Closing the atmospheric CO_2 budget:
inferences from new measurements of $^{13}C/^{12}C$ and O_2/N_2 ratios

by Martin Heimann

The regional and global quantification of sources and sinks of major biogeochemical elements such as carbon constitutes one of the ultimate goals of many IGBP endeavours. The degree to which this quantification results in a closed global budget provides a critical test of our understanding of the relevant source and sink processes, while the estimated uncertainties assigned to individual budget components highlight directions of future research. Clearly, a mere quantification *per se* only highlights our present state of knowledge; even more important is our understanding of how the budget changes with time as a function of natural and anthropogenic perturbations. This, in turn, requires long-term observations, detailed process studies and modelling. This article aims at providing a summary of recent developments regarding the relative partitioning of CO_2 uptake between land and sea based on old and new techniques.

The IPCC94 budget revisited.

The recent assessment by the IPCC 1994 of the different budget terms and their uncertainties (all uncertainties in this article are expressed as estimated 90% confidence intervals) is given in Table 1 (page 10). The listed numbers are representative of the decadal average 1980-1989. Table 1 has been reorganised such that all terms related to land biotic sources and sinks are listed at the end. Accordingly, emissions from fossil fuel use and cement production amount to 5.5±0.5 $GtCyr^{-1}$. The atmospheric increase of 3.2±0.2 $GtCyr^{-1}$, as determined from the background CO_2 monitoring stations, represents the best known term in the budget. The ocean uptake of 2.0±0.8 $GtCyr^{-1}$ is based on detailed calculations with ocean models. These include global 3-dimensional ocean general circulation models, but also simpler box model representations of the ocean. These models are either calibrated or validated by means of observations of transient tracers, such as radiocarbon, tritium and CFCs, which are to some extent analogue to the anthropogenic CO_2.

The fossil emissions, together with the increases in atmospheric and oceanic CO_2 storage imply that the terrestrial carbon pools, as a whole, must have been a very small net sink (0.3±1.0 $GtCyr^{-1}$) or effectively almost in balance during 1980-89. If so, any terrestrial CO_2 emissions due to land use changes (1.6±1.0 $GtCyr^{-1}$) must have been balanced by other terrestrial sinks *e.g.* regrowing forests in temperate latitudes (0.5±0.5 $GtCyr^{-1}$) or other processes such as fertilisation effects due to the increasing CO_2 concentration and from increased nitrogen deposition. The identification of these latter processes (often referred to as the "missing" or "unidentified sink") and their quantification on a regional and global scale represents a formidable challenge.

It is important to note, that global net fluxes between the atmosphere, ocean, and the terrestrial biosphere, are not only induced by the direct anthropogenic perturbation, *i.e.* by the rise in atmospheric CO_2. The global carbon cycle is also subject to interannual and longer term climate fluctuations which induce temporary imbalances in the natural exchange fluxes of carbon between the different. Depending on the approach and the time scale under consideration, climate driven fluxes may contribute considerably to a budget compilation such as given in Table 1.

New Approaches

How solid are the inferences on the net balance of terrestrial biospheric carbon? Clearly the logic represented in the lines (1)-(4) of Table 1 hinges crucially on the ocean uptake term. Two new approaches allow an independent check on this term.

A significant advance in the last few years has been the development of measurement techniques to determine changes in atmospheric oxygen content with very high-precision. Technically, the ratio of O_2/N_2 in air is measured, either by interferometric techniques or by mass-spectroscopy. Since the atmospheric content of nitrogen can be assumed to remain constant on timescales of decades to thousands of years, the O_2/N_2 ratio essentially reflects the oxygen content of the atmosphere. These measurements provide a new possibility to discriminate the contributions of oceanic and biospheric sources and sinks of CO_2. This follows from the fact that O_2 is produced during photosynthesis and consumed during any oxidation

