The Atmospheric CO_2 Perturbation

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Abstract. Althoug about one-half of released carbon has been sequestered by the ocean and the land biosphere, stabilization of atmospheric CO_2 levels, and thus a limitation of greenhouse gas warming, requires that carbon emissions are reduced well below 1990 levels. For if adverse climate changes do indeed materialise, trends may be persistent and even become aggravated.

Radiative forcing of greenhouse gases and aerosols

The continuously rising concentrations of infrared absorbing (greenhouse) gases such as carbon dioxide, methane, nitrous oxide, halocarbons and tropospheric ozone act to warm the Earth's surface. This warming is partially offset by the man-made increase in atmospheric aerosol loading (fig. 1). Among the absorbing gases, CO_2 contributes about 60 % to the increase in radiative forcing since pre-industrial time. CO_2 is expected also to be in future the most important anthropogenic greenhouse gas. The carbon cycle is therefore in the focus of the following text. I will first address the present understanding of the anthropogenic CO_2 perturbation and then discuss scenarios leading to stabilization of the atmospheric CO_2 concentration. For further information and references see the overviews by Houghton et al. (1994, 1996); Siegenthaler and Sarmiento (1993) and the data compendium by Boden et al. (1994).

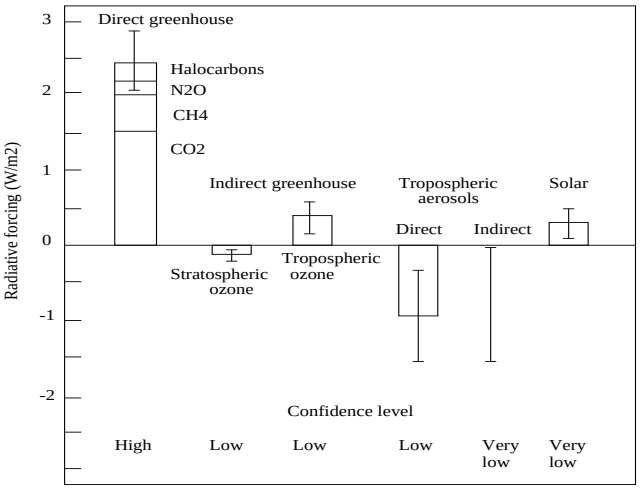

Figure 1. Estimates of the globally averaged radiative forcing due to changes in greenhouse gases and aerosols from pre-industrial time to present day and changes in solar variability from 1850 to present. The radiative forcing of a radiative agent is defined by the additional downward flux into the lower atmosphere mediated by an instantaneous increase of its concentration. The height of the bar indicates a mid-range estimate of the forcing while the lines show the possible range of values. An indication of relative confidence in the estimates is given below each bar. The negative values for aerosols should not necessarily be regarded as an offset against the greenhouse gas forcing as aerosols are distributed unevenly over the globe. Houghton et al. (1994)

1896: Arrhenius postulated global climate change

The basic greenhouse theory had been introduced in the beginning of the 18th century by the French mathemati-

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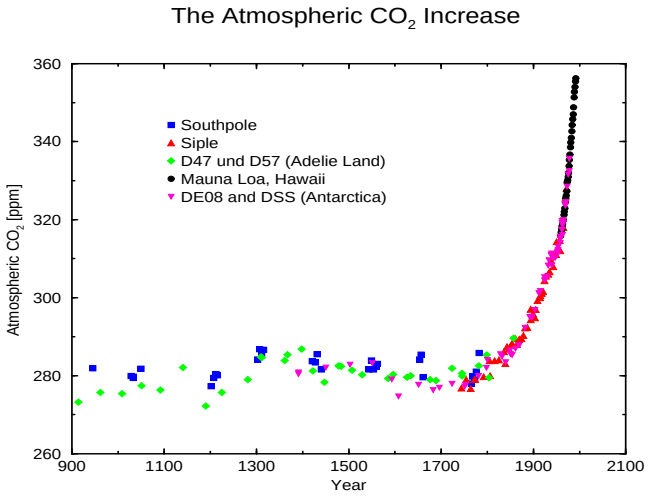

Figure 2. Atmospheric CO_2 has increased rapidly from its pre-industrial level of around 280 ppm to almost 360 ppm today. The data points are measurements on air bubbles entrapped in Antarctic ice cores as analyzed by groups in Australia, France, and Switzerland. Each dot of the most recent part of the record corresponds to the annual mean of direct atmospheric measurements taken at Mauna Loa, Hawai, since 1958. The ice core data overlap nicely with the atmospheric record. It is interesting to note that before the onset of industrialization the atmospheric concentration fluctuated only within a narrow range of a few percent.

