Carbon Cycle

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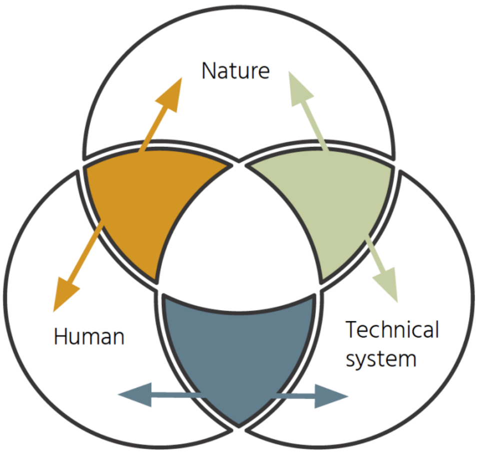
1. Introduction to carbon

1.1. Why are we talking about carbon?

- There are interactions between nature, the technosphere and human organizations.
- This cycle is disturbed by anthropogenic activities.



1.2. What is the link with the project?

Technical system				S <=> N	N <=> H	S <=> H
Stages	Description	Cause / Consequence	Modeling scale			
First life cycle stage : Conception		Cause	Macro			
			Meso			
			Micro			
		Consequence / impacts	Macro			
			Meso			
			Micro			
...						

1.3. What will you learn?

- Know the different resevoirs of carbon and how the carbon cycle works.
- Know the anthropogenic causes of the disruption of the carbon cycle.

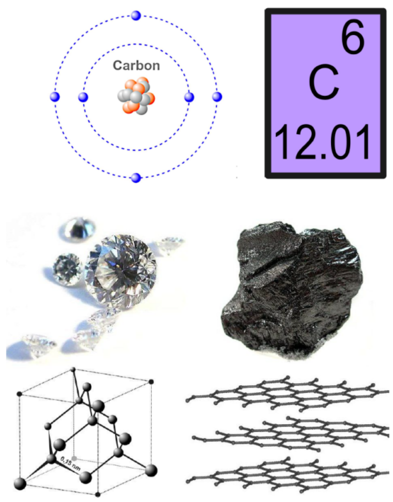
The competences developed are :

- systemic thinking
- critical thinking

1.4. What is carbon?

Définition

"Carbon : the building block of life. You may have heard this sentence, but have you fully considered what it really means? All living things are made of elements, the most abundant of which are, oxygen, carbon, hydrogen, nitrogen, calcium, and phosphorus. Of these, carbon is the best at joining with other elements to form compounds necessary for life, such as sugars, starches, fats, and proteins. Together, all these forms of carbon account for approximately half of the total dry mass of living things."



Carbon atom model, diamond and graphite

(Sundqvist, 2021)

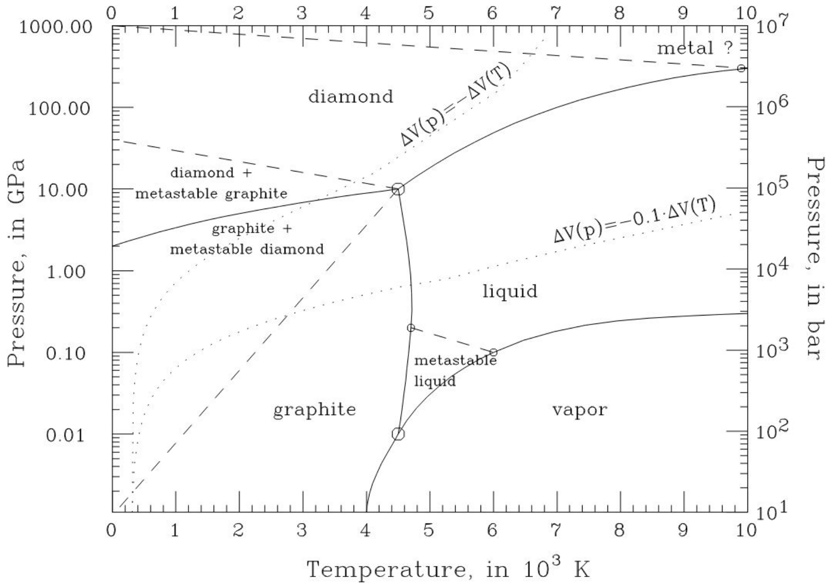
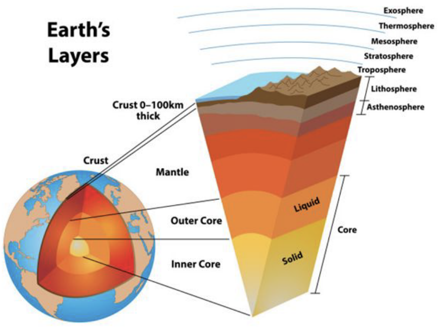


Figure : Phase diagram of carbon taken from
http://cds.cern.ch/record/691793/files/project-note-78.pdf

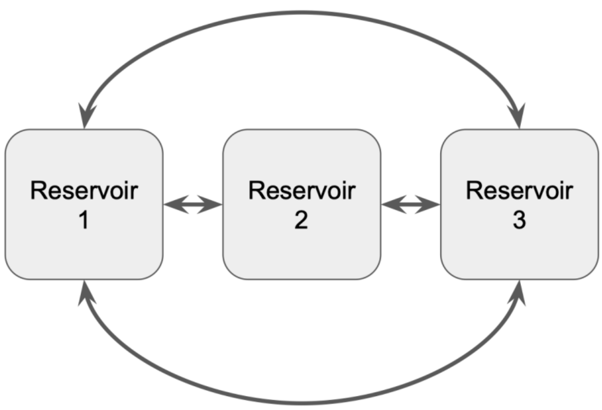
1.5. Reminder : Earth's Layers

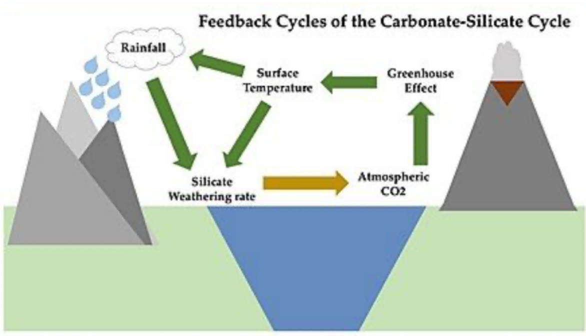


Video to watch
https://www.youtube.com/watch?v=QCKr-rP_o5U

2. Carbon Reservoirs

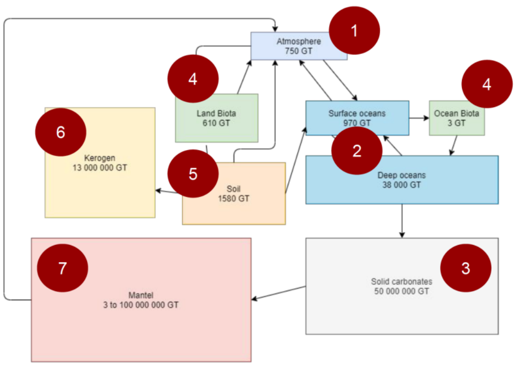
2.1. The concept of reservoir





source : Wikipedia

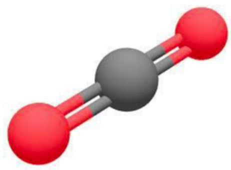
2.2. Carbon reservoirs



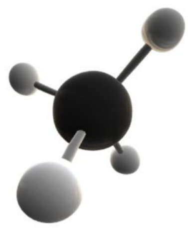
The global carbon-cycle showing the different reservoirs for carbon and the exchanges between reservoirs in GT (109) . The arrows represent natural processes of carbon transfer between atmosphere and earth.

Reservoir 1 : Atmosphere

- CO_2



- CH_4



Reservoir 2 : Ocean

- ⅔ of the Earth's surface.
- store and transporte heat.
- making the atmosphere warm and moist.
- enable life to flourish in the sea and on land.

Table 1.1 Properties of water and their implications for the ocean.

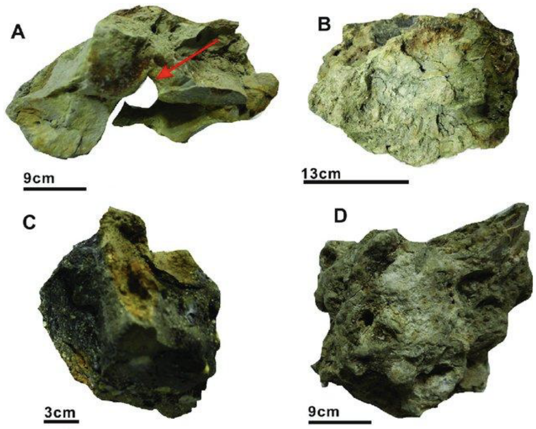
Property	Definition	How water compares with other substances	Implications for the ocean and climate system
Specific heat capacity	Heat required to raise temperature of a unit mass by 1 K.	Highest for all liquids and solids (except NH_3).	Limits temperature range over the Earth.
Latent heat of evaporation	Heat required to evaporate a unit mass.	Highest.	Phase changes are important for the storage and release of heat.
Solvent power	Ability to dissolve substances.	Highest.	Ocean has a high storage of dissolved elements, including nutrients.
Surface tension	Attraction of liquid surface to itself.	Highest.	Bubbles and drops form, which enhance the air–sea transfer of water and gases.
Conduction of heat	Transfer of heat between molecules.	Highest of all liquids.	Heat easily transferred, although turbulence usually dominates.
Molecular viscosity	Resistance to flow.	Less than most liquids.	Ocean easily circulates over the Earth.