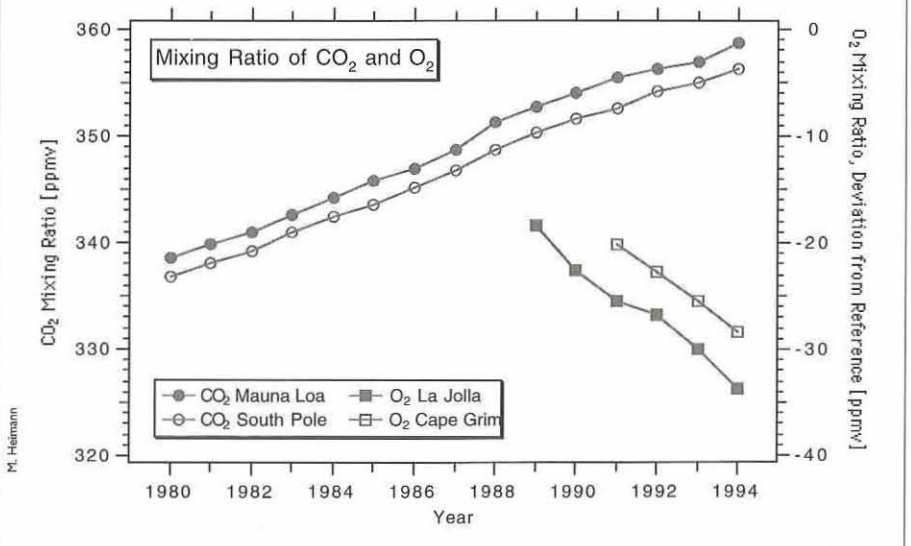

Figure 1: Observations of the annually averaged mixing ratio of CO_2 (left axis, circle symbols) and of oxygen (right axis, square symbols) in the northern hemisphere (solid symbols) and in the southern hemisphere (open symbols). Oxygen mixing ratios are shown as deviations from a reference value which is approximately 209,500 ppmv

Table 1: Atmospheric CO_2 Budget 1980-89 (IPCC 1994)		
(1) Fossil fuel and cement production		5.5±0.5
(2) Atmospheric increase (observed)		3.2±0.2
(3) Ocean uptake (model calculated)		2.0±0.8
based on observed O_2/N_2 ratio trend (1989-1994)	1.9±0.8	
based on observations of $^{13}C/^{12}C$ ratio	2.1±1.5	
(4) Net balance of terrestrial biosphere = (1) - (2) - (3)		0.3±1.0
(5) Land use change emissions (primarily tropics)		1.6±1.0
(6) Regrowth of temperate latitutde forests (based on forest statistics)		0.5±0.5
(7) CO_2 uptake by other terrestrial processes (a.o. CO_2 fertilisation effect, N-fertilisation, climate effects) = (4) + (5) - (6)		1.4±1.5
Fluxes expressed in GtCyr^{-1}, uncertainty ranges represent estimated 90% confidence intervals		

process in clearly defined stoichiometric ratios relative to CO_2. However, the oxygen gas is only very weakly soluble in oceanic waters, in contrast to CO_2 which is strongly chemically buffered in the oceanic carbonate system. Hence any oceanic uptake of CO_2 is not mirrored by a corresponding oxygen absorption or release from the ocean. As a consequence, the dynamical behaviour of the two gases is different and measurements of their behaviour are not redundant.

Figure 1 (page 9) shows the annually averaged records of the O_2 and CO_2 mixing ratio from representative background monitoring stations in the northern (La Jolla and Mauna Loa) and southern hemisphere (South Pole and Cape Grim) [Keeling *et al.*, 1996]. The oxygen measurements (scale on the right) are expressed as ppmv deviations from a standard which corresponds to approximately 209,500 ppmv. It is seen that the oxygen concentration is diminishing at a slightly faster rate than the increase of the CO_2 concentration. This reflects on one hand the stoichiometric relation between O_2 and CO_2 in burning of fossil fuels of about -1.4:1 and approximately -1.1:1 with respect to photosynthesis and respiration of organic carbon. More importantly it reflects also the fact that oxygen is not buffered by the ocean. The observations of the global trends in CO_2 and O_2 provide two budget equations, which permit the determination of the oceanic and biospheric contributions in the global CO_2 balance.