cian J.-B. J. Fourier, who suggested that certain gases could absorb long-wave radiation emitted from the surface and the lower atmosphere. The absorbed energy is re-emitted thereby increasing the incoming radiation at the Earth's surface. Without the natural occurring greenhouse gases, - the most important is H_2O - , our environment would be uncomfortably cold. By the late 1850s, the British physicist J. Tyndall had analyzed the radiative properties of atmospheric gases and demonstrated that carbon dioxide is among those that strongly absorb infrared radiation.

In 1896, the Nobel Prize-winning Swedish chemist Svanté Arrhenius proposed that carbon dioxide emitted into the atmosphere by burning of fossil fuels such as coal, oil and natural gas was causing a change in the transparency of the atmosphere that might result in a warming outside previous human experience (Arrhenius, 1896).

Measurements demonstrate 30% increase in atmospheric CO_2

Arrhenius' idea lapsed into obscurity, in part because scientist doubted that carbon emitted by fossil fuel burning accumulates in the atmosphere. Today, we know that it does. Atmospheric CO_2 has risen from its pre-industrial level of around 280 ppm to 355 ppm in 1990. This increase has been demonstrated by C. D. Keeling's (Scripps Institution of Oceanography) measurements of atmospheric carbon dioxide starting in 1958 at Mauna Loa, Hawai and by the first CO_2 measurements on air bubbles entrapped in Antarctic ice analyzed in the early 1980s at the Climate and Environmental Physics in Bern. This data set forms perhaps the most important geophysical data record of the century. Meanwhile, the CO_2 increase has been confirmed by other laboratories analyzing several different ice cores; the atmospheric concentration is monitored at more than 40 stations around the globe. Fig. 2 shows that atmospheric CO_2 has been constant within the small range of 3% during the last millennium, before its rapid rise starting at the beginning of the industrial revolution.

The increase is without precedence in the last several hundred thousand years. Ice core measurements demonstrate that CO_2 levels have not exceeded values above 300 ppm during the last glacial interglacial cycles.

Human influence on global climate

Which are the consequences of the increased levels of CO_2 and other radiative agents? It is estimated that the mean global surface temperature has warmed by a few tenths of a degree due to the anthropogenic change in radiative forcing of around 1.5 Wm^{-2}. Proxi indicators such as tree ring width and the instrumental record indeed indicate that the 20th century is unusually warm. The mean global surface temperature has increased by 0.3 to 0.6 degree C since the late 19th century. In agreement with the expected anthropogenic signal, one observes a cooling in the stratosphere, an asymmetrie in the warming between the North and the Southern Hemisphere, a reduced daily temperature range over land, a retreat of Northern Hemisphere glaciers and sea ice coverage. Statistically convincing evidence for a human influence on climate comes from studies which compare modeled changes with observed geographical, seasonal and vertical patterns of atmospheric temperature change.

There remain some uncertainties in the detection of the anthropogenic climate signal. The actual climate of the Earth is given by the combined natural and anthropogenic signal. Natural variability results from both internal fluctuations such as circulation changes and external causes such as volcanic eruptions. The anthropogenic component of the climate system lags the actual forcing as it takes centuries to millenia to heat up the ocean. Nevertheless, the balance of evidence suggests a discernible human influence on global climate.

