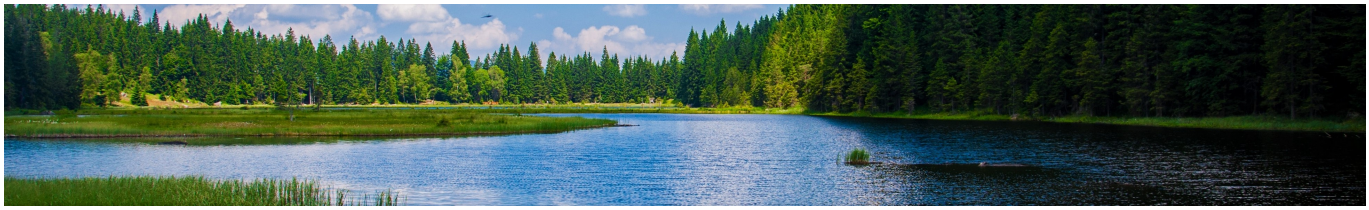
Summary Notes on

ES2101

Biogeochemical Cycles



Fall 2023

by

Susnata Chattopadhyay [1]

[22MS077]

Course Instructors:

Shrimati Sujata Ray

Indian Institute of Science Education and Research, Kolkata,
Mohanpur, West Bengal, 741246, India.

[1]Email: sc22ms077@iiserkol.ac.in

Contents

1 Week 1 **1**
- 1.1 Introduction . . . 1
  - 1.1.1 Recap of Quaternary Period . . . 1
  - 1.1.2 Random Discussions . . . 1
- 1.2 Keeling Curve . . . 2

2 Week 2 **3**
- 2.1 Weather and Climate . . . 3
- 2.2 Global Energy Balance . . . 3
- 2.3 δ^{18}O Method . . . 4
- 2.4 From Marine Sediments . . . 5

3 Week 3 **6**
- 3.1 Equilibrium Temperature and Realized Temperature . . . 6

4 Week 4 **7**
- 4.1 Effect of Aerosols . . . 7
- 4.2 Removal of methane in atmosphere . . . 7
- 4.3 Radiative Forcings and Climate Change . . . 8

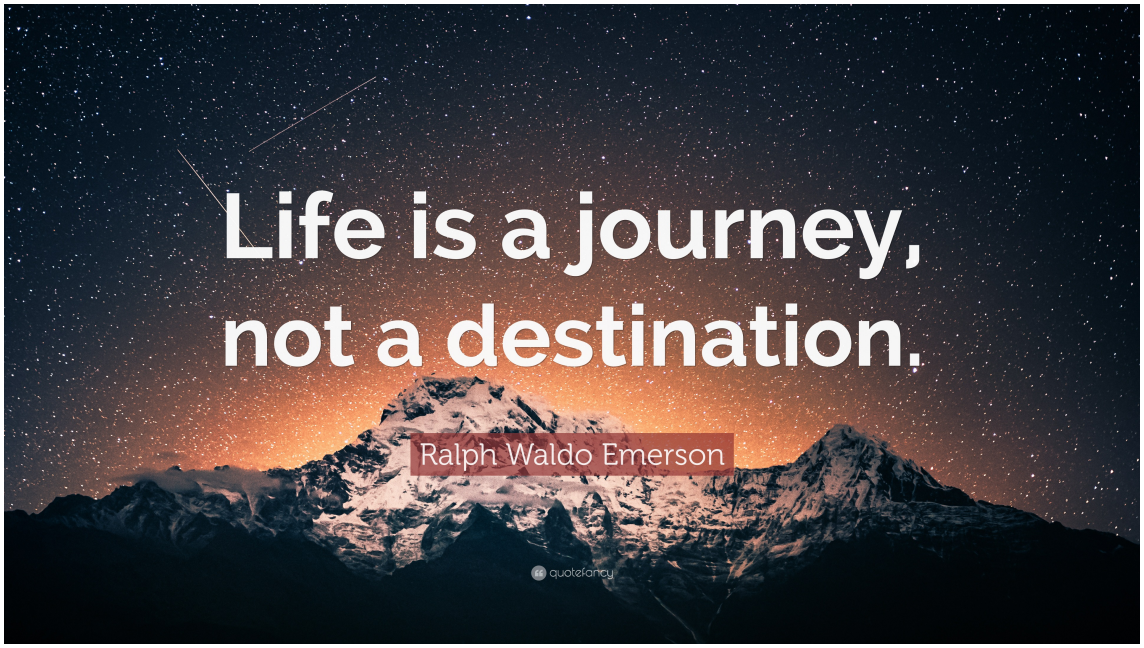
5 Week 5 **9**
- 5.1 Radiative Forcings with change in greenhouse gas concentration . . . 9
- 5.2 Carbon content of atmosphere . . . 9

6 Week 6 **10**
- 6.1 Blackbody Sensitivity . . . 10
- 6.2 Relationship between CO_2 and Global warming effects . . . 10
- 6.3 Energy in Fossil fuels . . . 10

7 Week 7 **11**
- 7.1 Estimating Carbon Emissions: Kaya Identity . . . 11
- 7.2 Global Warming Potential . . . 11
- 7.3 Ice Core . . . 12
- 7.4 Dating of events from ice core sample . . . 13

8 Week 8 **15**
- 8.1 Nitrogen Cycle . . . 15
  - 8.1.1 Nitrification . . . 16
  - 8.1.2 Denitrification . . . 16
- 8.2 Carbon Cycle . . . 16
  - 8.2.1 Carbon Reduction . . . 16
  - 8.2.2 Carbon Oxidation . . . 16
- 8.3 Sulphur Cycle . . . 16
  - 8.3.1 Sulphur Reduction . . . 16

9 BBC documentary summary **18**
- 9.1 Volcano . . . 18
- 9.2 Atmosphere . . . 18
- 9.3 Ice . . . 19
- 9.4 Oceans . . . 19
- 9.5 Rare Earth . . . 20


Life is a journey,
not a destination.
Ralph Waldo Emerson
quotefancy

1 Week 1

1.1 Introduction

Some BIG questions...

What contributes to the habitability of Earth?
How do microorganisms play a central role in driving the biogeochemical cycles?
How do the components of Earth system interacts with one another?
How do human activities affect Earth's habitability?
Ask yourself: How did the first person find this out?!

The period of Earth when modern human evolved and civilized themselves is called *Holocene* (10000 ya - present) Over the past few centuries the phase of the planet has been dynamic. Most of the complex life are limited to a thin *smear* on Earth's surface. Bio-geochemical cycles are near surface events.

1.1.1 Recap of Quaternary Period

- Early Hominids (*Homo Erectus*) evolved to Humans(*Homo sapiens sapiens*) , with developed brains.
- Rise and fall of sea-levels due to ice ages.
- Land bridges formed, connecting continents which allowed migration of humans.