- CO_2 (aqueous),
- H_2CO_3 (carbonic acid),
- HCO_3^- (bicarbonate ion),
- CO_3^{2-} (carbonate ion).

DIC = $[CO_2(aq)] + [H_2CO_3] + [HCO_3^-] + [CO_3^{2-}]$

Reservoir 3: Solid carbonates or carbonates rock

Calcite or calcium carbonate, $CaCO_3$

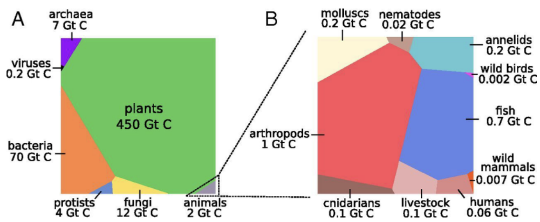


Photographs of typical seep carbonate rocks.

Layers of sedimentary rock in Makhtesh Ramon

Xi, Shichuan, Xin Zhang, Zengfeng Du, Lianfu Li, Bing Wang, Zhendong Luan, Chao Lian, et Jun Yan. 2018. « Laser Raman Detection of Authigenic Carbonates from Cold Seeps at the Formosa Ridge and East of the Pearl River Mouth Basin in the South China Sea ». Journal of Asian Earth Sciences 168 (décembre) : 207-24. https://doi.org/10.1016/j.jseaes.2018.01.023

Reservoir 4: Biomass (oceanic and continental)



- Polysaccharides
- Protein
- Lipids

Graphical representation of the global biomass distribution by taxa.

Bar-On, Yinon M., Rob Phillips, et Ron Milo. 2018. « The Biomass Distribution on Earth ». Proceedings of the National Academy of Sciences 115 (25): 6506-11. https://doi.org/10.1073/pnas.1711842115.

Reservoir 5 : Soil

950 GtC is inorganic carbon.

Credit: Antonio Jordán (distributed via imaggeo.egu.eu)

1500 Gt is organic carbon.

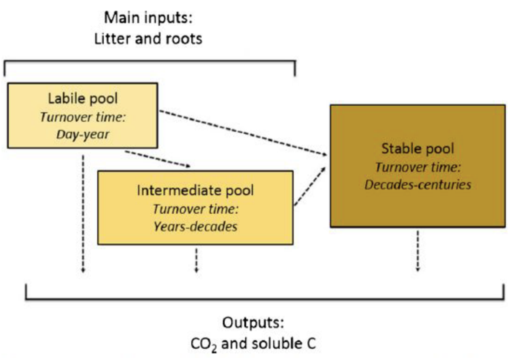
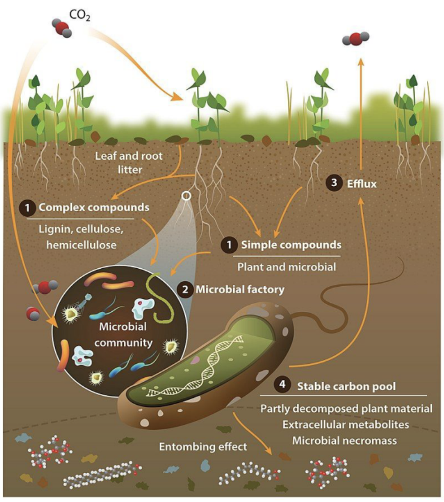


Fig. 1 Conceptual pools of soil C depending on its turnover time: labile, intermediate and stable pools

Dignac, Marie-France, Delphine Derrien, Pierre Barr , S bastien Barot, Lauric C cillon, Claire Chenu, Tiphaine Chevallier, et al. 2017. Increasing Soil Carbon Storage: Mechanisms, Effects of Agricultural Practices and Proxies. A Review . Agronomy for Sustainable Development 37 (2) : 14. https://doi.org/10.1007/s13593-017-0421-2.

Organic matter turnover (EN) = renouvellement de la matière organique (FR)

shoots (EN) = pousses (FR)



Naylor D, et al. 2020.
Annu. Rev. Environ. Resour. 45:29–59

Figure : Soil carbon (C) cycle through the microbial loop. Carbon dioxide (CO2) in the atmosphere is fixed by plants (or autotrophic microorganisms) and added to soil through processes such as ❶ root exudation of low-molecular weight simple carbon compounds, or deposition of leaf and root litter leading to accumulation of complex plant polysaccharides. ❷ Through these processes, carbon is made bioavailable to the microbial metabolic “factory” and subsequently is either ❸ respired to the atmosphere or ❹ enters the stable carbon pool as microbial necromass. The exact balance of carbon efflux versus persistence is a function of several factors, including aboveground plant community composition and root exudate profiles, environmental variables, and collective microbial phenotypes [i.e., the metaphenome (19)].

Naylor, Dan, Natalie Sadler, Arunima Bhattacharjee, Emily B. Graham, Christopher R. Anderton, Ryan McClure, Mary Lipton, Kirsten S. Hofmockel, et Janet K. Jansson. 2020. « Soil Microbiomes Under Climate Change and Implications for Carbon Cycling ». Annual Review of Environment and Resources 45 (1): 29-59. https://doi.org/10.1146/annurev-environ-012320-082720.

Reservoir 6 : Kerogen

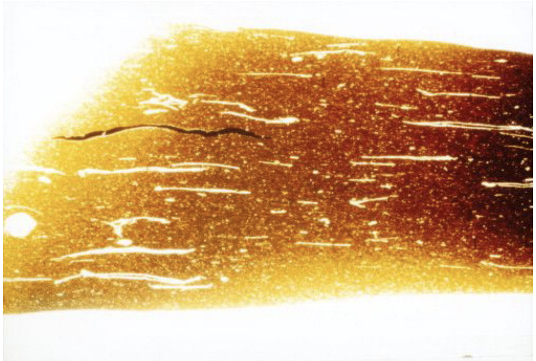
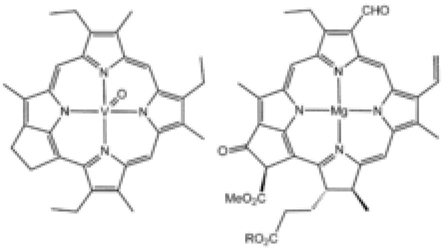


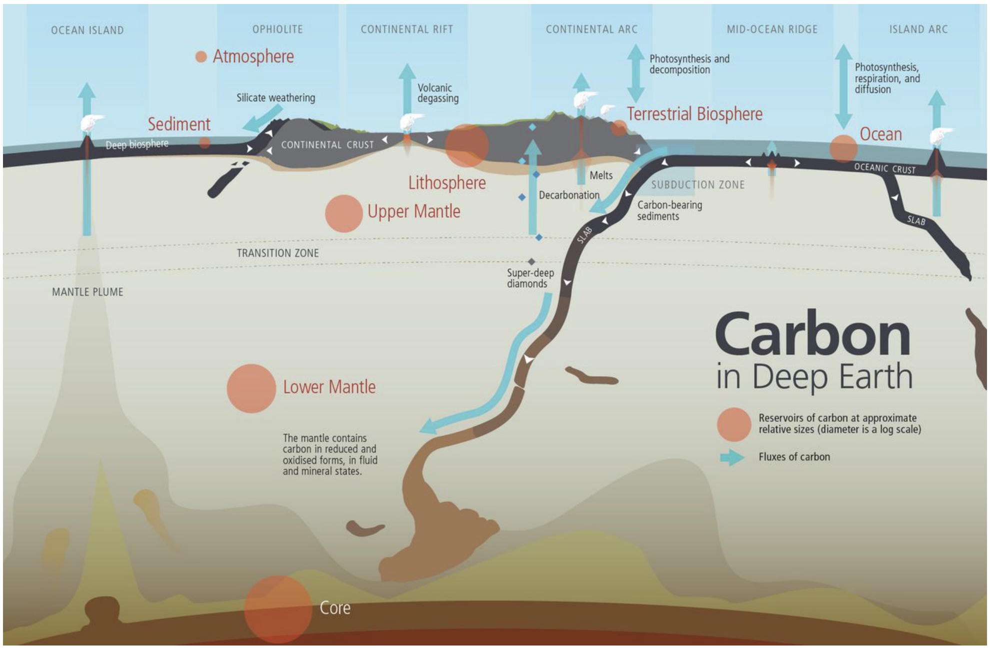
Figure. Photomicrograph of kerogen. This is the sapropelic Kimmeridge Coal (Upper Jurassic) from Dorset, UK. Cross-sections of bivalves are ubiquitous, and carbonized plant detritus is also visible. Reproduced with permission from Selley RC (2000) Applied Sedimentology, 2nd edn. London: Academic Press.