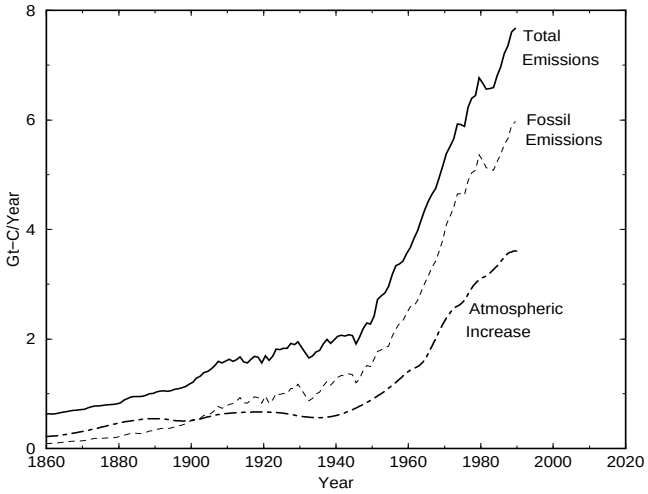

Figure 3. A comparison between the annual atmospheric growth rate in CO_2 and the anthropogenic emissions reveals that anthropogenic emissions where factor 2-3 larger than the increase in atmospheric carbon storage. The atmospheric growth rate is deduced from ice core and direct observations as shown in Fig. 2. Fossil emissions are compiled based on trade statistics by Marland and colleagues at the U.S. Department of Energy. The difference between fossil emissions and total anthropogenic emissions corresponds to the estimated carbon release due to land use changes and deforestation. For the period 1860-1989, the atmospheric increase of 138 Gt-C is about 2.5 times less than the cumulative anthropogenic emissions of 325 Gt-C. Thus, ocean and land biota acted as a sink for anthropogenic carbon.

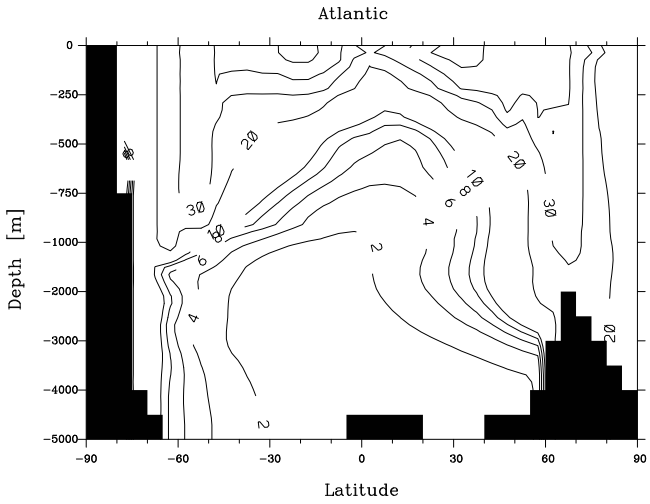

Figure 4. The distribution of anthropogenic carbon in the Atlantic (1990) as simulated by a dynamical 2-dimensional ocean model. The higher column inventories in the Southern Ocean and in the North Atlantic, - due the formation of sinking water and to more intense vertical overturning - , are in agreement with the high concentrations found for radioactive and transient tracers such as radiocarbon and CFCs in these regions. Note that the upper 1000 meters are expanded.

CO_2 increase is man-made

In less than two centuries, burning of fossil fuels has added 220 Gt-C (1 gigaton of carbon = 10^{12} kg C) to the atmosphere. This is only a small fraction of the total carbon in fossil fuel reserves, of which 1700 Gt-C is estimated to be recoverable with current technology. Another 110 Gt-C are estimated to have been released during land use changes and by deforestation. Fig. 3 shows that the atmospheric CO_2 increase is since 1900 for each decade lower than both the fossil emissions and the estimated total anthropogenic emissions. Besides the constancy in pre-industrial CO_2 levels and the large industrial emissions, more evidences demonstrate that the CO_2 increase is man-made. (1) CO_2 concentrations are larger in the Northern Hemisphere where 95% of the fossil carbon is released and the North-South difference has grown in parallel with emissions; (2) carbon of fossil origin has low concentrations of the carbon isotope ^{13}C and is free of ^{14}C which has vanished by its radioactive decay during the long storage. The atmospheric concentration of both isotopes has decreased in parallel to fossil emissions; (3) The observed decrease in atmospheric oxygen of a few ppm per year can be quantitatively linked with the anthropogenic CO_2 perturbation.

The key role of the ocean

Of the 330 Gt-C of anthropogenic emissions only about 43% are still found in the atmosphere; the rest has been taken up by the ocean and the land biota.

The ocean plays an unusually important role in the fate of emitted carbon dioxide. CO_2 reacts with water to form bicarbonate and carbonate ions. Due to this additional chemical components 65 times more carbon is found in the ocean than in the atmosphere. Without further understanding of the carbon chemistry and the slow ocean mixing, it may seem reasonable to assume that all the carbon added to the atmosphere would end up in the ocean in a short time.

