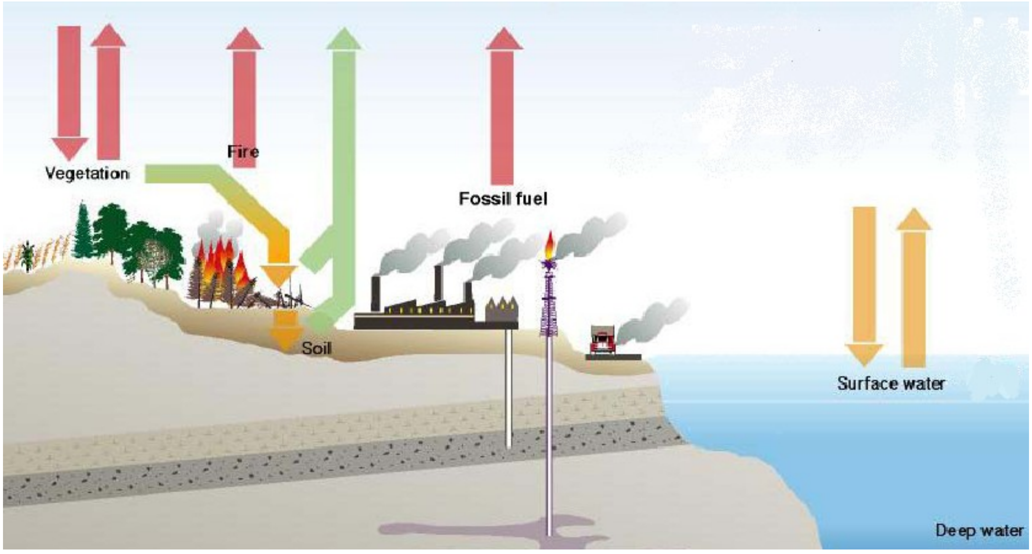
Environmental Science. Physics and Applications

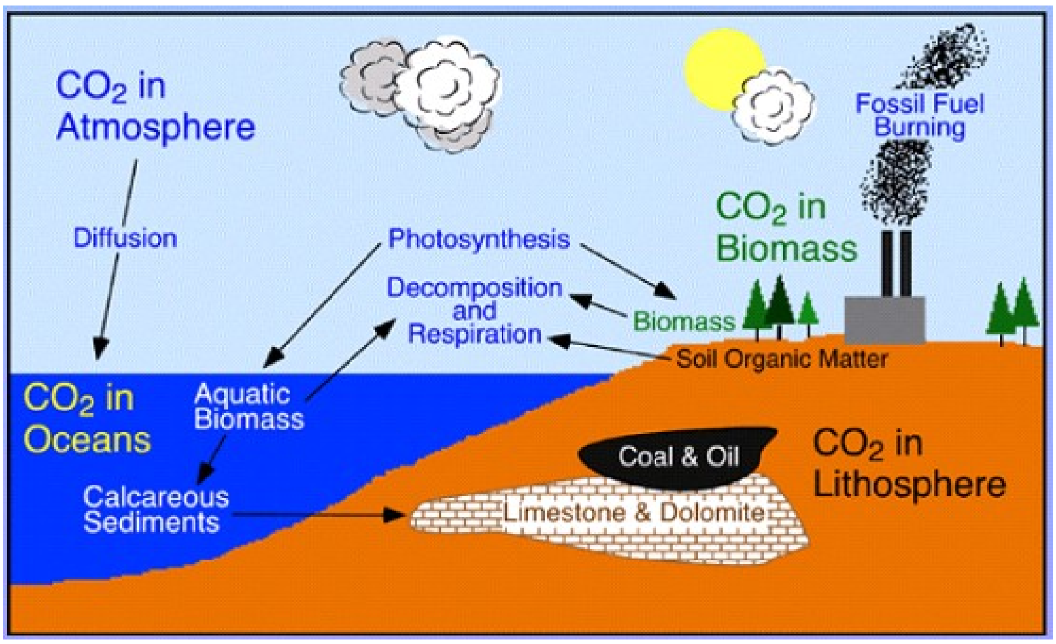
Chapter 4. Carbon Cycle



Picture from the IPCC report on the environment.