1.1.2 Random Discussions

- Earth behaves like a closed system. NOT isolated!!
- Browser- Herbivores-Cows/goats.
- Benthic predators dwell the bottom ocean sediments.
- Plankton literally means *drifters.*

1.2 Keeling Curve

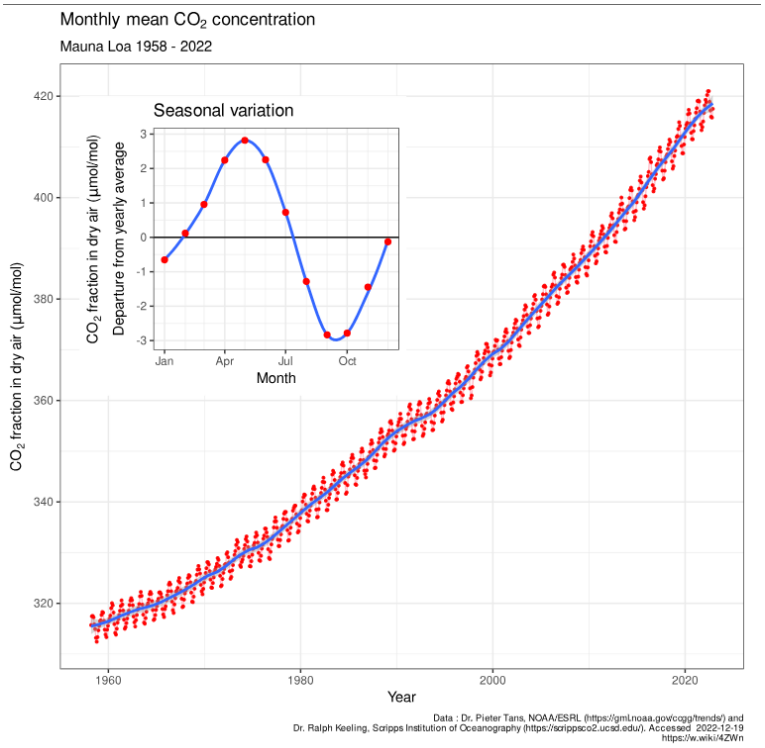


Figure 1: A Plot of Keeling Curve from 1958- 2022. **Inset:** Seasonal variation in CO_2 levels in atmosphere.

What is this? The Keeling Curve is not only a historical record of increasing CO_2 levels but also a visual representation of the link between human activities and the accumulation of greenhouse gases in the atmosphere. It has been a key piece of evidence in understanding and communicating the concept of anthropogenic (human-caused) climate change and its potential impacts on the planet's climate system.

Inference On an average, we can see a steadily increasing graph, which indicates the rate of production of CO_2 each year, is getting more than the rate in which it is consumed. CO_2 can be removed from atmosphere by photosynthesis and $CaCO_3$ deposition in ocean rocks. This is due to **anthropogenic factors**[2]. Within a year we also notice *sinusoidal oscillations* in the level. This is due to a superposition of various factors. When one hemisphere has summer, trees grow, thus rate of photosynthesis increases, whilst in the other half it's winter and the rate falls. Again the ocean is the largest sink of CO_2, which is a greater proportion of Southern Hemisphere. Algae/ cyanobacteria increases in these waters in summer. Hence, two different levels of photosynthesis is responsible for these seasonal variation.

[2]Just mention this term anywhere in your answer otherwise no marks. Madam deducted 1 marks from my answer because I missed this term. Sed :(

2 Week 2

2.1 Weather and Climate

Weather- It is a temporary short-lived meteorological process at a specific location over a short time span.

Climate- It is a statistics of weather, character of atmosphere. Generally summary of weather of a specific region over longer time scales (*typically 30 yrs*).

2.2 Global Energy Balance

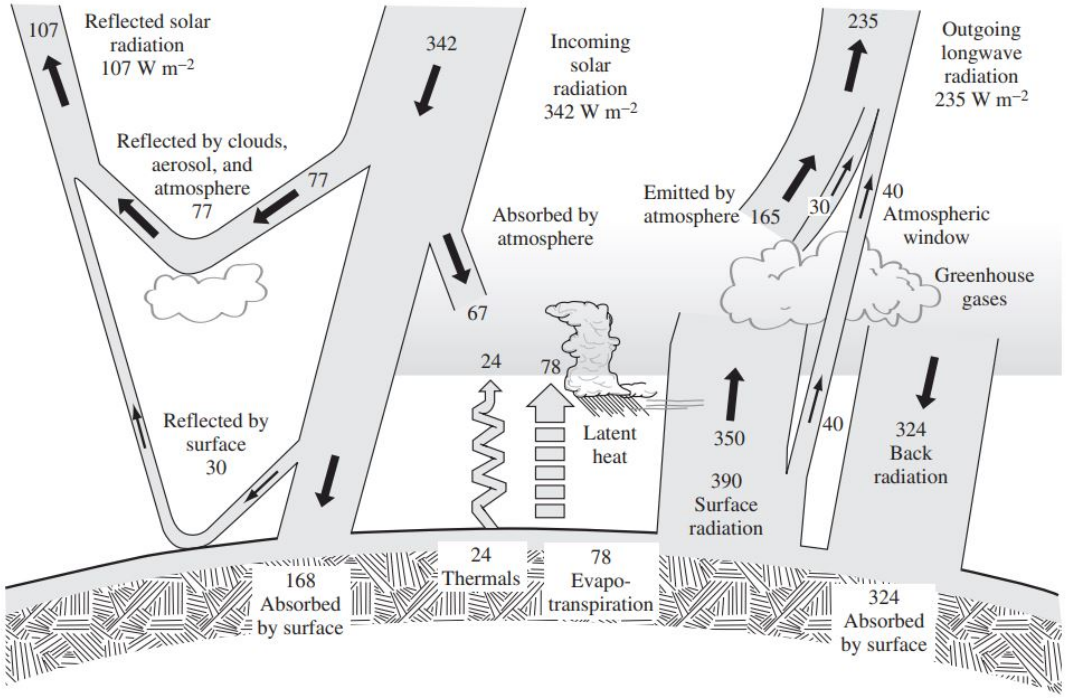


Figure 2: Global energy equilibrium model

Solar Constant (S_O): It is defined as the amount of solar radiation incident per unit time, per unit area on the outer atmosphere of Earth, when it is at a distance of 1 AU from sun. $S_O \simeq 1370\ W/m^2$. It is fairly constant, increasing by only 0.2% at the peak of each 11-year solar cycle, also called *Schwabe Cycle*.
Incoming solar flux distributed over entire surface of Earth, $Q_{in} \equiv \frac{S_O \pi R^2}{4\pi R^2} = \frac{S_O}{4}$.
The amount of incoming radiation reflected back into space per square meter of the Earth's surface is, $Q_{ref} = \alpha \times Q_{in} = \frac{S_O}{4}.\alpha$
Hence, the amount of energy actually absorbed by Earth, $Q_{abs} = Q_{in} - Q_{ref} = \frac{S_O}{4}(1-\alpha) = \sigma T_E^4 = Q_{rad}$ (if balanced).

Note that: $\alpha = 0.31$ is albedo of Earth.