In 1957, R. Revelle and H. Suess at the Scripps Institution of Oceanography, La Jolla, USA, published a paper that made major contributions to our understanding of the carbon cycle. They estimated carbon uptake by the ocean using a model to describe air-sea exchange, the carbon chemistry and ocean transport. They calculated that the chemical capacity of seawater to take up anthropogenic carbon is substantially less than might be expected by assuming that it would redistribute itself according to the present atmosphere and ocean inventories. Their chemical equilibration model that includes this 'Revelle effect' show that between 15 and 20% of the carbon dioxide added to the atmosphere will remain there permanently.

A big advancement was their use of radiocarbon mea-

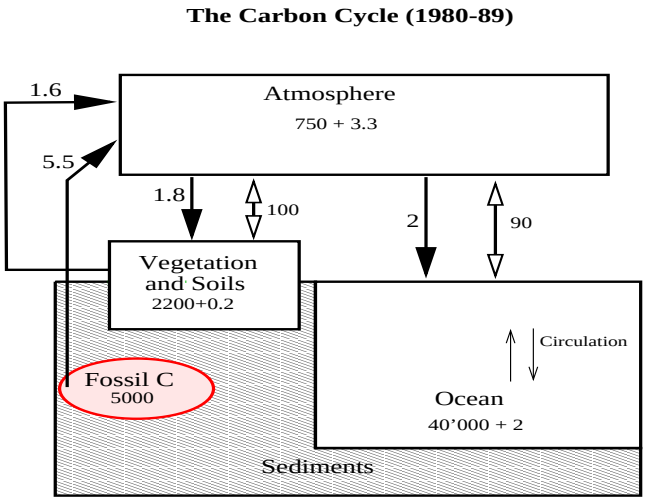

Figure 5. A simplified representation of the global carbon cycle and its perturbation by man. Arrows indicate net fluxes and exchange fluxes between different reservoirs in GtC yr^{-1}; numbers in boxes indicate inventories in Gt-C and their change in GtC yr^{-1}. Anthropogenic emissions by fossil fuel burning and land use changes amount to 7.1 GtC yr^{-1} during the last decade. On average, the ocean sequestered around 2 GtC yr^{-1} and the land biosphere (including soils) about 1.8 GtC yr^{-1}during the 1980-89 period. The net fluxes between the different reservoirs are much smaller than the exchange fluxes, e.g. primary production and plant plus soil respiration.

surements to demonstrate that ocean mixing is slow compared to the rate people release carbon. By cosmic rays, naturally produced radiocarbon enters the ocean by gas exchange and is mixed towards the abyss where its concentration decreases by the continuous radioactive decay. This 'radioactive clock' provides a measure of the surface-to-deep exchange rates and allowed Revelle and Suess to validate the transport in their ocean model.

The carbon budget for the last decade

Fig. 5 shows the budget of anthropogenic CO_2 for the last decade. In the 1980-89 period, 7.1 GtC yr^{-1} were added to the atmosphere by anthropogenic activities, namely by fossil fuel burning, and deforestation and land use changes. The carbon emission due to fossil fuel burning is known within 10% based on trade statistics, however, carbon emissions by land use changes are badly quantified (±60%). The average atmospheric increase of 3.3 GtC yr^{-1} is well known from observations. About 2 GtC yr^{-1} have been taken up by the ocean (fig. 4) and another 0.5 GtC yr^{-1} has been absorbed by regrowing forests in the Northern Hemisphere as revealed by forest inventories. This yields an imbalance in the budget of 1.4±1.5 GtC yr^{-1}.

In the past, this imbalance has been often referred as 'missing sink'. Meanwhile, analyses of the trends and distributions in atmospheric oxygen and the carbon isotope ^{13}C have lead to the conclusion that the carbon emission by land use changes and deforestation are offset by additional carbon sinks in the land biota (see Box: 'Constraints on the carbon budget'). The existence and magnitude of the budget imbalance and the required sink flux into the land biosphere are directly related to the estimated magnitude of this land use flux which remains uncertain. An indirect evidence for an enhanced biota activity is that the seasonal atmospheric CO_2 variations have increased significantly at many stations.

The mechanisms driving the additional terrestrial sink flux are not well quantified and a topic of intense research. Enhanced terrestrial carbon storage may have been stimulated by climatic variations. Probably important is a potential stimulus of primary production due to the elevated atmospheric CO_2 levels (CO_2 fertilization) and anthropogenically enhanced nitrogen input into the world's ecosystems.

Feedback processes

The natural carbon cycle, namely the interplay between air-sea gas exchange, ocean circulation and surface-to-deep export of particles formed by marine organisms, has set the pre-industrial CO_2 concentration. The natural carbon cycle has operated in an approximately constant mode during the historical period. In the future, its mode of operation may change.