Structure of a vanadium porphyrin compound (left) extracted from petroleum by Alfred E. Treibs, father of organic geochemistry. The close structural similarity of this molecule and chlorophyll a (right) helped establish that petroleum was derived from plants

Kvenvolden, Keith A. 2006. « Organic Geochemistry – A Retrospective of Its First 70 Years ». *Organic Geochemistry* 37 (1): 1-11. https://doi.org/10.1016/j.orggeochem.2005.09.001.

Reservoir 7 : Mantle

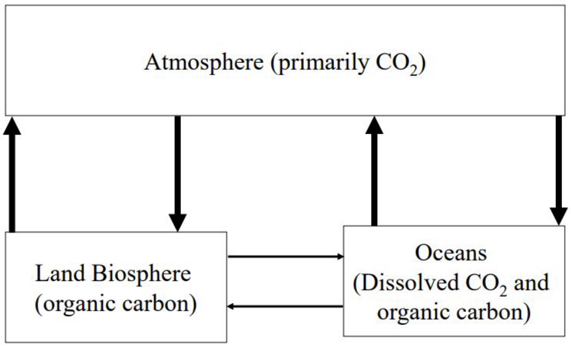


3. Carbon cycle

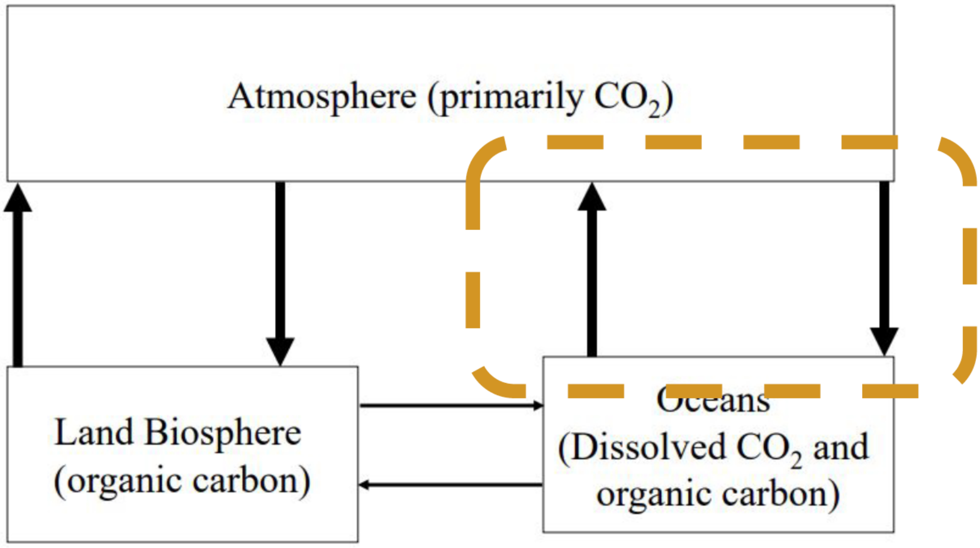
3.1. Short cycle

a) Carbon cycle : Short cycle part 1

SHORT CYCLE



Hydrosphere - atmosphere exchanges



Dissolution of atmospheric CO2 in the ocean and degassing of CO2 from the ocean to the atmosphere

- Exchange of 300 GT of CO2 per year ;
- Residence time = quantity of the element in the reservoir / sum of the flows of contribution in the reservoir.

Video to watch :

Henry's Law and Gas Solubility Explained https://www.youtube.com/watch?v=9JtTpPEesOk

At constant temperature and saturation, the partial pressure in the vapor phase of a volatile solute is proportional to the mole fraction of that body in the liquid solution.

So the higher the temperature, the less CO_2 is soluble, and the more carbon is redistributed to the atmosphere.

For a given amount of carbon in the ocean+atmosphere, the amount of CO_2 in the atmosphere increases if the temperature increases.

CO_2 control : CO_2 balance in the hydrosphere

$$CO_2(g) + H_2O \Leftrightarrow CO_2(aq) + H_2O$$

$$CO_2(aq) + H_2O \Leftrightarrow H_2CO_3$$

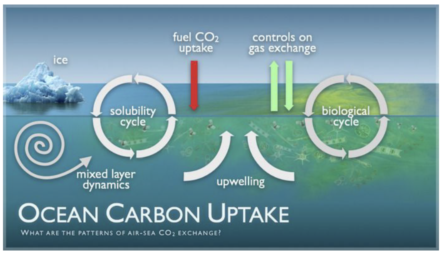
$$Ko = \frac{[H_2CO_3]}{P_{CO_2}}$$

$$H_2CO_3 + \Leftrightarrow H^+ + HCO_3^-$$

$$HCO_3^- \Leftrightarrow H^+ + CO_3^{2-}$$

Ocean pH	Prevailing form
pH<5	H_2CO_3
pH 7-8	HCO_3^-
pH>9	CO_3^{2-}

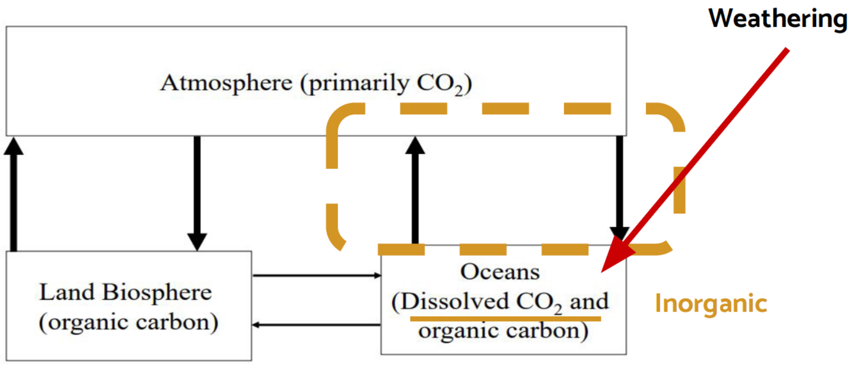
DIC = $[CO_2(aq)] + [H_2CO_3] + [HCO_3^-] + [CO_3^{2-}]$



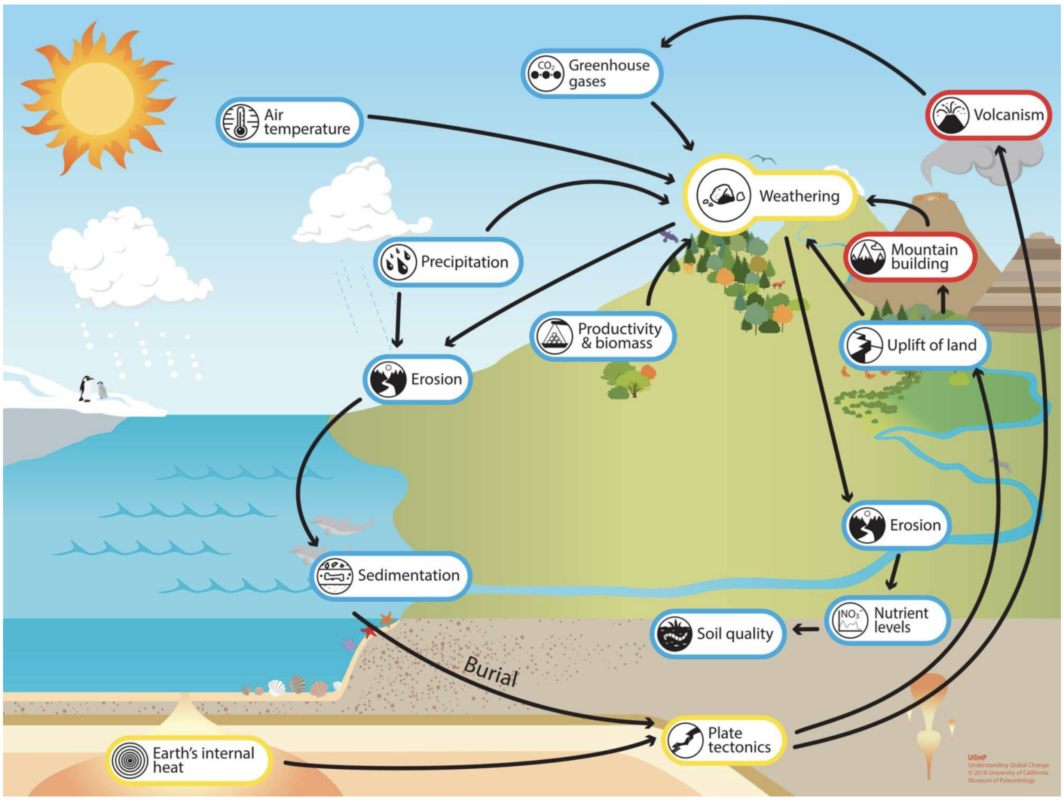
b) Carbon cycle : Short cycle part 2

Diversion and leakage in the hydrosphere-atmosphere physical exchanges

There is a diversion of carbon flux from the atmosphere to the ocean through the weathering of rocks.