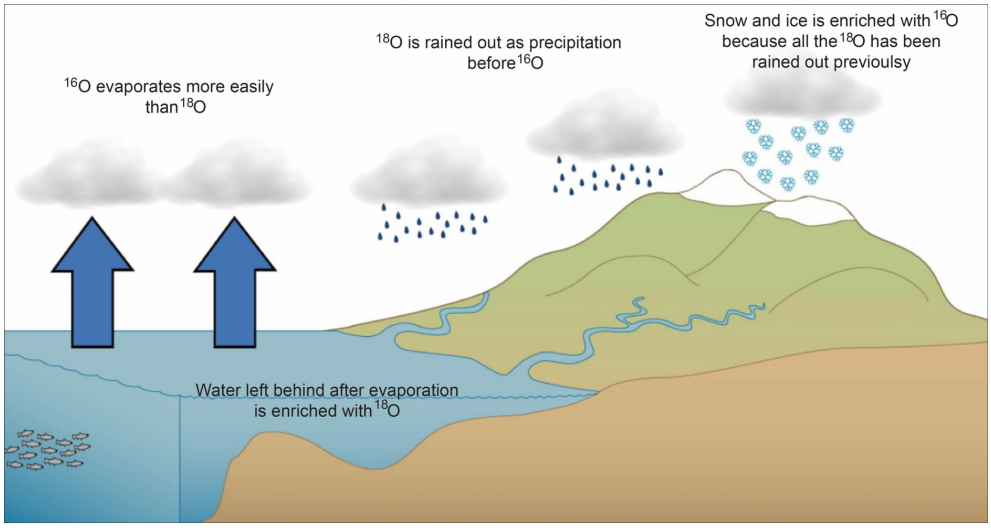


Figure 3: ^{18}O cycle

2.3 δ^{18}O Method

`Refer to 1st year notes on Variation of temperature with altitude and Milankovitch cycles.`

At this point it is necessary to understand the movement of ^{18}O and ^{16}O in Earth's atmosphere.

Note that:

$$\delta^{18}\mathrm{O} = \left[\frac{(^{18}\mathrm{O}/^{16}\mathrm{O})_{sample}}{(^{18}\mathrm{O}/^{16}\mathrm{O})_{std}} - 1\right] \times 10^3$$

where, the standard is set by VSMO (Vienna Standard Mean Ocean Water)

$\rightarrow$ $^{2}\mathrm{H}/^{1}\mathrm{H} = 0.00015575$

$\rightarrow$ $^{18}\mathrm{O}/^{16}\mathrm{H} = 0.0020052$

The ^{18}O cycle it is often used as a paleoclimate proxy to reconstruct past climatic conditions.

1. **Evaporation:** The cycle begins with the evaporation of water from the Earth's surface, primarily from oceans, lakes, and rivers. During this process, lighter water molecules (with ^{16}O) tend to evaporate more readily than heavier ones (with ^{18}O).

2. **Atmospheric Transport:** The evaporated water molecules rise into the atmosphere and form clouds. As they travel through the atmosphere, they can undergo various processes such as condensation, precipitation, and mixing.

3. **Precipitation:** When clouds containing water vapor cool, they precipitate in form of rain/snow. In this case ^{18}O will be readily precipitated than ^{16}O.

4. **Affect of climatic cooling:** Now if the atmospheric temperature cools, then all of the ^{18}O shall be precipitated out before it reaches the poles. Thus more ^{18}O is left behind in the ocean. This causes polar icecaps to be enriched in ^{16}O isotope.

5. **Incorporation into Ice and Sediments:** Some of the precipitation can fall as snow and accumulate in ice caps and glaciers or be incorporated into sediments, depending on the location and climate conditions. This preserved water can retain information about past atmospheric conditions, acting as a sort of "archive" of past climate.

Note that: From this cycle obtain an **important** analogy:

- More δ^{18}O in polar ice caps *or* Less δ^{18}O in equatorial ocean waters $\implies$ **Hotter** climate.
- Less δ^{18}O in polar ice caps *or* More δ^{18}O in equatorial ocean waters $\implies$ **Colder** climate.

2.4 From Marine Sediments

As the world's ice volume increases, it selectively removes ^{16}O from the hydrologic cycle and concentrates the remaining ^{18}O in the decreasing volume of the oceans. Hence, marine organisms that build their shells out of calcium carbonate in seawater will have a higher ratio of ^{18}O to ^{16}O in their shells when it is cold and more of the world's water is locked up in glaciers and ice. By dating marine sediments extracted from deep sea cores, and observing the ratio of the two oxygen isotopes in their carbonates, a historic record of the volume of ice storage on Earth can be created. Observe Fig 4.

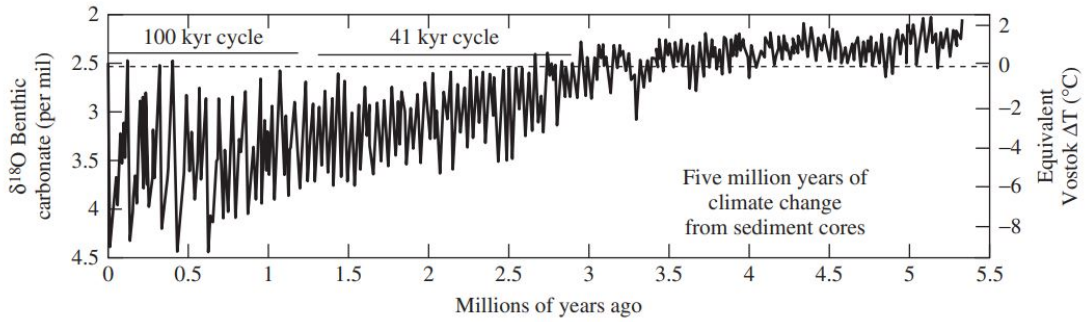


Figure 4: Five million years of climate change from deep sea sediment cores.

A relationship between the mean annual surface temperature of Greenland and the value of δ^{18}O of the snow pack on the Greenland ice sheet is given by-

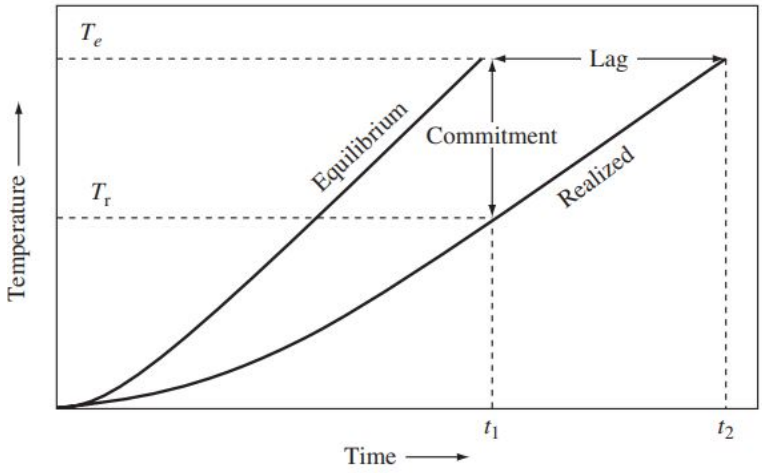
$$T(^{\circ}C) = 1.5\ \delta^{18}\text{O} + 20.4$$

Inferences

- More variation/spikes are seen near present time- due to glacials and interglacials- which are caused due to change of insolation, solar activity reaching Earth (Milankovitch cycles).
- Notice the isotope record in ocean sediments moves in the opposite direction to the isotope record in glacial ice.
- Warmer temperatures cause decrease of ^{18}O in in oceans and sediments.
- While, warmer temperatures increases ^{18}O in that year's layer of glacial ice.

3 Week 3

3.1 Equilibrium Temperature and Realized Temperature



The surface temperatures dealt with thus far, T_e and ΔT_e are known as *equilibrium temperatures*; they are temperatures that would eventually be reached for a given atmospheric configuration.

In reality, of course, the temperature of the Earth will not adjust instantaneously to changes in greenhouse gas concentrations. A considerable period of time is needed to warm the upper layer of the oceans and the surface of the land, which means **the actual realized surface temperature of the Earth will lag somewhat behind the equilibrium temperature.**

Suppose at time t_1, a change in greenhouse gas emission is observed, then we will still perceive the *realized temperature*, until it rises to an actual temperature of T_e, at time time t_2.