The coupled atmosphere ocean general circulation model of the General Fluid Dynamics Laboratory (GFDL) in Princeton, USA, predicts for an increase in atmospheric CO_2, a global warming, changes in the hydrological cycle and a consequent decrease in the oceanic transport rates. This yields a large reduction in oceanic CO_2 uptake, - hence more CO_2 in the atmosphere -, as compared to a model run with present circulation patterns. The magnitude of such a reduction depends how the marine biota will adapt to circulation changes. The importance of this feedback remains still under debate and the circulation of the GFDL model may react too sensitive. However, it illustrates that future climate change may affect the operational mode of the atmosphere-ocean system and the carbon cycle.

Other important processes which will affect the future relationship between anthropogenic carbon emissions and atmospheric CO_2 are related to the land biota. The magnitude of future land use and forest management practice, the capacity of the biota to adapt to global warming and the magnitude of plant fertilization induced by elevated CO_2 levels and nitrogen input still

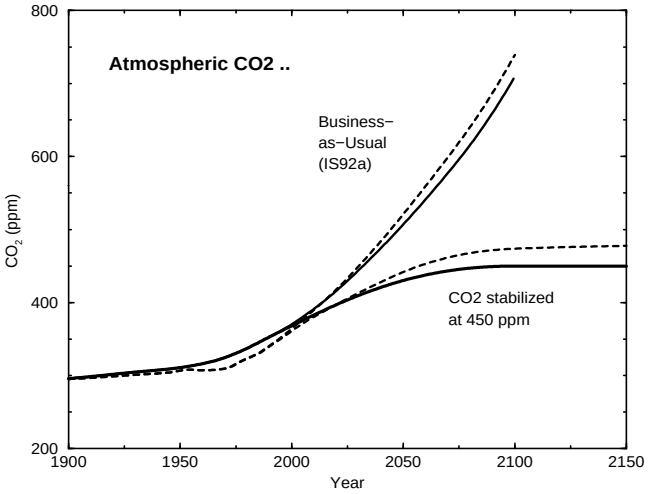

Figure 6. Atmospheric CO_2 concentration as calculated with the 'Bern' carbon cycle model for the central 'Business-as-Usual' scenario, IS92a, of the Intergovernmental Panel on Climate Change (IPCC). The scenario depends on assumption about population growth, economic growth, and various other factors. According to this scenario, carbon emissions increase from a present level of about 7 GtC yr^{-1} to about 20 GtC yr^{-1} at the end of the next century. The concentration profile to limit atmospheric CO_2 at 450 ppm was also developed by IPCC to illustrate emissions and climate change consequences. These are are shown in fig. 7 and fig. 8. Despite CO_2 other radiative forcing agents such as methane, nitrous oxide, halocarbons and aerosols are important. The dashed lines give the total radiative forcing of all relevant anthropogenic greenhouse gases and aerosols. For comparison, the total forcing has been expressed in units of CO_2(equivalent) . The relationship between CO_2 concentration and radiative forcing [forcing(W m^{-2}) =6.3 ln(CO_2 / 280 ppm)] allows one to convert the radiative forcing of other greenhouse gases and aerososls into units of CO_2(equivalent). The radivative forcing of non-CO_2 greenhouse gases happens to be roughly offset by the negative forcing due to aerosols. Uncertainties surrounding future emissions of aerosol precursor gases and related radiative forcing are large.

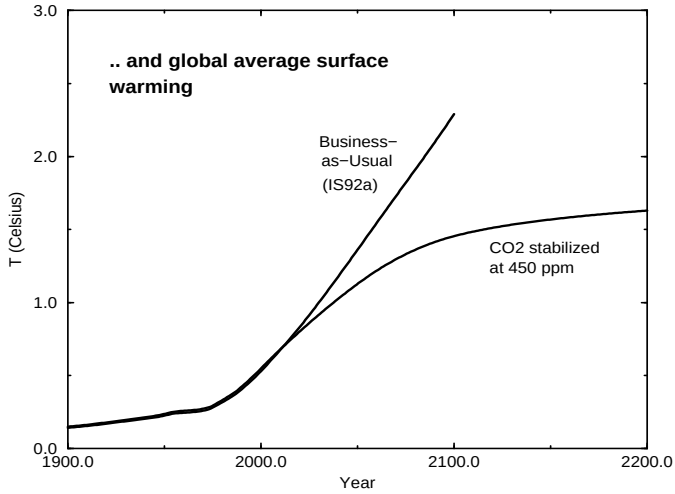

Figure 7. Global average surface warming as calculated by the 'Bern' model for scenario IS92a and the profile for stabilizing CO_2 at 450 ppm (fig. 6, dashed lines). The model is used to calculate the oceanic heat uptake. The temperature sensitivity is prescribed to be 2.5 degree for a doubling of atmospheric CO_2. This is the central value of sensitivities estimated by atmosphere general circulation models. The temperature continues to increase even after CO_2 stabilization as it takes many centuries to warm up the ocean.

