in relatively rapid exchange with the atmosphere

We have two compartments—one for terrestrial biota X_2, another for the upper layer of the ocean X_3—and two fluxes from the atmosphere to these compartments f_{21}, f_{31}. We denote f_{ij} as flux from compartment j to i. Some of the carbon goes back to atmospheric carbon (CO_2) by respiration (fluxes f_{12}, f_{13}); the rest is stored, consumed, and decomposed (fluxes f_{42}, f_{73}) and part is recycled (fluxes f_{24}, f_{37}). At slower rates, carbon transfers to fossil organic matter, sediments, and sedimentary rocks (fluxes f_{54}, f_{64}, f_{67}). Sedimentary deposits contain most of the global carbon. Human action accelerates release of CO_2 by burning fossil fuels (coal, oil, gas) at rate u_f and from the terrestrial biota by deforestation at rate u_d. The time scale is mixed: Some processes occur rapidly as the exchanges between atmosphere and *biota*, and others slowly, such as sedimentation. We will use a time scale of years and gigatons or Gt for carbon amount in compartments. The fluxes are then in Gt/yr. One Gt is one peta g or 10^{15} g.

Estimated values for the compartments X_1, X_2, …, X_7 are 740, 1760, 1000, 1500, 10000, 20 million, and 39000 Gt, respectively. These values are just approximations.

Example 2.2

Let us calculate atmospheric carbon using net rates of inflow and outflow assuming that these rates do not vary with the stocks in the compartment. Assume that the flow from rocks to atmosphere is negligible. What is the total flow of C into the atmosphere and what is the total flow of C out of the atmosphere? What would be the C content in the atmosphere 50 years from now? Answer: Calculate flux out of the atmosphere as uptake from land and oceans $F_{out} + F_{to\_land} + F_{to\_oceans} = 102 + 92 = 194$ Gt/yr. Calculate flux into the atmosphere as emissions from land biota, ocean biota, deforestation, and burning fossil fuels: $F_{in} + F_{from\_land} + F_{from\_oceans} + F_{from\_def} + F_{from\_fossil} = 100 + 90 + 2 + 5.3 = 197$ Gt/yr.

The difference in flux into and out gives us net rate of change: $\Delta F = F_{in} - F_{out} = 3.3$ Gt/yr. Content 50 years from now: $C_{50yr} = 740$ Gt + 3.3 Gt/yr × 50 yr = 905 Gt.

Atmospheric carbon or carbon dioxide in the atmosphere contributes to determine the greenhouse effect, which in turns affects global air temperature, as we will discuss in a couple of sections. Let us first examine existing data on changes of atmospheric carbon.

2.2 CARBON DIOXIDE IN THE ATMOSPHERE AND GLOBAL TEMPERATURE

2.2.1 Increasing Atmospheric CO_2 Concentration

An important piece of our knowledge of planetary carbon dynamics comes from the measurement of atmospheric CO_2 concentrations recorded in Mauna Loa, Hawaii [4,5]. A visit to the website of NOAA's Global Monitoring Division [6] will inform us of recent values of monthly average of CO_2 concentration in parts per million (ppm). For example, at the time of this writing, the most recent value was for May 2017 and was 409.65 ppm, ~2 ppm up from 407.70 ppm for the same month the previous year (May 2016).

Concentration in ppm express dry air mole fraction defined as the number of molecules of carbon dioxide divided by the number of all molecules in air, including CO_2 itself, after water vapor has been removed [6]. The May 2017 value of 409.65 ppm represents a mole fraction of 0.000409. On the website, we can see a graph of CO_2 in ppm as monthly average and its trend (seasonal correction) for the last 5 years of record. The trend is calculated by a moving average of seven (an odd number) adjacent seasonal cycles centered on the month to be corrected [6]. The trend changes from 395 to 406 ppm in 5 years, which is an average increase of ~2 ppm/year.

Besides the graph, the website offers the data for download. Figure 2.3 illustrates the CO_2 trajectory for the entire record of measurement (since March 1958) using the data downloaded from this website. From the data set we plot the same two lines shown at the website. The dashed line represents the monthly average values (centered on the middle of each month), which fluctuates up