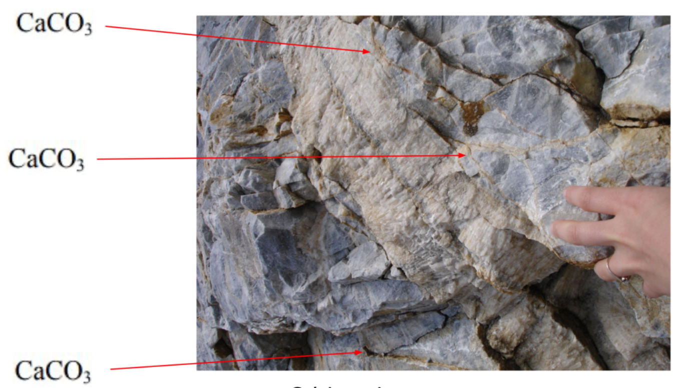
To know more about weathering of rocks : https://www.youtube.com/watch?v=sk B_A2sfBcY



There is a leakage of carbon from the hydrosphere to the lithosphere : the formation of carbonates.

1 Gt of calcite per year.

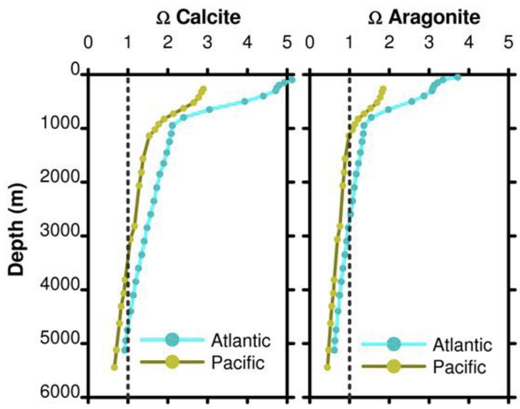
Brow calcite crystals



Calcite veins

Calcium carbonate solubility

$$CaCO_3 \Leftrightarrow Ca^{2+} + CO_3^{2-} \qquad \Omega = \frac{\text{have}}{\text{need for saturation}} = \frac{[Ca^{2+}\text{ present}][CO_3^{2-}\text{ present}]}{[Ca^{2+}\text{ needed}][CO_3^{2-}\text{ needed}]}$$



Ω > 1 Precipitation

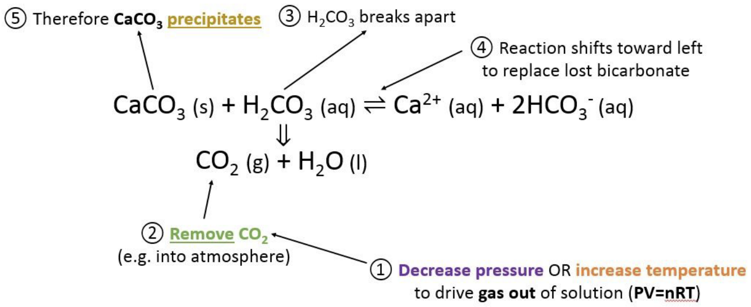
Ω = 1 Equilibrium

Ω < 1 Dissolution

Modern Sea Surface Ω ≈ 2-5

Sea surface is supersaturated with respect to $CaCO_3$, but calcium carbonates are not constantly precipitating.

To precipitate calcium carbonate :



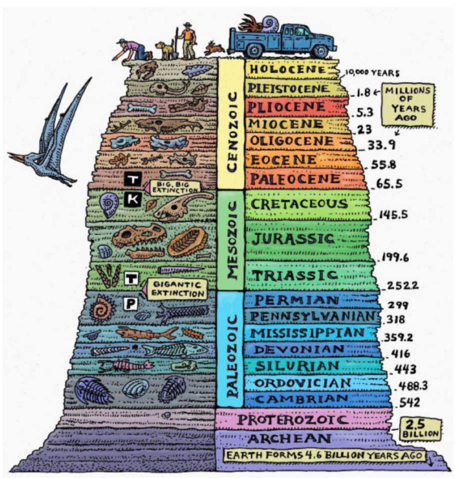
(http://www.luckysci.com)

$$CaAl_2Si_2O_8 + 3H_2O + 2CO_2 = Al_2Si_2O_5(OH)_4 + Ca^{2+} + 2HCO_3^-$$

Anorthite Kaolinite bicarbonate ion

with $Ca^{2+} + HCO_3^- \Leftrightarrow CaCO_3 + H_2CO_3$

$$CaAl_2Si_2O_8 + 2H_2O + CO_2 \rightarrow CaCO_3 + Al_2Si_2O_5(OH)_4$$



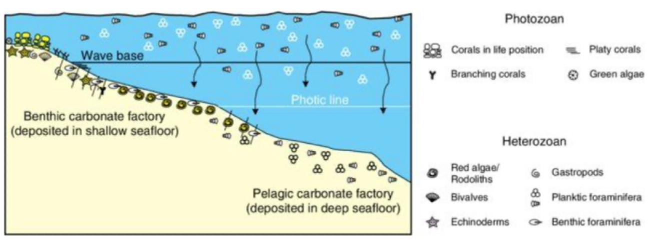
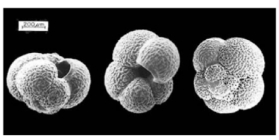


Figure. Main tropical marine biogenic carbonate producers and carbonate factories with respect to water depth.

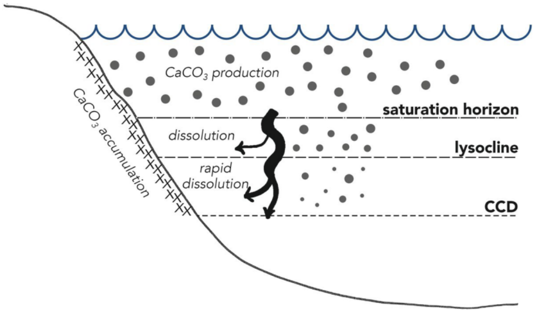
Sgc, Servicio Geológico Colombiano. 2019. « Chapter 9 ». 38. Bogotá: Servicio Geológico Colombiano. https://doi.org/10.32685/pub.esp.37.2019.09.

Coccolithophorales

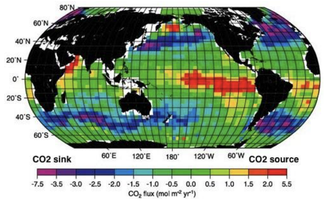


Foraminifera

Corals



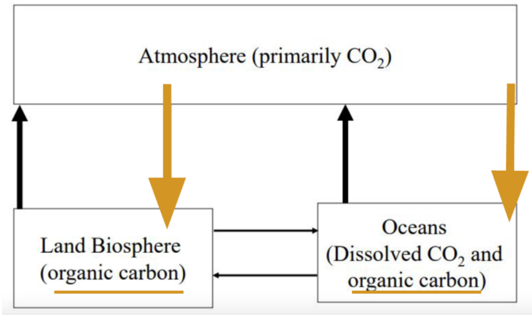
Woosley, Ryan J. 2018. « Carbonate Compensation Depth ». In *Encyclopedia of Geochemistry*, édit par William M. White, 204-5. Encyclopedia of Earth Sciences Series. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-39312-4_85.



c) Carbon cycle : Short cycle part 3

Photosynthesis and respiration

From atmosphere to biomasse continental and oceanic



Photosynthesis

440 Gt of CO_2 per year, shared equally between the oceans and the continents.

Oxygenic photosynthesis

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

carbon dioxide — water — glucose — oxygen — water

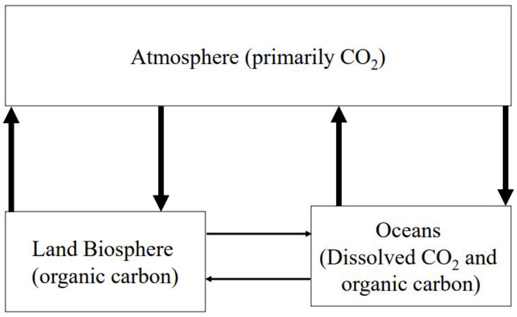
Anoxygenic photosynthesis

$$CO_2 + 2H_2A + \text{light energy} \longrightarrow [CH_2O] + 2A + H_2O$$

carbon dioxide — electron donor* — carbohydrate — water

*$H_2A = H_2O$, H_2S, H_2, or other electron donor

From biomass to atmosphere

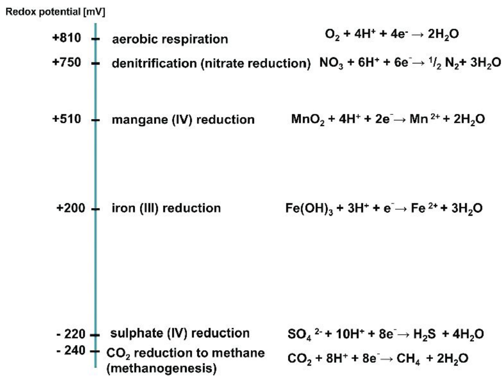


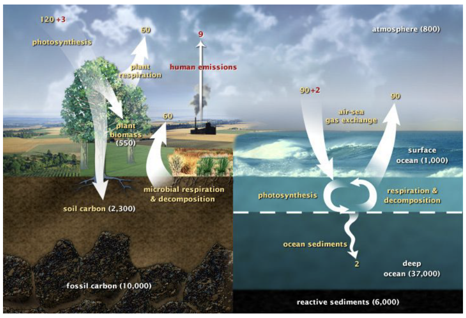
- Breathing 90°
- Natural combustion 10°

Aerobic respiration chemical reaction :

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6H_20 + 6CO_2 + \textbf{energy}$$