At any given time, the difference between realized and equilibrium temperature is referred to as the temperature *commitment*, while the time it takes to achieve equilibrium is the *lag time*. Coupled atmosphere-ocean general circulation models indicate that the realized temperature is roughly 60 to 85 percent of the equilibrium temperature.

Problem 1 Direct greenhouse gas radiative forcing in the mid-1990s is estimated to be about 2.45 W/m^2. If realized temperature is 75 percent of equilibrium temperature, what negative forcing by aerosols, and so on, would be needed to match the $0.6°C$ realized global temperature increase actually observed? Assume that an appropriate climate sensitivity factor is 0.57.

Solution: $\Delta F_{\text{aero}} + \Delta F_{\text{greeng}} = \Delta F_{\text{Actual}}$. To find Forcing due to Aerosols?
Given, $\Delta T_r = 0.6°C = 0.75 \times \Delta T_E$. So, $\Delta F_{\text{Actual}} = \Delta T_E/\lambda = 0.8/0.57 = 1.4$ W/m^2. So $\Delta F_{\text{aero}} = -2.45 + 1.4 = \boxed{-1.05}$ W/m^2

4 Week 4

4.1 Effect of Aerosols

Note that: Radiatively active gases that absorb wavelengths longer than $4\mu m$ are called greenhouse gases. Gases and particulate matter added to the atmosphere can exert both direct and indirect radiative forcing effects. *Direct* forcing is caused by substances in the atmosphere that have actually been emitted from some source. *Indirect* forcings are those that occur when those substances go on to cause other atmospheric changes that affect radiative properties of the atmosphere. They have *short lifetimes* in atmosphere compared to greenhouse gases.
Suspensions of particles having an effective diameter of less than 10μm is called aerosol. It's sources include:

- *Anthropogenic*- Combustion of fossil fuels and biomass
- *Natural*- wind-blown soil dust, evaporation of sea-spray droplets, and volcanic eruptions

Properties

Interestingly, aerosols show both cooling and heating effects.

Heating-

- It contributes to greenhouse effect, by absorbing longwave radiation.
- Aerosols are easily transported and deposited on ice/snow, thus melting them and destroying their albedo (Black carbon.)

Cooling-

- Sulphates(volcanic eruptions) increase the albedo of clouds, by reflecting more sunlight.
- They also felicitate the formation of clouds, by providing cloud condensation nuclei.

4.2 Removal of methane in atmosphere

Methane is removed from the atmosphere primarily through reactions with the hydroxyl radical (OH), as the following reaction suggests-
$\mathrm{CH_4 + OH + 9\,O_2 \longrightarrow CO_2 + 0.5\,H_2 + 2\,H_2O + 5\,O_3}$

But note that apart from direct effects there are a number of indirect effects that provide additional impacts, which the above reaction helps to explain:

1. When methane reacts with hydroxyl (OH), the concentration of OH decreases. With less OH available, the rate of removal of slows down, lengthening the atmospheric lifetime of the remaining methane. With a longer lifetime for in the atmosphere, it continues to absorb infrared for a longer time, increasing its global warming potential.
2. As methane reacts with hydroxyl, it produces water vapor. When this reaction occurs in the troposphere, the increase in water vapor is insignificant, but in the stratosphere it becomes quite important.
3. Finally the reaction indicates the destruction of methane produces an increase in ozone, which is itself a greenhouse gas. The sum of all of these indirect effects greatly increases methane's climate impact.

4.3 Radiative Forcings and Climate Change

Note that: The units of ΔF & ΔQ are W/m^2. Make sure to divide by the Area (of Earth) !!
Initially, the balanced system has energy absorbed equal to energy radiated:

$$Q_{abs} = Q_{rad}$$

After it is perturbed by a radiative forcing-

$$(Q_{abs} + \Delta Q_{abs}) + \Delta F = Q_{rad} + \Delta Q_{rad}$$

$$\Delta F := \Delta Q_{rad} - \Delta Q_{abs}$$

Note that: $\Delta Q_{abs} = \Delta Q_{in} - Q_{ref} = \frac{S}{4}(1 - \alpha)$

For a given change in radiative forcing, the change in equilibrium surface temperature of Earth is related by a quantity called **Climate Sensitivity Parameter**(λ).

$$\Delta T_s = \lambda \Delta F$$

$$\Rightarrow \lambda = \left(\frac{\delta Q_{rad}}{\delta T_s} - \frac{\delta Q_{abs}}{\delta T_s} \right)^{-1}$$

Given is an empirical relationship-

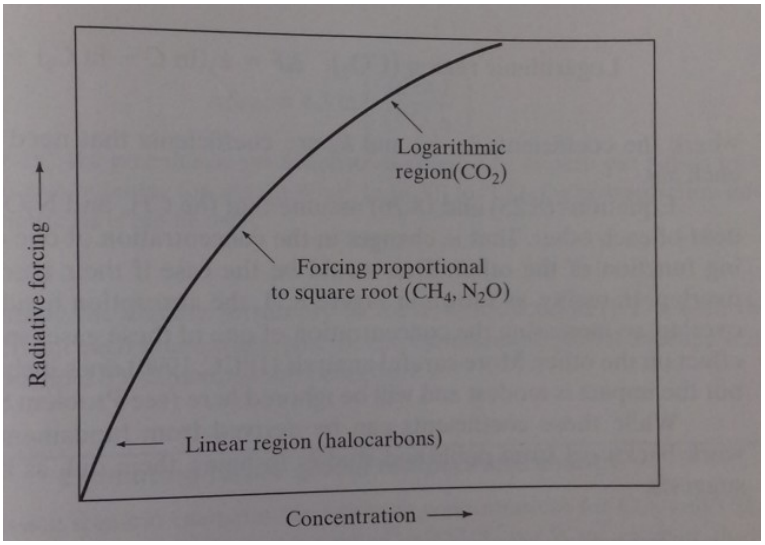
$$Q_{rad}(W/m^2) = 1.83\ T_s(^\circ C) + 209$$

Problem 2 It is believed that doubling the atmospheric conc. of carbon dioxide causes a radiative forcing of 4.35 W/m^2. If the earth's albedo, doesn't change, then estimate the CSP and use it to estimate the eventual change in surface temperature of earth needed to balance the incoming and outgoing radiation.

Solution: $\Delta F = \Delta Q_{rad} - \Delta Q_{abs}$
Now, albedo of earth = const. $\therefore \Delta Q_{ref} = 0 \implies \Delta Q_{abs} = 0$
So, $\Delta F \equiv 4.35 = 1.83\ \Delta T_s \implies \Delta T_s = 2.38$
Similarly $\lambda = 1/1.83 = 0.546$ C° - m^2/W. **Ans**

5 Week 5

5.1 Radiative Forcings with change in greenhouse gas concentration



The radiative forcing must indeed be a function of green-house gas concentrations, with $\Delta F = f(C) - f(C_0)$.

- $\Delta F_1 = k_1(C - C_0) \rightarrow$ Halocarbons
- $\Delta F_2 = k_2(\sqrt{C} - \sqrt{C_0}) \rightarrow CH_4$, N_2O
- $\Delta F_3 = k_3 \ln\left(\frac{C}{C_0}\right) \rightarrow CO_2$

So use them to estimate ΔT_i for a given λ.

5.2 Carbon content of atmosphere

How do we find relation between the conc. of CO2 and amt of carbon in atmosphere?

To be Remembered!