remain to some degree unresolved.

Ice core measurements show that atmospheric CO_2 has varied due to oceanic processes within the range of 180 to 280 ppm between glacial-interglacial cycles. This changes took place on a time scale of several thousand years. Such Paleo observations offer a window to test our understanding of the climate-carbon cycle system.

Ḿusiness-as-Usual' scenarios

The atmospheric concentration of CO_2 will further rise in the near future as people continue to add carbon to the climate system. The magnitude of future emissions is difficult to predict and depends on various socio-economic factors. So called 'Business-as-Usual' scenarios prepared by the Intergovernmental Panel on Climate Change span the range of possible developments under the assumption that no policy measures are implemented to reduce carbon emissions. For the central scenario (IS92a) emissions are increasing rapidly and atmospheric CO_2 will double (=560 ppm) in the middle of the next century (fig. 6). If emissions are stabilized at 1990 levels, atmospheric CO_2 will continue to growth and reach a value of about 500 ppm at year 2100. To stabilize the concentration, it is therefore not sufficient to stabilize emissions.

For a (hypothetical) doubling of atmospheric CO_2 only, global mean surface temperature is modelled to increase in the range between 1.5 to 4.5 degree Celsius at equilibrium. Besides CO_2 other radiative forcing agents have to be considered as well. For the transient signal, the heat uptake by the ocean is crucial. According to the central 'Business-as-Usual' scenario of IPCC (IS92a), the global mean surface temperature would increase by more than 2 degrees Celsius until the end of the next century (fig. 7).

Is this a substantial change? The global mean surface temperature is a climate indicator. Apparently small changes of a few tenths of a degree correspond to a large climate change. For example, the global temperature difference between the last glacial and the present warm period is reconstructed to be around 5 degrees Celsius.

Regional changes in temperature, precipitation, frequencies of storms and droughts are relevant for the impact of a changing climate on the human society but also more difficult to predict. Even for an increasing global

mean temperature, some regions may still experience a cooling trend. Due to natural variability, we will also in future observe relatively cool years but with a decreasing probability.

1992: United Nations commitment to stabilize the climate system

The United Nations negotiated at the Rio Earth Summit in 1992 as an ultimate aim:

... to achieve stabilisation of greenhouse gas concentrations ... at a level that would prevent dangerous interference with the climate system ... within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

How do we need to change carbon emissions to meet this goal? For illustration, fig. 6 shows a possible pathways to stabilize the CO_2 concentration at 450 ppm. The pathway to stabilization is to some degree arbitrary. However, the cumulative allowed emissions for a certain concentration target is fixed as CO_2, unlike other gases, is not destroyed but redistributed within the climate system.
The emission consequences can be calculate using a carbon cycle model which allows one to calculate the carbon uptake by the land biota and the ocean. The model used here includes formulations for air-sea exchange, carbonate chemistry, surface-to-deep ocean mixing and a parameterization for CO_2 fertilization of the land biosphere. Fig. 8 shows that the anthropogenic emissions have to drop substantially compared to the 'Business-as-Usual' scenario of fig. 6 and eventually need to be phased out to meet the target of a stable atmospheric CO_2 concentration. For the next decades, carbon uptake by the different reservoirs are roughly of equal importance. In the long run, most of the emitted carbon will eventually end in the ocean.
Fig. 7 shows the temperature consequences for stabilization of CO_2 at 450 ppm. Here, emissions of other greenhouse gases and of aerosols have been assumed to remain constant on 1990 levels. The global mean temperature signal is expected to further growth in the next decades and will do so for many years even after the concentrations of radiative forcing agents have already been stabilized. Finally, it approaches according to this scenario a value of almost 2 degrees Celsius. If the global mean surface temperature signal should not change by more than half the glacial-interglacial temperature change, then, atmospheric CO_2 must probably be stabilized at levels below 500 ppm. Economic cost-benefit calculations suggest that measures to mitigate