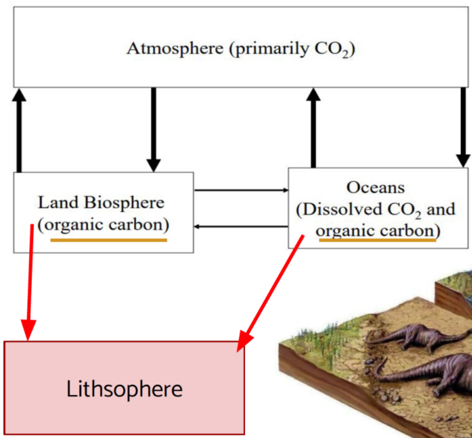
(glucose + oxygen → water + carbon dioxide + energy)

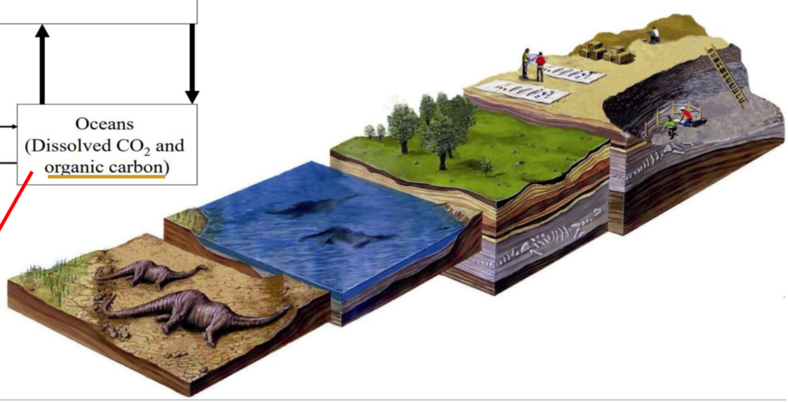




d) Carbon cycle : Short cycle part 4

Organic carbon leakage to lithosphere :kerogen formation





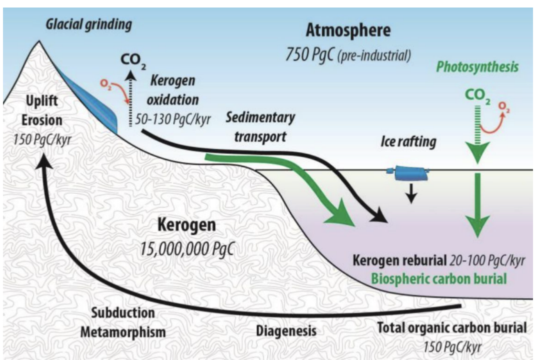
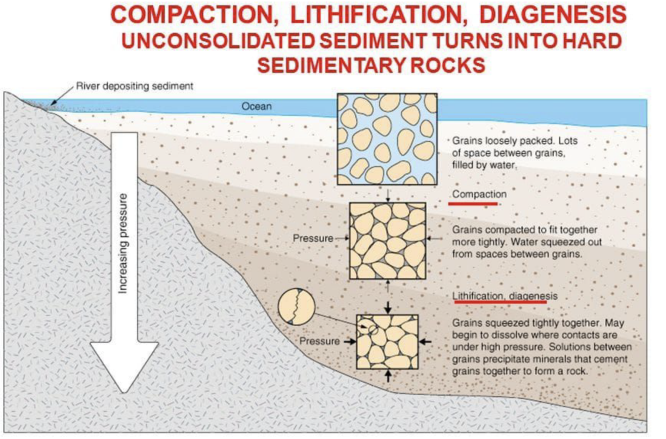
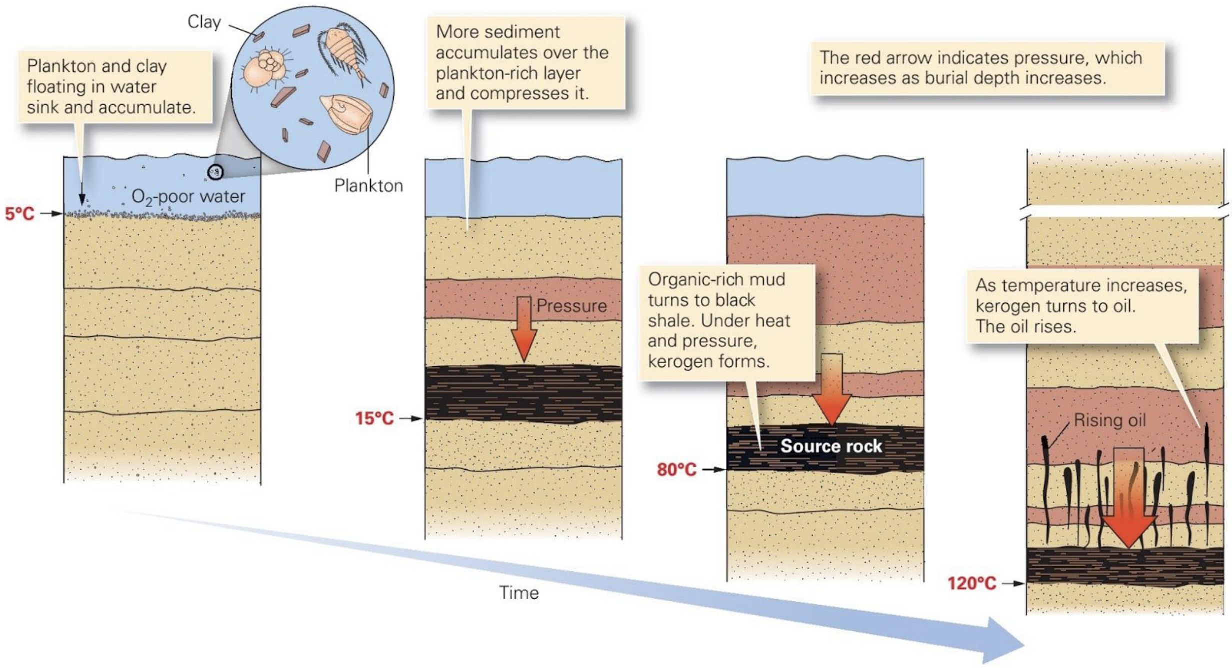


Figure : Organic carbon cycle with the flow of kerogen (black solid lines) and the flow of biospheric carbon (green solid lines) showing both the fixation of atmospheric CO2 by terrestrial and marine primary productivity. The combined flux of reworked kerogen and biospheric carbon into ocean sediments constitutes total organic carbon burial entering the endogenous kerogen pool (Galy et al., 2015; Hedges and Oades, 1997).