1 ppm (CO_2) $\equiv$ 2.12 Gton of C

The *airborne fraction* of CO2 is the fraction of anthropogenic CO2 emissions that remains in the atmosphere after natural processes have absorbed some of them. At present it is $\simeq 38\%$. Which means about 38% of the CO_2 that humans emit into the atmosphere remains there.

Total mass of atmosphere = 5.12 $\times 10^{21}$ kg
1 mol of gas occupies = 22.4 L = $\frac{22.4}{1000}$ $m^3 = V_0$
Let, molecular wt. of a gas be, M g/mol, with it's percentage in atmosphere = p $\in (0, 1]$
Then its density is calculated as- $\rho = p \times M/V_0$

6 Week 6

6.1 Blackbody Sensitivity

The blackbody sensitivity is defined as:

$$\lambda_B = \left(\frac{\mathrm{d}Q}{\mathrm{d}T}\right)^{-1},\ Q = Q_{rad} = \sigma T_e^4$$

It is related to climate sensitivity parameter, by

$$\boxed{\lambda_B = \lambda(1-g)}$$

where g, is the gain factor which can be expressed as sum of individual feedback factors.

6.2 Relationship between CO_2 and Global warming effects

As we pump more and more CO_2 into the atmosphere, the marginal impact of each additional ton decreases as its absorption bands approach saturation. That suggests a nonlinear relationship between CO_2 and the resulting global warming that it causes.

$$\frac{\Delta T_e}{\Delta T_{2X}} = \frac{1}{\ln 2} \ln \frac{(CO_2)}{(CO_2)_0}$$

where, ΔT_e is equilibrium, global, mean surface temperature change; ΔT_{2X} is equilibrium temp change for doubling of atmospheric CO_2.

6.3 Energy in Fossil fuels

The amount of carbon released per unit of energy delivered is called the **carbon intensity**. Some fuels have high carbon intensity, such as coal, and some conversion systems release no direct carbon at all, such as wind turbines or nuclear power.

The **higher heating value (HHV)** includes the heat released when water condenses into liquid form after combustion. While, the **lower heating value (LHV)**, or net heat of combustion, is based on the heat of reaction when water is assumed to remain in the vapor state.
LHV efficiency = HHV efficiency - (energy required for water vaporization/energy content of the fuel)

$$\text{Carbon Intensity (gC/kJ)} = \frac{\text{Amt of } \textit{Carbon} \text{ liberated (g/mol)}}{\text{LHV or HHV kJ/mol}}$$

kJ/mol	**LHV**	**HHV**
Natural Gas	15.3	13.8
Petroleum	20	19.7
Coal	25.8	24.2

The *Carbon Emission Rate* ($\mathcal{C}$) determines how nature friendly a fuel ζ (of Molar wt. M) is. Lower values of $\mathcal{C}$ is preferred.

$$\mathcal{C} = \frac{\text{g } CO_2\text{-eq released (including leakage)}}{\text{Total energy output (MJ)}}$$

g CO_2-eq = Energy leaked/used (MJ)×(LHV or HHV (gC/MJ))×GWP (g CO_2/ g ζ)×(M gζ/ 12n C)

7 Week 7

7.1 Estimating Carbon Emissions: Kaya Identity

This is a model which is used to predict the future carbon emissions rate(C) by taking into account various factors like population, GDP affluence and technology- all of which are modelled exponentially.

$$\begin{aligned} C(t) &= P(t)G(t)E_n(t)C_I(t) \\ C(t) &= C_o e^{rt} \\ r &= r_{pop} + r_g + r_{en} + r_i \end{aligned}$$

It is measured in GtC/yr. Thus the cumulative emissions from a quantity growing exponentially at a rate r, over a period of time T is given by-

$$C^T_{tot} = \int_0^T C_o e^{rt} \mathrm{d}t = \frac{C_o}{r}(e^{rT} - 1) \text{ GtC}$$

For the world, $r = (1.4 + 1.53 + -0.97 - 0.24)\% = 1.72\%$/year. Therefore, the new CO_2 concentrations(ppm) after T years, is

$$\boxed{(\mathrm{CO_2})_{2023+T} = (\mathrm{CO_2})_{2023} + \frac{(C^T_{tot} + C_{land} + \dots) \times f_A}{2.12\text{Gtc/ppm}}}$$

where $f_A = 0.38$ (generally) is the **airborne fraction**. It is the ratio of the amount of Anthropogenic carbon emitted to the amount that remains in the atmosphere. If deforestration $\uparrow$, CO_2 reduction $\downarrow \implies f_A \uparrow$, and vice -versa if plant growth and vegetation increases.

7.2 Global Warming Potential

The Global Warming Potential (GWP) is a weighting factor that allows comparisons to be made between the cumulative global warming impact over a specified period of time of some greenhouse gas and a simultaneous emission of an equal mass of CO_2.

There are three primary factors that affect GWPs. The first is the *radiative forcing* associated with the addition to the atmosphere of a unit mass of each greenhouse gas. The second is based on estimates of the *rate* at which that unit mass injected *decays over time*. The third is related to the *cumulative radiative forcing* that the unit addition to the atmosphere will have over some period of time into the future.

$$G.W.P_g = \frac{\int_0^T F_g R_g(t)\mathrm{d}t}{\int_0^T F_{\mathrm{CO_2}} R_{\mathrm{CO_2}}(t)\mathrm{d}t}$$

For most greenhouse gases, injection of 1 kg into the atmosphere decays exponentially with time (but not CO_2), so their GWP equation can be simplified into-

$$G.W.P_g = \frac{\int_0^T F_g R_g(t)\mathrm{d}t}{\int_0^T F_{\mathrm{CO_2}} R_{\mathrm{CO_2}}(t)\mathrm{d}t} = \frac{F_g}{F_{\mathrm{CO_2}}} \frac{\int_0^T e^{-t/\tau}\mathrm{d}t}{\int_0^T R_{\mathrm{CO_2}}(t)\mathrm{d}t}$$

where τ is the residence time or the atmospheric lifetime of the gas. The integral of impulse function of $CO_2 = \int_0^T R_{\mathrm{CO_2}}(t)\mathrm{d}t$ for T = 20, 100, 500 is $\simeq$ 13.2, 43.1, 138 yrs respectively.

Note that: $G.W.P_{\mathrm{CO_2}} = 1 \ \forall \ T$. The 100-year GWPs are often used to describe non-CO_2 emissions in terms of carbon dioxide equivalents (CDE, or CO_2-eq). The total carbon dioxide equivalence of the combined emissions of gas g, over period T_g is:

$$\sum_g [(GWP)_{T_g} \times \text{Annual Anthropogenic emission (Mt/yr)}] = E \text{ MtCO}_2\text{-eq}$$

$$\frac{12}{44} \times \text{ MtCO}_2\text{-eq} = \text{ MtC-eq}$$

7.3 Ice Core

Ice core samples are taken from a region known as *ice divide*. At the ice divide, the ice motion is predominately vertical downward and sluggish so that ice deposited as snow on the surface at this one location accumulates there for a long time. Due to the spreading of the ice flow lines, a block of ice deposited at the surface is horizontally stretched as it descends, which causes the block to thin vertically.