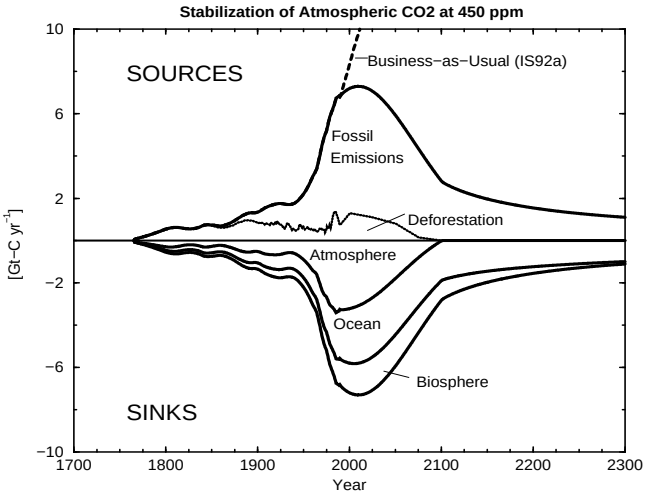

Figure 8. Anthropogenic emissions which are compatible with stabilization of the atmospheric CO_2 concentration at 450 ppm (profile of fig. 6) need to fall well below present level and must be phased out eventually. The anthropogenic emissions (SOURCES) are the sum of carbon release due to deforestation and other sources, namely fossil fuel burning. Their total has been deduced from the change in carbon inventories of the atmosphere, ocean and biosphere (SINKS; here plotted in a cumulative way). The atmospheric concentration was prescribed in the 'Bern' carbon cycle model and then ocean and biosphere carbon uptake was calculated. The dashed line gives the emission trend of the central 'Business-as-Usual' scenario (IS92a) as developed by the Intergovernmental Panel on Climate Change.

CO_2 emissions should be taken within the next few years if a 500 ppm threshold should not be exceeded.

Final remarks

Inertia in the global socio-economic and climate system is large. More than hundred years have passed since Arrhenius pointed out that emitted CO_2 accumulates in the atmosphere and leads to global warming. It takes years to decades to negotiate appropriate strategies, to implement policy measures, to develop new technologies, to replace existing high carbon emitting technologies, and to adapt infrastructure. Still larger inertia is found in the climate system. CO_2 emitted today will partially remain airborne for many centuries. Global temperature and sea level responses lag behind the radiative forcing imposed by greenhouse gases and other forcing agents as it takes many centuries to heat the water masses of the ocean. Still larger inertia is found when considering the response of the large ice sheets. Trends in the global society and climate system can not be changed immediately. The bottom line is that if indeed potentially adverse climate changes take place then the adverse trend may be a persistent one or even aggravate for some time.

As Revelle and Suess (1957) said in their paper:

Human beings are now carrying out a large-scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future. Within a few centuries we are returning to the atmosphere and oceans the concentrated organic carbon stored in sedimentary rocks over hundreds of millions of years.

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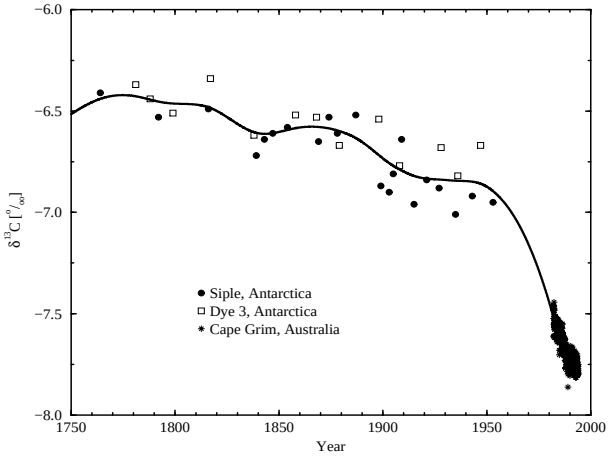

Figure 9. Different carbon reservoirs have different isotopic compositions which are usually expressed in units of per mil δ^{13}C,i.e. the normalized $^{13}C/^{12}C$ ratio. The decrease in atmospheric δ^{13}C is due to the addition of isotopically light fossil fuel and plant carbon to the atmosphere. The isotopic budget for the atmosphere combined with the estimated source strength of fossil ^{13}C provides an additional constraint on the magnitude of the carbon uptake by the ocean and the biota. Filled circles and open squares represent measurements taken by Friedli, Leuenberger and colleagues at Climate and Environmental Physics in Bern, Switzerland, at air bubbles entrapped in Antarctic ice cores. The direct atmospheric samples from Cape Grim, Australia, (stars) have been analyzed by Roger Francey's group at CSIRO (most recent, unreleased ice core measurements fill the data gap between 1950 and 1980).