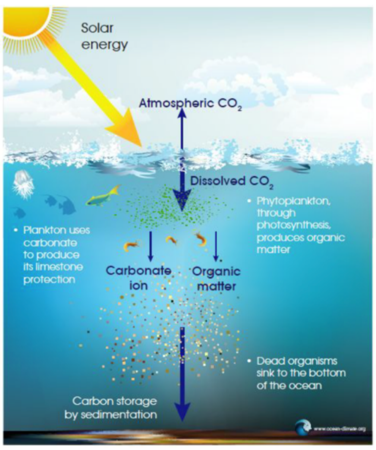


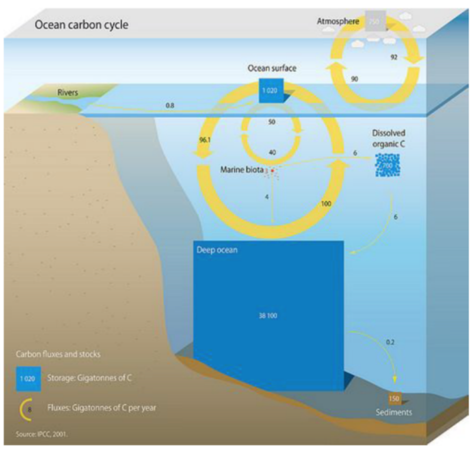
Similar to snow turning to ice

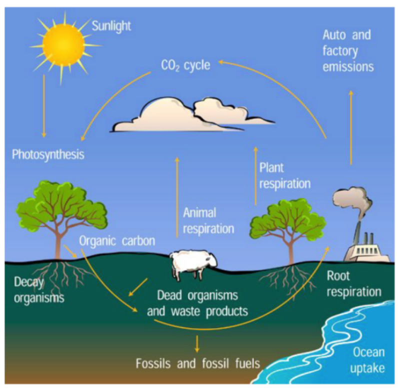
Davidson 4.25



e) Conclusion of the short cycle

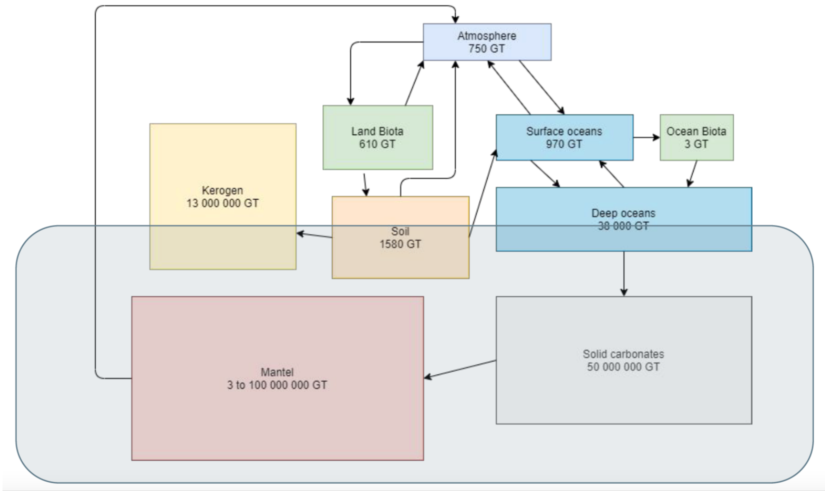


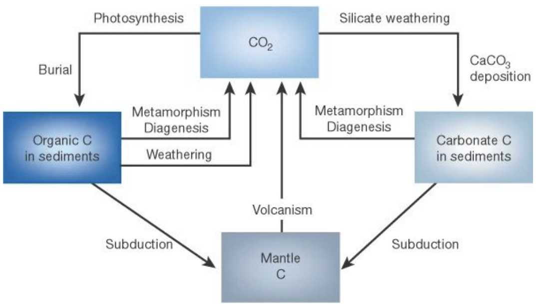




3.2. Long cycle

Long carbon cycle

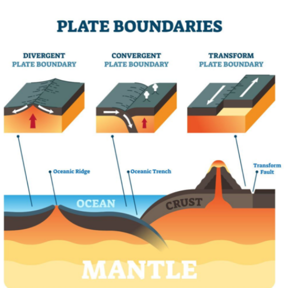


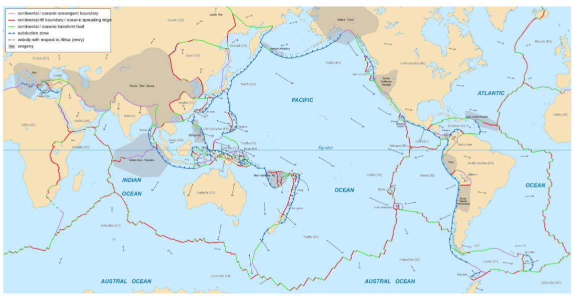


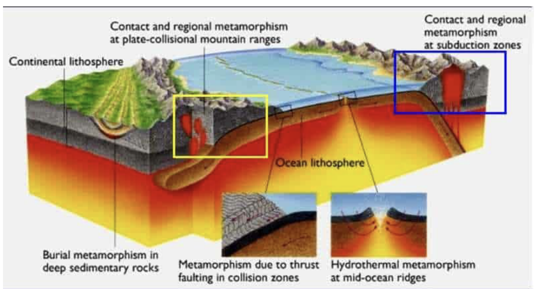
1. $CO_2 + CaSiO_3 <-> CaCO_3 + SiO_2$

2. $CO_2 + H_2O <-> CH_2O + O_2$

Berner, Robert A. 2003. « The Long-Term Carbon Cycle, Fossil Fuels and Atmospheric Composition ». Nature 426 (6964): 323-26. https://doi.org/10.1038/nature02131.







$CO_2 + CaSiO_3 <-> CaCO_3 + SiO_2$

Contact Metamorphism Vs. Regional Metamorphism https://www.geologypage.com/

Trap rock forming a characteristic pavement, Giant's Causeway, Northern Ireland (left)

Three Devil's Grade in mid-Moses Coulee , USA (right)

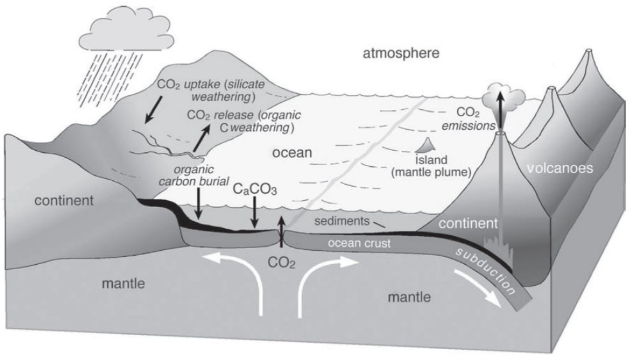
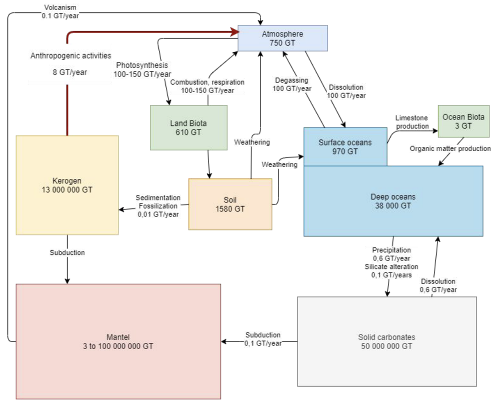


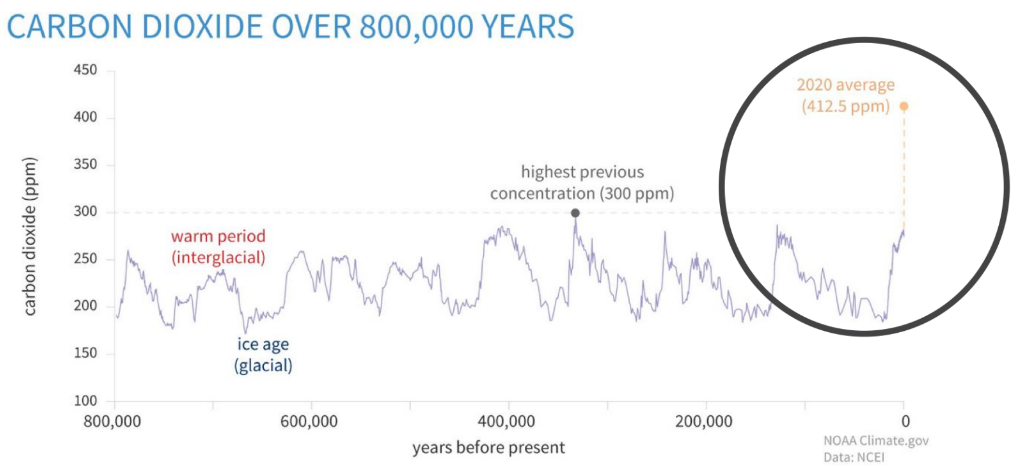
Figure 1.8 Schematic figure of the long-term carbon system involving the exchange of carbon between the atmosphere, ocean and terrestrial systems on geological timescales. Carbon is transferred from the atmosphere to ocean sediments via chemical weathering, where acidic rain reacts with silica rocks, forming calcium and carbonate ions washed out to sea, which precipitate and form calcium carbonate sediments: $CO_2 + CaSiO_3 \rightarrow CaCO_3 + SiO_2$. Subduction of ocean crust below continents leads to eventual melting, releasing carbon dioxide contained within any organic carbon or calcium carbonate in the sediments through volcanic emissions, hydrothermal vents or mantle plumes. For a detailed discussion of the chemical and geological processes, see Berner (1999); drawn by K. Lancaster.



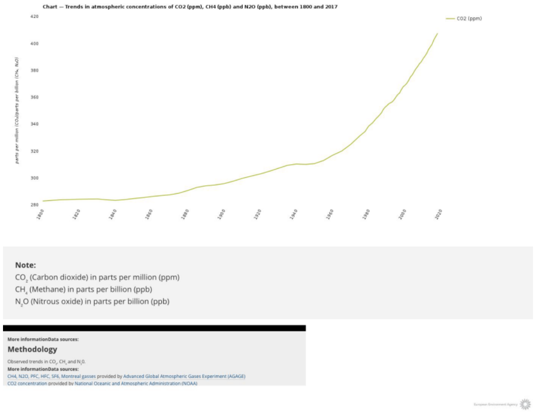
4. Anthropogenic activities and carbon cycle

4.1. Disruption of the carbon cycle-causes

a) Observation of disruption of the carbon cycle



Atmospheric carbon dioxide concentrations (CO2) in parts per million (ppm) for the past 800,000 years. On the geologic time scale, the increase to today's levels (orange dashed line) looks virtually instantaneous. Graph by NOAA Climate.gov based on data from Lüthi et al., 2008, via the NOAA NCEI Paleoclimatology Program.