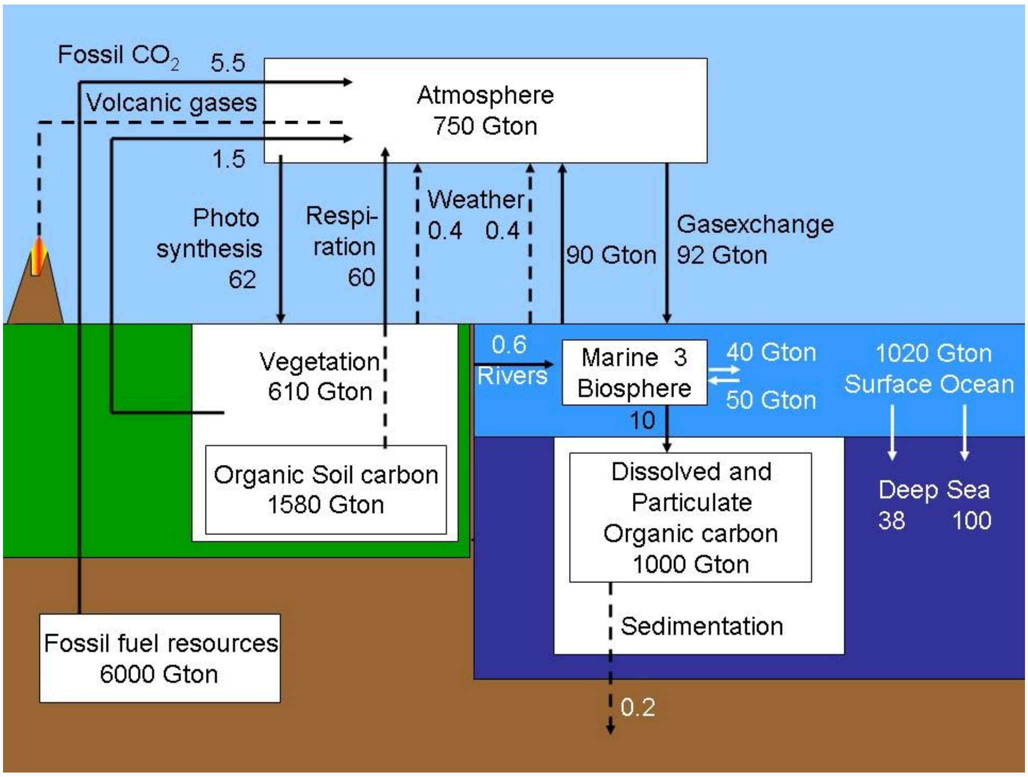
4.1 Carbon cycle, introduction

The cycle of carbon has a great impact on life on Earth, and is also of great interest for the anthropogenic Greenhouse effect. In the atmosphere an enormously large amount of carbon dioxide is present, around 750 Gton.



The carbon dioxide of the atmosphere absorbs in the oceans by diffusion and enters the

lithosphere from the oceans. Man uses the oil and coal for energy production resulting in fossil fuel burning making the carbon dioxide enter to the atmosphere. Already volcanic out-gassing enters the atmosphere and has been doing so for millions of years. After the industrial revolution the CO_2 volume fraction has increased from around 280 ppm to 360 ppm, i.e. an increase of 30%. This has happened since 1850, while the amount 280 ppm had been stable for more than 900 years.
Still there are large amounts contained as fossil fuel resources, of the order of 6000 Gton.



In the figure the global carbon cycle is shown where the units are in Gton. The interaction however is given in Gton/year and all figures are taken from ESCOBA, European study of the Global Carbon Cycle in Ocean, Atmosphere and Biosphere, European Commission 1999. It can also be found in Environmental Science, Boeker-Grondelle.

Let us perform a calculation on the Carbon in the atmosphere. From the figure we see that the amount is around 750 Gton. Let us derive the volume fraction of carbon in the atmosphere. The mass of the atmosphere can be calculated by looking at the total pressure at the surface:

$$p_0 = 1\,\text{atm} = 101.3\,\text{kPa} = 1.013 \times 10^5\ \text{N/m}^2$$

The force on a mass m is $F = mg$ and the area of the Earth is $A = 4\pi R^2$.