Figure 5: Ice core sample taken from drill. Source: http://www.ncdc.noaa.gov/paleo/globalwarming/gallery.html

Thus, the age of ice increases exponentially with depth beneath the ice divide. By extracting a core of ice at, or near, an ice divide, one can obtain a continuous record of atmospheric sediment that contains more and more years per length of core near the bottom. Every ice core is characterised by a time constant (τ).

$$\tau = H/\dot{a}$$

For an ice sheet of thickness H in equilibrium with a climate supplying accumulation at a rate $\dot{a}$ (thickness of ice per unit time), the vertical velocity near the ice-sheet surface is $\dot{a}$ and this velocity decreases to zero at the ice-sheet bed. Clearly *high resolution* ice core sample are found at regions with higher accumulation rate. While samples from regions with low $\dot{a}$ have poor resolution as it contains a lot of unconformity due to melting of ice, which results in loss of information.

Age difference between trapped gas bubbles and surrounding ice: A very important complication in interpreting ice core records, and in defining depth-age relations, is the fact that snow transforms to ice 50 to 100 m below the surfaces of most polar ice sheets. This means the gas trapped in ice is actually younger than the solid ice at the same depth (Fig 6 (b)), and that a variety of processes can transport and redistribute gases in this snowy upper layer (called the *firn*). At the ice-sheet surface, motion of water vapor very rapidly converts faceted and angular snow to solid ice spherules. Subsequently, the weight of overlying accumulation forces these into a more compact configuration by slip at their boundaries and creep deformation. Thereby the density of a given layer steadily increases through time into ultimately glacial ice. Thus there is a

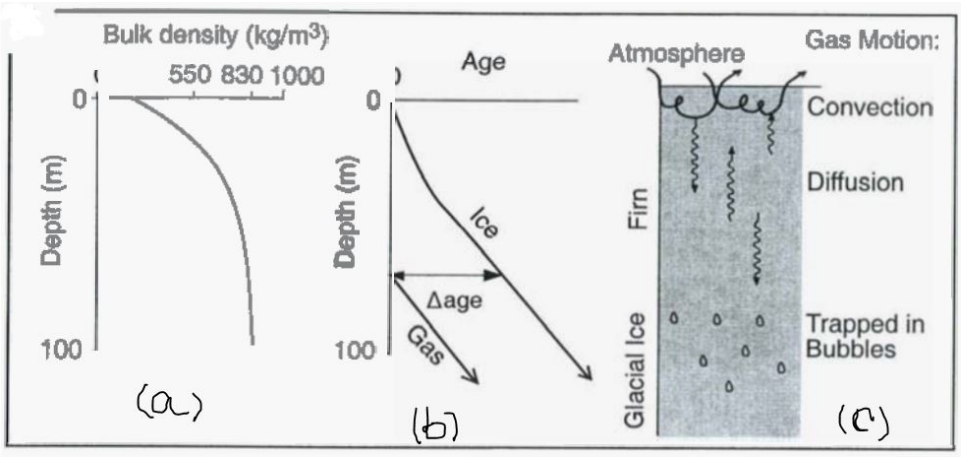


Figure 6: (a) Characteristic density variations, (b) Age-depth relations for ice and gas (c) Mechanism of gas transport.

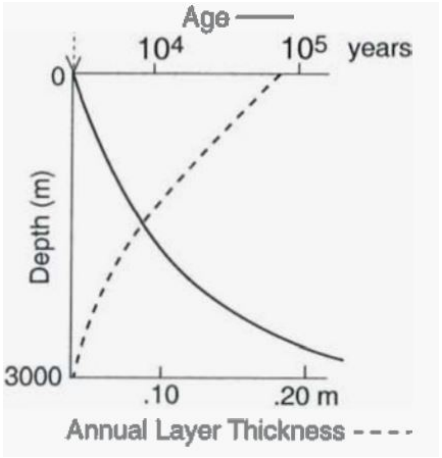


Figure 7: Characteristic depth-age relation and variation of thickness with depth in an ice core.

marked increase of density with depth below the surface, with most of the variation occurring in the upper 100 m. Correspondingly, the air-filled pore spaces between ice grains become smaller and more isolated as depth (or age) increases. These pores are finally isolated as distinct bubbles at a bulk density of around 830 kg/m^3. Above this level, which is generally 40 to 100 m deep, air spaces are interconnected and open to the atmosphere above. This entire zone is called the firn. In the firn, gases are free to move to and from the atmosphere, by wind-driven convection in the upper 10 m and by diffusion below this(Fig 6 (c)). Thus the gas trapped in bubbles is younger than the age of the adjacent ice. This difference of age is called Δ_{age}.

7.4 Dating of events from ice core sample

Once a core is extracted, measurements of seasonally varying properties allow identification of annual layers. Useful seasonally varying properties include dust content, isotopic composition, concentrations of some chemical impurities, electrical conductivity (a proxy for *core acidity*), and physical stratigraphy (seen as variations in transmitted light seen through a sliced core). In addition to such continual counting methods, one can determine the absolute age of ice by identifying the *fallout from volcanic eruptions* of known age. Annual layers must be preserved in the ice sheet for absolute age determination to be possible in this fashion. Annual layer preservation is good at high accumulation-rate sites.

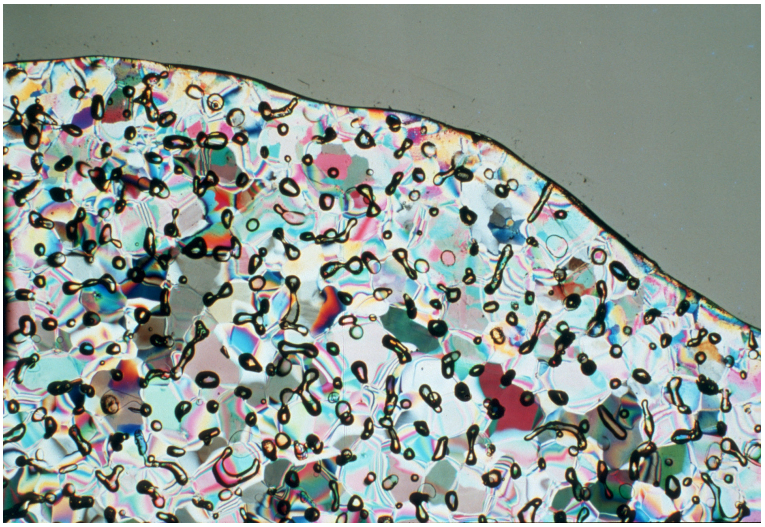


Figure 8: Bubbles in an Antarctic ice sample illuminated with polarised light. Source: http://www.scienceimage.csiro.au/image/518

8 Week 8

Microbial Ecology and their effect on Biogeochemical cycles

Living systems can be classified into various divisions based on various categories:

- **Energy Source-** *photo* if sunlight and *chemo* if by breaking chemical compounds.
- **Electro/ H-atom donor-** *organo* if organic (C_xH_y) and *litho* if inorganic (NH_3)
- **Carbon Source-** *heterotroph* if organic and *autotroph* if inorganic/ atmospheric like CO_2.

Few examples are- *photolithoheterotroph-* purple non sulfur bacteria, *photolithoautotroph-* green plants, *chemolithotrophic aerobic-* Nitrifiers, *chemorganoheterotroph-* me.