The quantitative analysis using the longer O_2 record from La Jolla yields an average oceanic CO_2 uptake of 1.9±0.8 GtCyr^{-1} (the error is the estimated 90% confidence interval) over the time period 1989-1994. With an increasing length of the record and provided that there are no problems with long-term stability of the standards, the uncertainty of the oxygen based ocean uptake rate is expected to decrease further. The oxygen analysis yields also an estimate of the global net terrestrial balance over the 1989-1994 time period amounting to 1.8±1.1 GtCyr^{-1}. This is much larger than the base period adopted by the IPCC as given in Table 1. The reason is that during the early 1990's the atmospheric CO_2 growth rate was much smaller than during the 1980's.

Observations of the isotopic composition of oceanic carbon, either of the temporal changes in the vertical ^{13}C or of the surface $^{13}C/^{12}C$ distribution also allow an independent determination of the oceanic uptake of excess CO_2. Because of the presently insufficient database of oceanic ^{13}C measurements, together with uncertainties in some of the other isotopic budget terms, the current estimates based on the ^{13}C technique are subject to considerable uncertainties, yielding 2.0±1.5 GtCyr^{-1}over the time period 1970-1990 [Heimann and Maier-Reimer, 1996].

It is reassuring that both the oxygen and the ^{13}C based approaches confirm the model based ocean CO_2 uptake rates, albeit with considerable uncertainties. It is also important to note, though, that both the $^{13}C/^{12}C$ and O_2/N_2 based estimates of the oceanic CO_2 uptake refer to different timeperiods than the IPCC 1994 budget.

Spatial constraints

Figure 1 also demonstrates the gradient in the CO_2 and the oxygen mixing ratio which exists on annual average between the northern and the southern hemisphere. The primary cause of this gradient are the emissions of CO_2 and the corresponding losses of oxygen from the burning of fossil fuels taking place predominantly in the northern hemisphere.

A quantitative assessment of these interhemispheric mixing ratio differences and of the more detailed spatio-temporal structures as revealed in the CO_2 records from the global monitoring station networks since the late 1970's requires models that accurately describe the mixing of air in the global troposphere. The most conspicuous result from atmospheric modelling studies was the inference of a strong, presumably natural, CO_2 sink in the northern hemisphere, offsetting about 40% of the gradient induced from the fossil fuel source. Whilst this finding is thought to be rather robust, there remain substantial uncertainties related to modelling of the atmospheric transport as witnessed by a recent model intercomparison. Furthermore, seasonal terrestrial biosphere exchanges also impact the mean annual mixing ratio gradient between the hemispheres. A continuation of the atmospheric transport model intercomparison and validation by means of observations of long-lived atmospheric tracers such as sulphur hexafluoride (SF_6) is currently conducted within the TRANSCOM project of IGBP-GAIM.

The nature of the northern hemisphere sink, whether of oceanic or terrestrial origin has been controversial. Again, analyses based on measurements of O_2/N_2 and of $^{13}C/^{12}C$ provide new insights. The oxygen observations allow a separation between oceanic and biospheric components in the north-south gradient. Assuming that the southern hemisphere biosphere plays a negligible role, the gradient information together with the global budget allows the determination of the net terrestrial biospheric contributions from the tropics and from the northern temperate and high latitudes. The analysis of the data for the time period 1991-1994 yields a biospheric sink of about 1.9±1.5 GtCyr^{-1}in the extratropical northern northern hemisphere. This value, together with the global net biospheric balance of 2.0 GtCyr^{-1}for the same time period, implies that the terrestrial equatorial regions must have been almost in balance during 1991-1994. If so, any net CO_2 releases from these regions due e.g. to deforestation must have been balanced by corresponding CO_2 uptake at other locations in the tropics. The picture provided by the oxygen measurements for the early 1990's is grossly in accordance with a recent analysis of the interhemispheric gradient in the atmospheric $^{13}C/^{12}C$ ratio, which, however, refers to a shorter time period.