We derive the pressure at the surface: $p_0 = \dfrac{F}{A} = \dfrac{mg}{4\pi R^2}$

This gives the mass of the atmosphere: $m = \dfrac{p_0 4\pi R^2}{g} = \dfrac{1.013 \times 10^5 \times 4\pi \times \left(6.37 \times 10^6\right)^2}{9.81}\,\text{kg} \Rightarrow$

$m = 5.2 \times 10^{18}\ \text{kg}$.

In order to derive the volume fraction of CO_2 we apply the ideal Gas law:

$$pV = RnT \quad \Rightarrow \quad V = n\frac{RT}{p} \propto n \text{ , where } n = \frac{m}{M}$$

The atmosphere consists of around 80% nitrogen (28g/mol) and 20% of oxygen (32g/mol) and carbon dioxide has 12+32 g/mol $\Rightarrow$ $M_{CO_2} = 44 \text{ g/mol}$.

The relation between carbon and carbon dioxide is $m_{CO_2} = \frac{44}{12} m_C$.

The corresponding expression for air is $M_{air} = 80\% \times 28 + 20\% \times 32 = 29 \text{ g/mol}$

Now we can calculate the volume fraction of CO_2:

$$\frac{\frac{44}{12} m_C \frac{1}{44}}{m_{air} \frac{1}{29}} = \frac{29}{12}\frac{m_C}{m_{air}} = \frac{29}{12} \cdot \frac{750 \times 10^{12}}{5.2 \times 10^{18}} = 3.48 \times 10^{-4} \approx 350 \times 10^{-6} = 350 \text{ ppmv}$$

This value, 350 ppmv, can also be seen in the diagram of the development of carbon dioxide through the years up to now, which is shown in Chapter 3.4, The increase in Greenhouse gases.

4.2 The oceans

The oceans have an exchange of carbon with the atmosphere by CO_2. The exchange is of the order of 90 x 10^{12} kg annually, towards the atmosphere and somewhat more to the oceans. However, these are just average numbers and in the warm tropics the out-gassing towards the atmosphere is dominating, while at higher latitudes the inverse holds.
The oceans can store large amounts of carbon in the form of CO_2 or H_2CO_3. We have the following reactions:

CO_2 (gas phase) + H_2O $\leftrightarrow$ H_2CO_3 (liquid phase)

H_2CO_3 (liquid phase) + H_2O $\leftrightarrow$ H_3O^+ (liquid phase) + HCO_3^-

HCO_3^- (liquid phase) + H_2O ↔ H_3O^+ (liquid phase) + CO_3^{2-}

The equilibrium constants are ruling the equations. The pH is important for the concentrations and seawater has a pH ≈ 8. Around this value of pH the HCO_3^- is dominating, within a couple of percent from 100%. Sine we in the marine environment have Ca^{2+}-ions, we will get the following reaction:

Ca^{2+} + $2HCO_3^-$ (liquid phase) ↔ $CaCO_3 + CO_2 + H_2O$

This means that carbon will be found as calcium carbonate where some is being used for the build-up of tissues and shells. Still, some will sink down to the bottom of the oceans.