8.1 Nitrogen Cycle

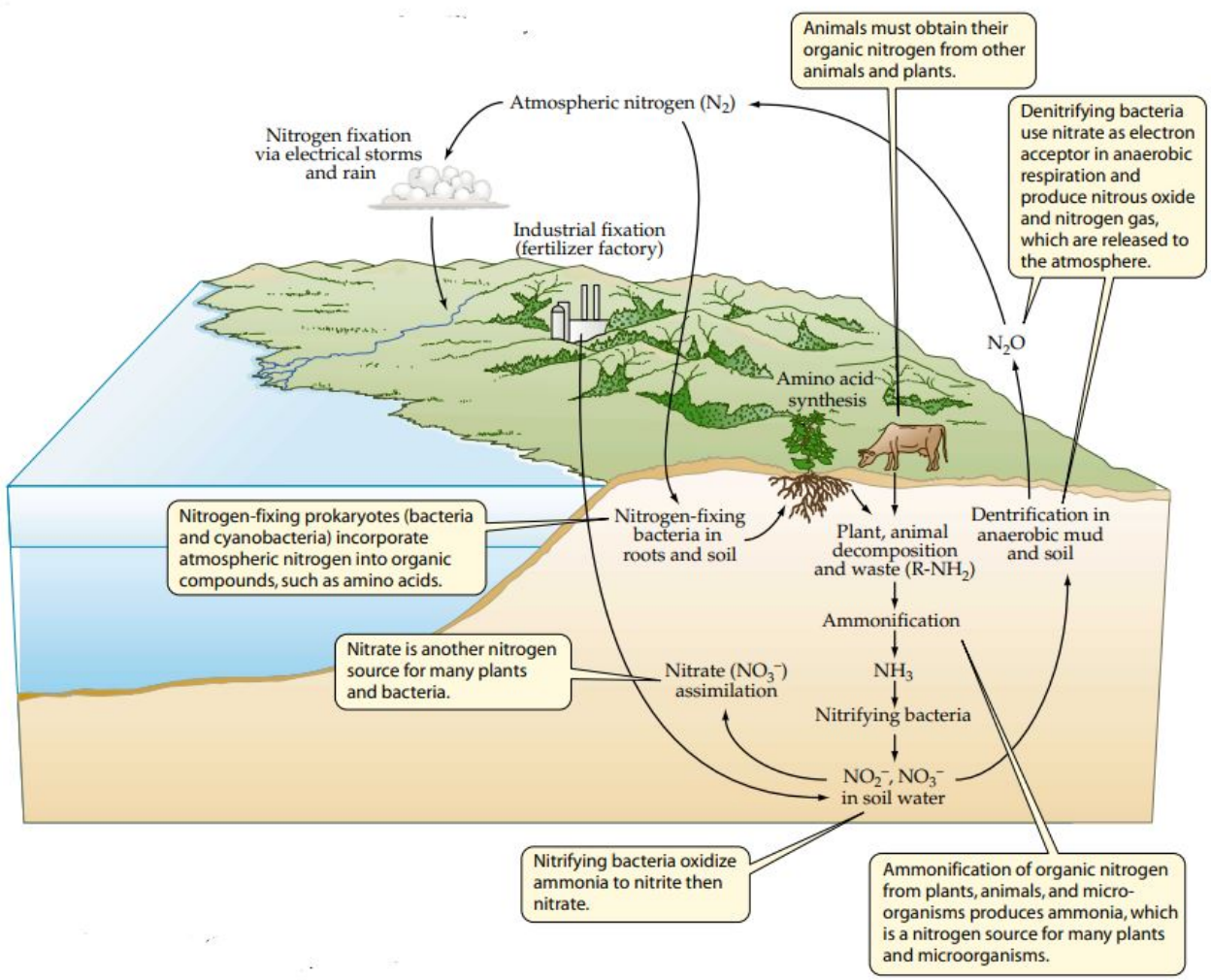


Figure 9: Nitrogen Cycle

There are mainly 2 processes which governs Nitrogen cycle-

8.1.1 Nitrification

Carried out by *chemolithoautotrophs* in aerobic conditions.

- Nitrosomonas
  $\mathrm{NH_4^+} \xrightarrow{\mathrm{O_2}} \mathrm{NO_2^-} + \mathrm{H_2O} + \mathrm{H^+} + \text{energy}$
- Nitrobacter
  $\mathrm{NO_2^-} \xrightarrow{\mathrm{O_2}} \mathrm{NO_3^-} + \text{energy}$

Balancing and adding
$2\,\mathrm{NH_4^+} + 4\,\mathrm{O_2} \longrightarrow 2\,\mathrm{NO_3^-} + 2\,\mathrm{H_2O} + 4\,\mathrm{H^+} + \text{energy}$

8.1.2 Denitrification

Carried out by *chemoorganoheterotrophs* in anaerobic conditions.
$\mathrm{NO_3^-} + \mathrm{CH_3OH} + \mathrm{H^+} \longrightarrow \mathrm{N_2} + \mathrm{HCO_3^-} + \mathrm{H_2O}$

8.2 Carbon Cycle

8.2.1 Carbon Reduction

Carried out by *chemolithoautotrophs* called Methanogens.
$\mathrm{CO_2} + 4\,\mathrm{H_2} \longrightarrow \mathrm{CH_4} + 2\,\mathrm{H_2O}$

8.2.2 Carbon Oxidation

Carried out by *chemoorganoheterotrophs* called Methanotrophs.
$\mathrm{CH_4} + 2\,\mathrm{O_2} \longrightarrow \mathrm{CO_2} + 2\,\mathrm{H_2O}$

8.3 Sulphur Cycle

8.3.1 Sulphur Reduction

Carried out by *chemoorganoheterotrophs* in anaerobic conditions.
$\mathrm{CH_4} + \mathrm{SO_4^{2-}} \longrightarrow \mathrm{HCO_3^-} + \mathrm{HS^-} + \mathrm{H_2O}$