The interhemispheric CO_2 mixing ratio gradient in the 1980's (at least 1980-87) was similar in magnitude as during the

early 1990's (Figure 1), despite the fact that the atmospheric increase was substantially smaller in the later period. Unfortunately there exist no observations of the O_2/N_2 interhemispheric gradient for the 1980's. If one assumes, in accordance with ocean model calculations, that the oceanic contributions to the meridional gradient were similar in the 1980's than in the early 1990's, then one can postulate a large scale scenario of land-sea partitioning of the surface sources and sinks also for the 1980's. Accordingly, the tropical terrestrial regions must have been a net source of almost 1 $GtCyr^{-1}$ in the 1980's which subsequently decreased to the balanced conditions during the 1991-1994 period. It remains to be seen, whether shifting patterns of land-use or other factors, such as climate driven fluctuations are responsible for this trend.

Reference:

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In Search of a Language that Connects

John Stone, Richard Rockwell, and Chris Rapley

There is a need to connect the efforts of the research community working to understand our changing planet with the day-to-day concerns of the public and policy makers worldwide. In spite of substantial public interest in environmental issues, and significant media attention, there is a widespread lack of appreciation of the significance of the changes under way.

It is not just that scientists often find it difficult to explain themselves in plain language, but they have a tendency to assume that the relevance of research is self evident, when it is not.

How can we improve our effectiveness at getting the message across?

The following question and answer session, based on what we believe are deep human concerns, offers one approach:

Are we being poisoned?

Poisons involve more than eating or drinking things that make us ill or kill us. We are adding poisons to the air that we breathe. The sources include emissions from vehicles, from industry and from agriculture. Although some emissions are being controlled in some nations, the overall levels continue to increase because of growing populations and expanding economies. The problem is global. Even remote areas over the tropical ocean are found to be polluted by the products of agricultural burning on distant continents.

We can also be harmed by radiation. The Earth's outer ozone layer protects us and our crops from damage by ultraviolet radiation. The ozone layer has been thinning for several decades due to the emissions of certain man-made chemicals. In spite of international agreements which seek to eliminate the problem, ultraviolet radiation levels are not expected to decline significantly for some years yet.

Are we damaging our life support system?

The Earth's ecosystems provide a variety of services essential to our well-being - services for which we do not pay and which we take for granted. These include the purification of water and air, the recycling of nutrients, the generation and preservation of soils, the pollination of crops, and even the regulation of the atmosphere's oxygen content.

Ecosystems are being damaged by human activities. We know about the effects of acid rain on forests and lakes, of toxic chemicals on fish and wildlife, of increases in ultraviolet radiation on all forms of life, and of the major impacts of changes in land use. In the longer term, shifts in rainfall and temperature patterns, resulting from climate change, will also become important.

The Earth's ecosystems are being strained to the point where their capacity to provide services upon which we rely may be seriously impaired.

Is there a future for my children?

There is a tradition amongst some societies to "tread lightly on the Earth" - that we are only here as caretakers for our children, and that our actions must take into account the interests of future generations.

In practice the uncertainties are so great that we cannot predict the kind of future that our children will face. However, it is likely that they will experience profound changes in ecosystems, in the climate system, in the availability of water and food, and in the distribution of diseases.

When we reduce species diversity, we know that we are depriving our children of future resources. And yet we do not know enough at the moment to choose which resources to save and which to let go.

What can science contribute?

Nations, communities and individuals with the greatest understanding of global change and its consequences will be in a stronger position to take advantage of new opportunities and to adapt to the problems. Scientific research provides the best means of obtaining such understanding. Given the vast size and complexity of the Earth system, we cannot rely on the traditional methods of science. An unprecedented degree of interdisciplinary and international co-operation is necessary. To succeed will be science's greatest challenge, but progress will depend on a wide acceptance of the importance of the goal.

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