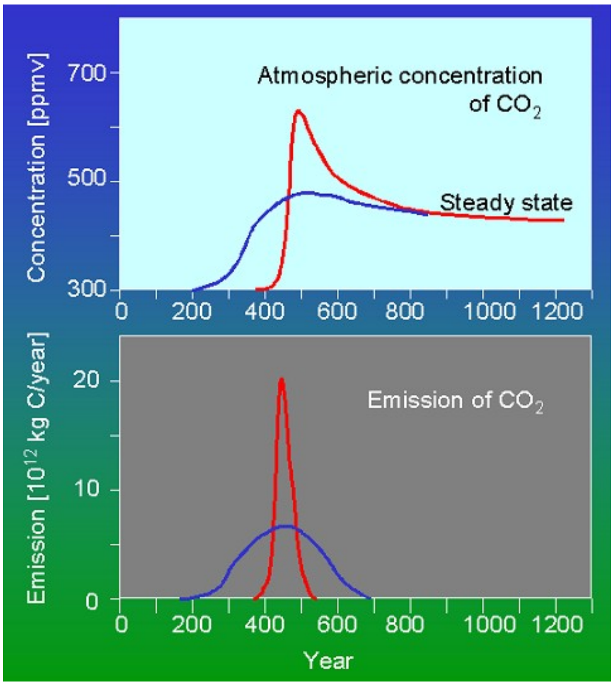
4.3 The land

In *Nature* of April 2000 one reads "Old and middle aged forests are net absorbers of CO_2". This is comforting since there are two processes competing, namely the *photosynthesis* that converts carbon dioxide into oxygen, and the *respiration* that ejects CO_2. If we look at the figure on page 2, we find both processes where the photosynthesis absorbs 62 x 10^{12} kg/year, whereas the respiration of carbon dioxide reaches 60 x 10^{12} kg/year. The difference in these large numbers is a net uptake or 2 x 10^{12} kg/year. One can say that these forests work as sinks for CO_2. However, as pointed out in *Nature*: "Respiration may be more sensitive to long-term climate change than photosynthesis. The answer to this question determines the role of the forests as a carbon sink."

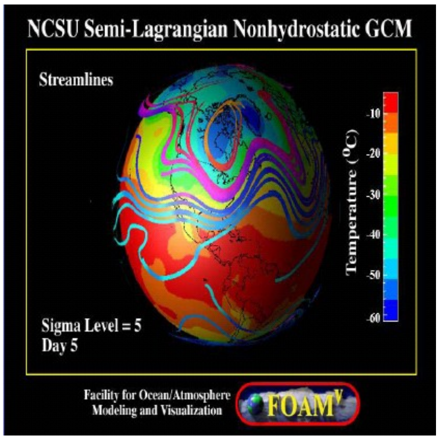
One an also look at figures taken from the carbon dioxide budget where one has given rather accurate estimations of industrial emissions (5.5 x 10^{12} kg/year) as well as from land use changes (1.6 x 10^{12} kg/year). Together they measure up to 7.1 x 10^{12} kg/year with an uncertainty of 1.1 x 10^{12} kg/year. Measurements show that the uptake in the atmosphere is around 3.3 x 10^{12} kg/year, and physical models predict that there is around 2.0 x 10^{12} kg/year that enters the oceans, why the inferred land uptake must be 1.8 x 10^{12} kg/year of carbon dioxide.

4.4 Steady state

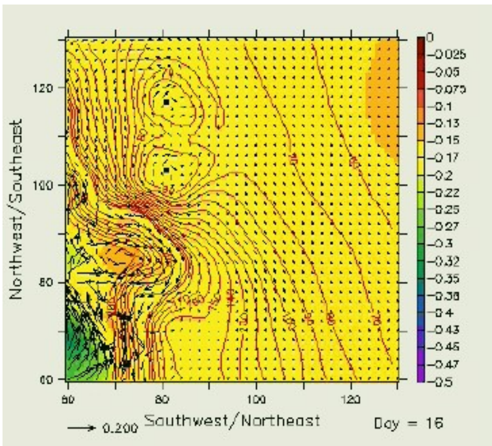
If one looks at the diagram on page 2, the figures just show how it is today. Estimates can be made for the future by looking at different situations. Let us study the fossil fuel resources not yet used (6000 Gton) and imagine that all this fuel is used and all its content of carbon dioxide is emitted into the atmosphere. We realize that we cannot use all these resources with our recent techniques, perhaps only (1500-2000) x 10^{12} kg. We now have a problem with time-scales. There are several time-scales involved, namely day-night cycles, summer-winter cycles, glacial and interglacial time-scales. Modelling of emission and absorption will be tricky. Houghton *et al* [The science of climate change] has shown some models leading to a steady state where a concentration of CO_2 in the atmosphere will reach a steady state of 400 ppmv after around 1500 years, independent of a fast emission (200 years) and a slow emission (400 years). This is shown in the figure below:



Below are shown two different examples on modelling of physical situations within



Deep see water currents around the Earth



Tide water currents in the Bering's sea

environmental studies. In the first picture we observe streamlines of the deep-water currents traveling around the Earth. In the second picture we observe modeling of tide currents in the Bering’s sea (http://pmel.noaa.gov).