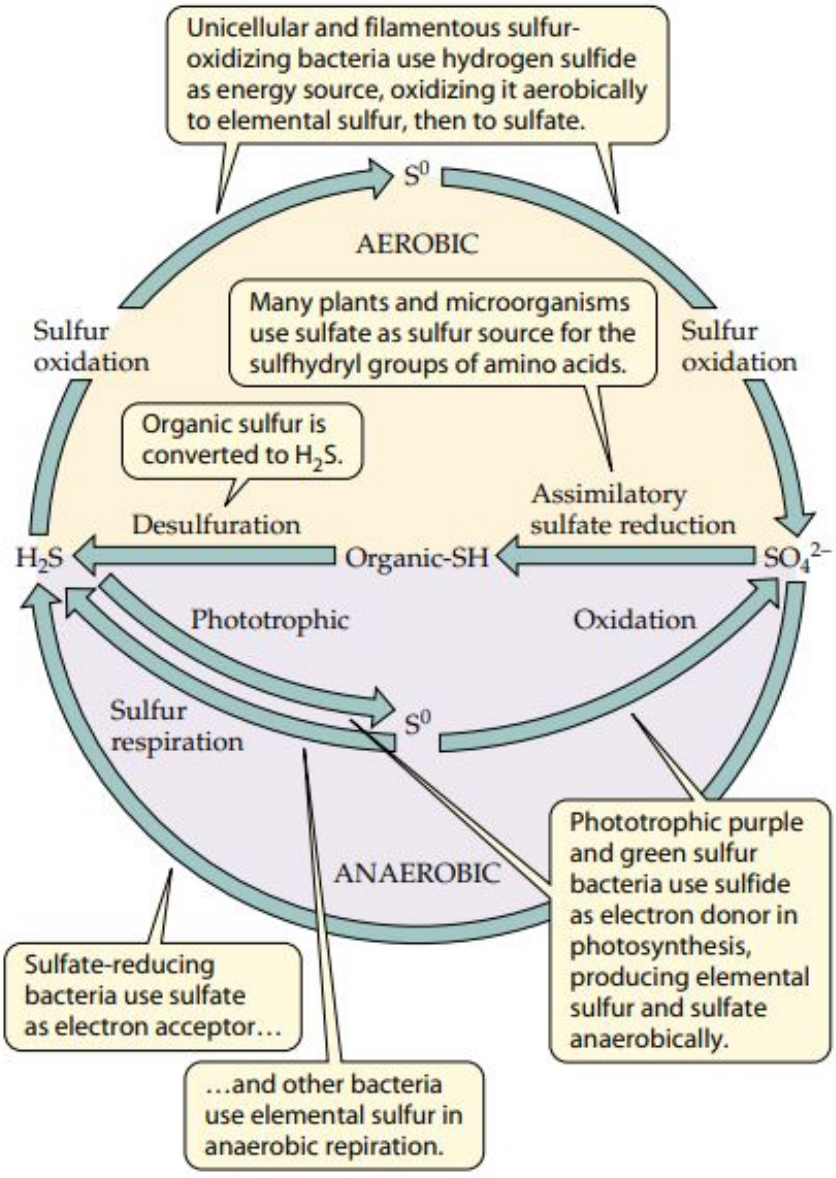


Figure 10: Sulphur Cycle

9 BBC documentary summary

This section contains the summary points of the 5 part documentary series BBC: The Power of the Planet by Ian Stewart. These videos were shown in the class and questions were also asked in the endsemester exams.

9.1 Volcano

The episode explores the power and destructive nature of volcanoes, while also highlighting their crucial role in shaping our planet and nurturing life.

- Volcanoes are a fundamental force on Earth, continuously reshaping the planet's surface and contributing to its overall heat energy.
- Earth's inner heat, generated by trapped radioactive material and the residual heat from its formation, powers volcanic activity.
- This inner heat drives plate tectonics, the movement of the Earth's crust, which creates mountains, continents, and ocean basins.
- Volcanic activity played a crucial role in the origin of life on Earth by providing a warm, chemically rich environment for early organisms to evolve.
- Volcanoes potentially saved Earth from a global snowball event by releasing carbon dioxide and warming the atmosphere.
- The end of Snowball Earth facilitated the emergence of complex life forms, marking a major turning point in the history of life on Earth.
- The episode explores different locations around the world to illustrate volcanic activity and its impact, including Ethiopia, Iceland, New Zealand, and South Australia.

9.2 Atmosphere

- The atmosphere is a vital layer of gas surrounding Earth, essential for life. It protects us from the harshness of space, regulates temperature, and provides oxygen.
- The atmosphere is made up of 5 layers: troposphere, stratosphere, mesosphere, thermosphere and exosphere
- The atmosphere is a fluid, capable of shaping the planet's surface. It transports nutrients across vast distances, fertilizing land.
- Weather is the result of heat moving within the atmosphere, creating storms and other phenomena.
- Early life forms, known as stromatolites, released oxygen into the atmosphere. This oxygen eventually built up, forming the ozone layer and allowing complex life to thrive.
- Burning fossil fuels releases carbon dioxide into the atmosphere, trapping heat and causing global warming. Melting permafrost, caused by warming temperatures, has the potential to release large amounts of methane, a powerful greenhouse gas.

9.3 Ice

- Ice is more than just frozen water. It has extraordinary power to shape the planet, carve landscapes, and even influence human evolution. These massive rivers of ice are nature's bulldozers, capable of reshaping landscapes and carving out dramatic features like *El Capitan* in Yosemite.
- Glaciers are formed from snow, not frozen water. Each snowflake is unique, and as layers of snow accumulate and compress, the air is forced out, transforming it into ice.
- They have carved out many of our most dramatic landscapes, including the Yosemite Valley and Manhattan Island. Their influence on the Earth's climate is also significant.
- By exploring the tunnels within a glacier, we can see firsthand how it works and how the ice interacts with rock, grinding and polishing the surface. These pockets of water within the ice help explain how glaciers can flow and deform, despite appearing solid from the outside.
- Ice ages have come and gone throughout Earth's history, and we are currently living in a relatively warm period within an ice age. However, the impact of human activity on the climate is raising concerns about the future of our planet's ice.

9.4 Oceans

- Role of Phytoplankton: Phytoplankton, though tiny, play a vital role in the oceanic ecosystem. They are the foundation of the ocean food chain and produce about 50% of Earth's oxygen through photosynthesis.
- Ocean Currents: The oceans' power extends to a vast network of currents that connect all oceans, distributing nutrients, oxygen, and heat. The Gulf Stream, a warm current, influences the climate in regions like the British Isles.
- Ocean Conveyor: The Great Ocean Conveyor is a powerful system of currents linking surface and deep waters globally. It transports oxygen, nutrients, and warmth, affecting climate and sustaining life.
- Historical Catastrophe: The collapse of the ocean conveyor 250 million years ago led to a mass extinction event, emphasizing the critical role of ocean systems in maintaining life
- **Oceanic Sensitivity:** The example of golden jellyfish in Palau illustrates the sensitivity of marine life to temperature changes, emphasizing the potential consequences of global warming.
- **Ocean Acidification:** Increased carbon dioxide leads to ocean acidification, endangering coral reefs and potentially impacting phytoplankton, with unknown consequences for life on Earth.
- Uncharted Territory: The stability of the oceans for millions of years is changing due to human activities, and the full implications of these changes remain uncertain.
- Current Threats: Present-day threats include human-induced climate change and ocean acidification due to increased carbon dioxide levels, potentially causing coral reef degradation and impacting phytoplankton.
- Call for Conservation: The oceans are fundamental to all life on Earth, and as human activities alter their temperature and chemistry, there is a call for conservation to ensure the health and survival of the planet.

9.5 Rare Earth

- The rarity of planets like Earth is discussed, introducing the **rare earth** theory. This theory suggests that while simple life forms may be common in the universe, the evolution of complex life, like plants and animals, requires a sequence of extraordinary events. The series emphasizes the incredible good fortune that has led Earth to become a home for diverse and rich life over four and a half billion years.

- A pivotal event in Earth's history is highlighted—the collision with a twin planet called *Theia* shortly after its formation. This collision led to the creation of the Moon, increased Earth's gravity, and played a crucial role in shaping the planet's atmosphere, magnetic field, and climate stability.

- The importance of Earth's atmosphere in protecting the planet from meteorites is illustrated through examples of meteorite craters, emphasizing the rarity of such large impacts. The atmosphere's protective role is further demonstrated through the work of scientists studying meteorites, particularly those with corner reflectors placed on the Moon by Apollo astronauts.

- It also explores how the Moon, with its gravitational effects, contributes to Earth's climate stability and prevents wild climatic swings. It introduces the work of scientists like Jerry Wyant, who measures the distance to the Moon and reveals that the Moon is gradually moving away from Earth, though this process will take billions of years.

- The narrative continues by highlighting Earth's fortunate position in the solar system, with the right distance from the Sun to support liquid water—the essential ingredient for life. The long lifespan of Earth's sun is noted as a crucial factor that allowed complex life to evolve over billions of years.

- **Jupiter's** role as Earth's protector is discussed, emphasizing its massive gravitational field that attracts and deflects dangerous objects that could otherwise collide with Earth. The series suggests that, considering all these factors, Earth might indeed be a rare planet capable of supporting complex life in the vast universe