“Recent increases in global averaged temperature over the last decade already appear to be outside the normal variability of temperature changes for the last thousand years. A number of different analyses strongly suggest that this temperature increase is resulting from the increasing atmospheric concentrations of greenhouse gases, thus lending credence to the concerns about much larger changes in climate being predicted for the coming decades.” (Wuebbles, 2001)

b) Source of the disruption

« Human-related emissions from fossil fuel use have been estimated as far back as 1751. Before 1863, emissions did not exceed 0.1 GtC/year. However, by 1995 they had reached 6.5 GtC/year, giving an average emission growth rate slightly greater than 3% per year over the last two and a half centuries. Recent growth rates have been significantly lower, at 1.8% per year between 1970 and 1995. Emissions were initially dominated by coal. Since 1985, liquids have been the main source of emissions despite their lower carbon intensity. The regional pattern of emissions has also changed. Once dominated by Europe and North America, developing nations are providing an increasing share of emissions. »

« Physical processes and feedbacks caused by land-use change, that may have an impact on the climate, include changes in albedo and surface roughness, and the exchange between land and atmosphere of water vapour and greenhouse gases [see section 4, chapter 7]. [...] Land-use change may also affect the climate system through biological processes and feedbacks involving the terrestrial vegetation, which may lead to changes in the sources and sinks of carbon in its various forms [see chapter 3)]. » (IPCC, 2001)

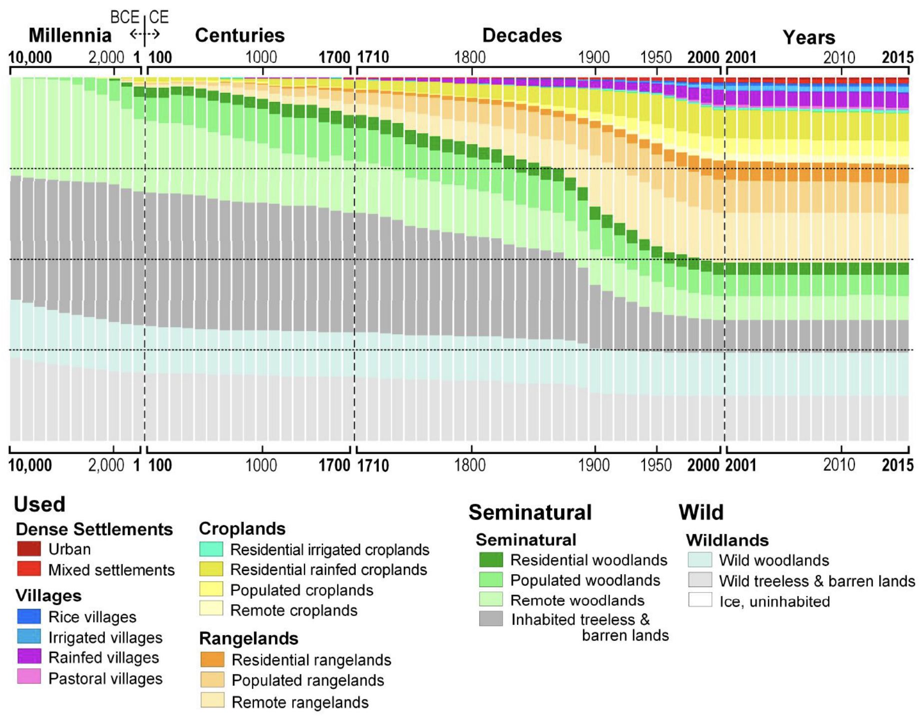


Figure 3. Changes in anthrome areas from 10,000 BCE to 2015 CE for all time intervals in the Anthromes 12K dataset. Relative global areas are indicated using stacked bars, which add up to the total global land area, not including Ice, uninhabited, which showed no significant changes over time.

4.2. Disruption of the carbon cycle-environmental issues

a) Consequences on the Earth System

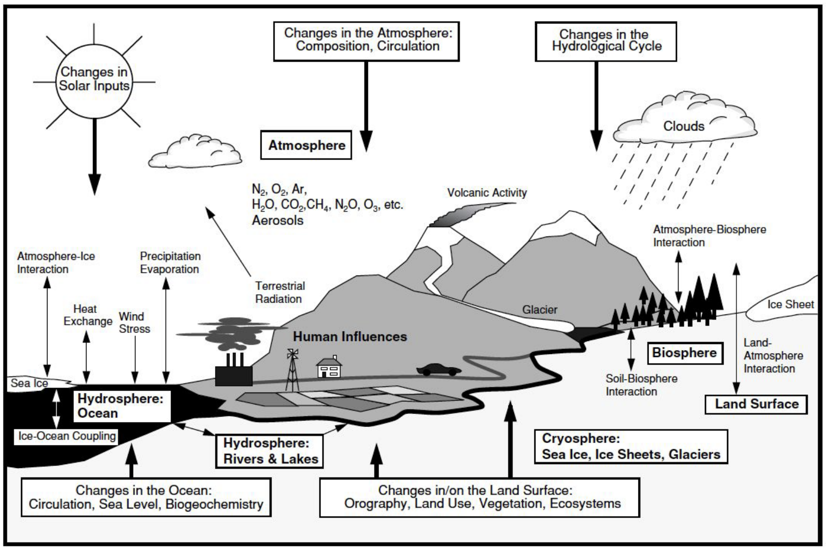
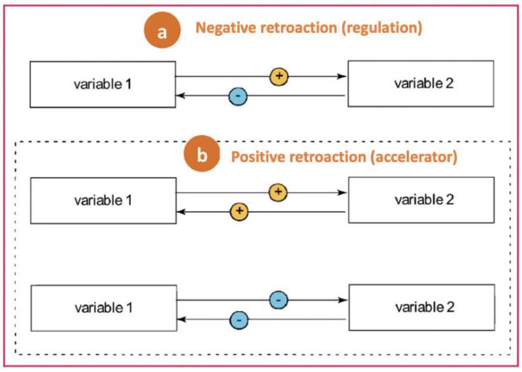


Figure 1.1: Schematic view of the components of the global climate system (bold), their processes and interactions (thin arrows) and some aspects that may change (bold arrows).

Figure: Schematic representation of negative (a: regulating effect on the system) and positive (b: runaway effect on the system) feedback loops.

An arrow with a "+" indicates a positive correlation between the two variables, and an arrow with a "-" indicates a negative correlation.



b) Feedback loops

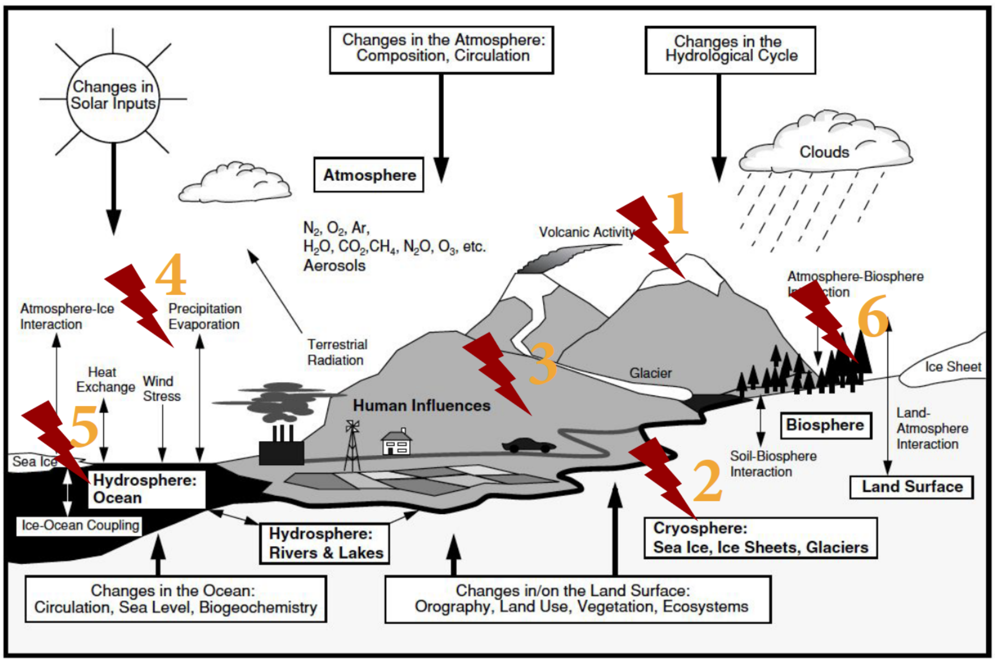
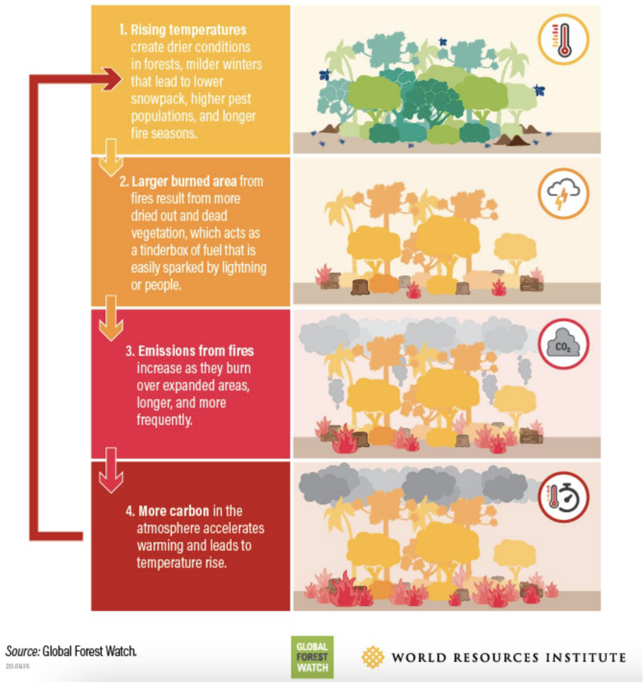


Figure 1.1: Schematic view of the components of the global climate system (bold), their processes and interactions (thin arrows) and some aspects that may change (bold arrows).

