015) "*the increased atmospheric aerosol loads produced by fires have been shown to decrease droplet size, increase cloud height and cloud lifetime and inhibit rainfall, particularly in the dry season in the SSE Amazon. Thus, fires and drought may create a positive feedback in the SSE Amazon such that drought is more severe with continued deforestation and climate change.*"[9]



http://www.coolgeography.co.uk

Contribution to climate change

Tropical forests are very important carbon sinks, but deforestation and degradation are **turning these sinks into carbon SOURCES.** The degradation (reduction in quality of tropical forests) and deforestation releases the carbon stored within the trees back into the atmosphere. Around 30% of anthropogenic carbon emissions come from burning the rainforests alone. Forests that experienced disturbances such as logging and fires store 40% less carbon than undisturbed forests. [13] This makes climate change alone a major impact of tropical forest destruction with respects to the carbon cycle.

The impacts of climate change on the Amazon

According to the WWF:

- Some Amazon species capable of moving fast enough will attempt to find a more suitable environment. Many other species will either be unable to move or will have nowhere to go.
- Higher temperatures will impact temperature-dependent species like fish, causing their distribution to change.
- Reduced rainfall and increased temperatures may also reduce suitable habitat during dry, warm months and potentially lead to an increase in invasive, exotic species, which then can out-compete native species.
- Less rainfall during the dry months could seriously affect many Amazon rivers and other freshwater systems.
- The impact of reduced rainfall is a change in nutrient input into streams and rivers, which can greatly affect aquatic organisms.
- A more variable climate and more extreme events will also likely mean that Amazon fish populations will more often experience hot temperatures and potentially lethal environmental conditions.
- Flooding associated with sea-level rise will have substantial impacts on lowland areas such as the Amazon River delta. The rate of sea-level rise over the last 100 years has been 1.0-2.5 mm per year, and this rate could rise to 5 mm per year.
- Sea-level rise, increased temperature, changes in rainfall and runoff will likely cause major changes in species habitats such as mangrove ecosystems. [15]

Impacts of deforestation on soils

Removing trees deprives the forest of portions of its canopy, which blocks the sun's rays during the day, and holds in heat at night. This disruption leads to more extreme temperature swings that can be harmful to plants and animals. [8] Without protection from sun-blocking tree cover, moist tropical soils quickly dry out.

In terms of Carbon, Tropical soils contain a lot of carbon. The top meter holds 66.9 PgC with around 52% of this carbon pool held in the top 0.3 m of the soil, the layer which is most prone to changes upon land use conversion and deforestation. [14] Deforestation releases much of this carbon through clearance and burning. For the carbon that remains in the soil, when it rains soil erosion will wash much of the carbon away into rivers after initial deforestation and some will be lost to the atmosphere via decomposition too.

Impacts of deforestation on Rivers

Trees also help continue the water cycle by returning water vapor to the atmosphere. When trees are removed this cycle is severely disrupted and areas can suffer more droughts. There are many consequences of deforestation and climate change for the water cycle in forests;

1. There is increased soil erosion and weathering of rainforest soils as water acts immediately upon them rather than being intercepted.
2. Flash floods are more likely to happen as there is less interception and absorption by the forest cover.
3. Conversely, the interruption of normal water cycling has resulted in more droughts in the forest, increasing the risk of wild fires
4. More soil and silt is being washed into rivers, resulting in changes to waterways and transport
5. Disrupt water supplies to many people in Brazil

References

1 - Malhi, Y. *et al. The regional variation of aboveground live biomass in old-growth Amazonian forests*. *Glob. Chang. Biol.* **12**, 1107–1138 (2006).

2 - Fernando D.B. Espírito-Santo et al. *Size and frequency of natural forest disturbances and the Amazon forest carbon balance. Nature Communications* **volume 5**, Article number: 3434 (2014) Accessed 3rd of January 2019 retrieved from https://www.nature.com/articles/ncomms4434#ref4

3 - Project Amazonas. Accessed 3rd of January 2019 retrieved from https://www.projectamazonas.org/amazon-facts

4 - Rhett Butler, 2012. IMPACT OF DEFORESTATION: LOCAL AND NATIONAL CONSEQUENCES. Accessed 3rd of January 2019 retrieved from https://rainforests.mongabay.com/0902.htm

5 – Mark Kinver. *Amazon: 1% of tree species store 50% of region's carbon*. 2015. BBC. Accessed 3rd of January 2019 retrieved from https://www.bbc.co.uk/news/science-environment-32497537

6 - Sophie Fauset et al. *Hyperdominance in Amazonian forest carbon cycling*. Nature Communications volume 6, Article number: 6857 (2015). Accessed 3rd of January 2019 retrieved from https://www.nature.com/articles/ncomms7857

7- Brienen, R.J.W et al. (2015) Long-term decline of the Amazon carbon sink, Nature, https://www.nature.com/articles/nature14283

8 – National Geographic – *Deforestation - Learn about the man-made and natural causes of deforestation–and how it's impacting our planet.* Accessed 20th of January 2019 retrieved from https://www.nationalgeographic.com/environment/global-warming/deforestation/

9 - Michael T. Coe, Toby R. Marthews, Marcos Heil Costa, David R. Galbraith, Nora L. Greenglass, Hewlley M. A. Imbuzeiro, Naomi M. Levine, Yadvinder Malhi, Paul R. Moorcroft, Michel Nobre Muza, Thomas L. Powell, Scott R. Saleska, Luis A. Solorzano, and Jingfeng Wang. (2015) *Deforestation and climate feedbacks threaten the ecological integrity of south–southeastern Amazonia*. 368, Philosophical Transactions of the Royal Society B: Biological Sciences. Accessed 20th of January 2019 retrieved from http://rstb.royalsocietypublishing.org/content/368/1619/20120155

10 - Lathuillière MJ, Mark S, Johnson MS & Donner SD. (2012). *Water use by terrestrial ecosystems: temporal variability in rainforest and agricultural contributions to evapotranspiration in Mato Grosso, Brazil*. Environmental research Letters Volume 7 Number 2. http://iopscience.iop.org/article/10.1088/1748-9326/7/2/024024/meta

11- Nathalie Butt, Paula Afonso de Oliveira & Marcos Heil Costa (2011). *Evidence that deforestation affects the onset of the rainy season in Rondonia, Brazil* JGR Atmospheres, Volume 116, Issue D11. https://doi.org/10.1029/2010JD015174

12 – WWF, *Amazon Deforestation*. Accessed 20th of January 2019 retrieved from http://wwf.panda.org/our_work/forests/deforestation_fronts/deforestation_in_the_amazon/

13 - Berenguer, E., Ferreira, J., Gardner, T. A., Aragão, L. E. O. C., De Camargo, P. B., Cerri, C. E., Durigan, M., Oliveira, R. C. D., Vieira, I. C. G. and Barlow, J. (2014), *A large-scale field assessment of carbon stocks in human-modified tropical forests.* Global Change Biology, 20: 3713–3726. https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12627

14 - N.HBatjes, J.ADijkshoorn, (1999). *Carbon and nitrogen stocks in the soils of the Amazon Region.* Geoderma, Volume 89, Issues 3–4, Pages 273-286. Accessed 20th of January 2019 retrieved from https://www.sciencedirect.com/science/article/pii/S001670619800086X

15 – WWF, Impacts of climate change in the Amazon. Accessed 20th of January 2019 retrieved from http://wwf.panda.org/knowledge_hub/where_we_work/amazon/amazon_threats/climate_change_amazon/amazon_climate_change_impacts/