Box1: Constraints on the carbon budget

Why remains the budget of anthropogenic CO_2 still uncertain? The difficulties arise both from the spatial and temporal scales involved. The dimensions of our planet as well as daily, seasonal, and inter-annual fluctuations make it very difficult to measure directly the carbon uptake by the land biota and by the ocean. The net fluxes between the atmosphere ocean and biosphere are only a few percent of the total exchange fluxes, e.g. primary production and respiration. The estimated enhanced carbon storage in the land biota (1850-1990: 100 Gt-C) is small compared to the total standing stocks in the living vegetation and in soils (2200 Gt-C). Similarly, estimated ocean uptake of 120 Gt-C (1800-1990) is only a minor fraction of the total ocean carbon inventory of 40'000 Gt-C.

Fortunately, there exist a variety of other constraints on the budget of anthropogenic carbon.

(1) Oxygen is in many aspects complementary to carbon. During respiration of plant material and during fossil fuel burning approximately one mol oxygen is consumed for the production of one mol CO_2. Thus, oxygen decreases in parallel to the increase in atmospheric CO_2. However, unlike carbon the ocean mitigates only a minor amount of the atmospheric trends as only one percent of the combined atmosphere-ocean inventory is in the ocean. Based on most recent measurements R. Keeling and colleagues estimated net carbon fluxes into the ocean of 1.9 $\pm$0.5 GtC yr^{-1}and into the biota of 1.8 $\pm$0.7 GtC yr^{-1} during 1989 to 1994.

(2) The atmospheric as well as the oceanic distribution of the isotope ^{13}C (Fig. 9) provides a further constraint. Fossil and plant material is tagged by a lower $^{13}C/^{12}C$ isotope ratio than atmospheric and oceanic carbon. This allowed Heimann and Maier-Reimer to estimate a mean ocean uptake of 2.2 $\pm$0.8 GtC yr^{-1} for the period 1970 to 1990.

(3) Revelle's and Suess' classical method to determine the carbon uptake by an ocean model has remained one of the quantitatively most reliable method. The three key processes that need to be taken into account are the air-sea gas exchange rate, the carbonate seawater chemistry and the surface-to-deep transport. Ocean transport remains the crucial and rate limiting step. The present hierarchies of ocean models includes spatially aggregated box models which describe the ocean mixing in a parameterized way, and 2-dimensional and 3-dimensional ocean models, which resolve the topography and derive the circulation from first order physical principles (equation of motion and state). Meanwhile the distribution of a variety of radioactive or transient tracers such as CFCs, bomb-produced radiocarbon, Argon-39 has been mapped and allows one to check the transport rates of ocean models vigorously.

(4) The net uptake by the ocean is driven by a tiny difference in the global atmosphere and surface ocean partial pressure. A net transfer of 2 GtC yr^{-1}into the ocean corresponds to a partial pressure difference of only about 8 ppm which is one order of magnitude smaller than natural variability. Despite this difficulties, present sets of pCO_2 observations confirm the model estimates.

(5) The natural oceanic distribution of carbon is regulated by the interplay of gas exchange, solubility, ocean circulation, and the continuous surface-to-deep export of organic matter and calcite mediated by the biological activity in the surface ocean. Sophisticated methods are used to subtract the contributions of this processes using observed distributions of total inorganic carbon and nutrients like phosphate to obtain an estimate of the standing stock of 'anthropogenic' carbon. Again, the results confirm the ocean model estimates.

(6)The atmospheric distribution of carbon and carbon isotopes can be linked to regional sources and sinks by using atmospheric transport models. Though present results are still controversial this method offers a large potential for the future to resolve sources and sinks as the network of CO_2 stations is increasing.

Dr. Fortunat Joos is a research assistant at the Climate and Environmental Physics in Bern, Switzerland. His main interest is in the global carbon cycle. He has contributed as a lead author and modeler to the Second Scientific Assessment of Climate Change by the Intergovernmental Panel on Climate Change.