Feedback loop 1

Feedback loop 2

Feedback loop 6



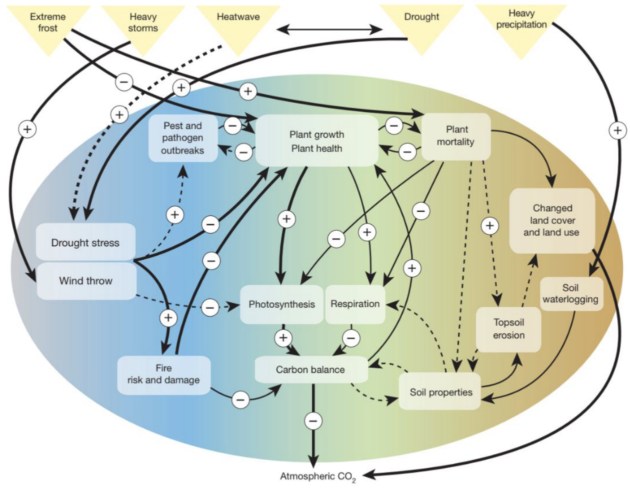
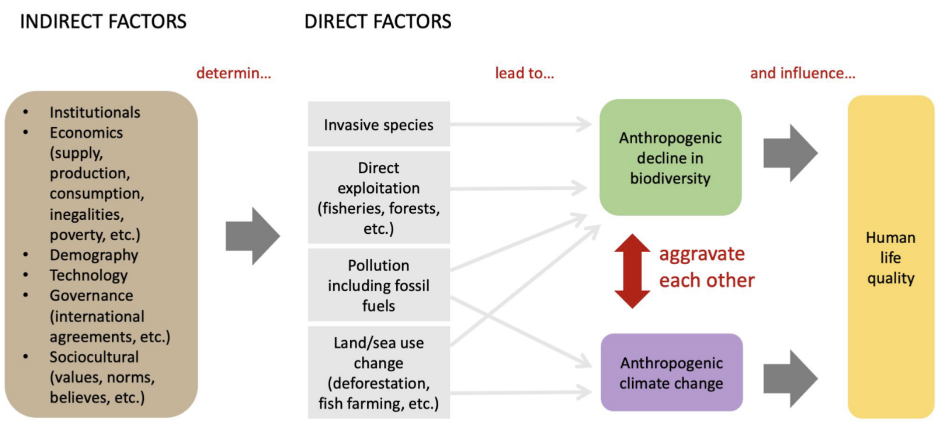


Figure 1 | **Processes and feedbacks triggered by extreme climate events.** The extreme events considered are droughts and heatwaves, heavy storms, heavy precipitation and extreme frost. Solid arrows show direct impacts; dashed arrows show indirect impacts. The relative importance of the impact relationship is shown by arrow width (broader arrows are more important).

Feedback loop 6 : focus biodiversity

- Climate change = main cause of biodiversity loss
- Preserving biodiversity = mitigating climate change
- /!\ technological solutions to mitigate climate change can have negative impacts on biodiversity
- Same causes: our socio-economic way of life



Anthropocene Atlas, Gemenne

Interesting source : https://ipbes.net/sites/default/files/2021-06/20210609_workshop_report_embargo_3pm_CEST_10_june_0.pdf

4.3. Disruption of the carbon cycle-social issues

a) Social impacts

- Migrations
- Wars

El-Hinnawi (1985): *« those people who have been forced to leave their traditional habitat, temporarily or permanently, because of a marked environmental disruption (natural and/or triggered by people) that jeopardize their existence and/or seriously affects the quality of their life »*.

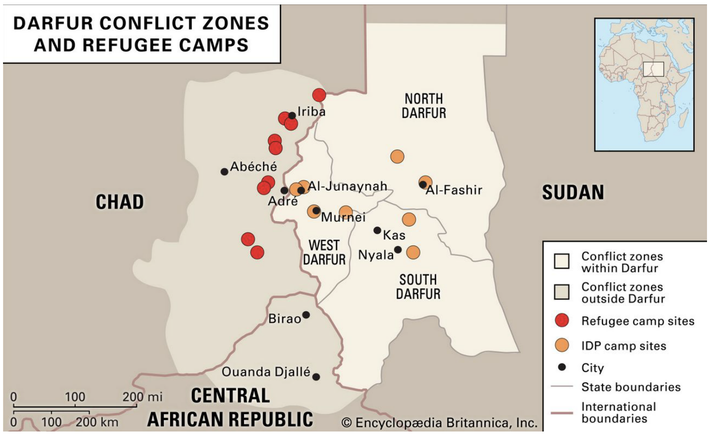
Table 4: Typology of Potential Migrations

Direct Climate Changes	Indirect Climate Changes	Type of Movement	Time Span
Gradual climate change	Chronic disasters such as drought, degradation	Seasonal labour migration. Temporary circulation	Seasonal
Gradual climate change	Chronic disasters-drought/ degradation	Contract labour migration	Yearly
Sudden or gradual climate change	Natural disasters/ severe drought/ Famine/Floods	Forced/distress migration	Temporary
Sudden or gradual climate change	Extreme Temperatures/ Sea Level Rise	Permanent migration	Lifetime

(Partially adapted from Kothari, 2002:20)

Climate Refugees *Définition*

- 1951 Refugee Convention: refugee = from political persecution (UN)
- “Climate Change Displaced People” : people whose habitat is threatened or is already at risk of being extinguished due to climatic change (Hodgkinson et al., 2009)
- “Climate refugees” or “forced climate migrants”



Britannica, The Editors of Encyclopaedia. "Darfur". Encyclopedia Britannica, Invalid Date, https://www.britannica.com/place/Darfur. Accessed 15 September 2021.

The complex ethnic distinctions in Darfur are perhaps less important than the contrast between agriculturalists and pastoralists. The relationship between the two is governed by competition for land and water resources, which can be affected by short- and long-term climate change (whether random, cyclical or greenhouse-induced), both in terms of absolute availability and geographical extent of the resources.

Jeffrey Mazo (2009) Chapter Three : Darfur : The First Modern Climate-ChangeConflict, The Adelphi Papers, 49:409, 73-86, DOI: 10.1080/19445571003755538

Armed Conflicts

Définition

3 elements (Sakaguchi, 2017):

1. There are correlation between climate change and violence but no robust conclusion.
2. There are weak empirical support to the link between climate change and violence
3. Methodologies used in the different students have an impact on results

« Migration is generally considered to be the intermediate stage which links environmental degradation and disasters to conflict (Homer Dixon, 1991 and 1994) »

(Assessing the Impact of Climate Change on Migration and Conflict, Raleigh)

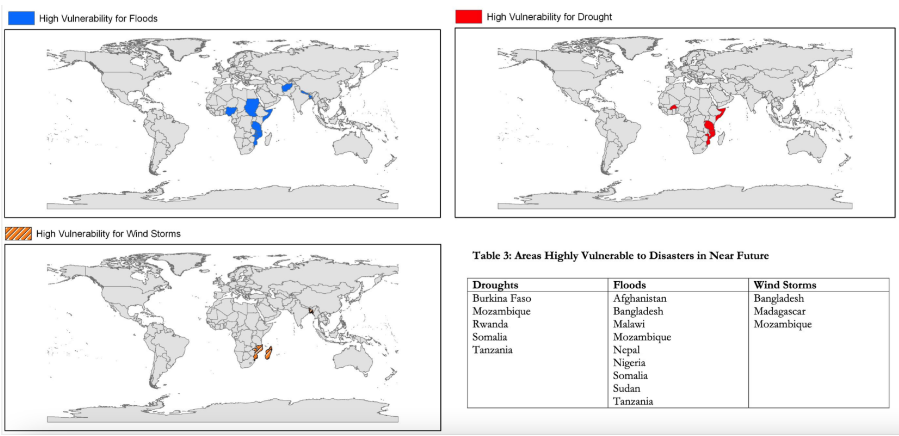


Table 3: Areas Highly Vulnerable to Disasters in Near Future

Droughts	Floods	Wind Storms
Burkina Faso Mozambique Rwanda Somalia Tanzania	Afghanistan Bangladesh Malawi Mozambique Nepal Nigeria Somalia Sudan Tanzania	Bangladesh Madagascar Mozambique

4.4. Conclusion

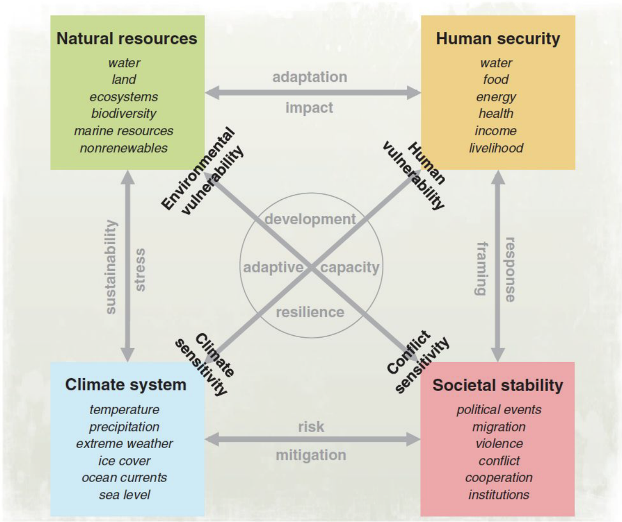


Fig. 1. Analytical framework of linkages between the climate system, natural resources, human security, and societal stability [based on (*28*)].

Scheffran, 2012 based on Scheffran, 2009