The Atmospheric CO$_2$ Perturbation

F. Joos
Climate and Environmental Physics
Sidlerstr. 5, CH-3012 Bern, Switzerland

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F. Joos
KUP
Sidlerstr. 5
CH-3012 Bern
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Abstract. Although 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).

1896: Arrhenius postulated global climate change

The basic greenhouse theory had been introduced in the beginning of the 19th century by the French mathematician.
Atmospheric CO₂ 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, Hawaii, 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.

Figure 2. Atmospheric CO₂ 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, Hawaii, 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.

Measurements demonstrate 30% increase in atmospheric CO₂

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 CO₂ 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, Hawaii and by the first CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 W m⁻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 asymmetry 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 millennia to heat up the ocean. Nevertheless, the balance of evidence suggests a discernible human influence on global climate.
In less than two centuries, burning of fossil fuels has added 220 Gt-C (1 gigaton of carbon = 10¹² 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 deforestation. Fig. 3 shows that the atmospheric CO₂ 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 CO₂ levels and the large industrial emissions, more evidences demonstrate that the CO₂ increase is man-made. (1) CO₂ 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 ¹³C and is free of ¹⁴C 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 CO₂ 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. CO₂ 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-
The carbon cycle for the last decade

Fig. 5 shows the budget of anthropogenic CO₂ for the last decade. In the 1980-89 period, 7.1 Gt C 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 Gt C yr⁻¹ is well known from observations. About 2 Gt C yr⁻¹ have been taken up by the ocean (fig. 4) and another 0.5 Gt C 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 Gt C 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 ¹³C 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 CO₂ 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 CO₂ levels (CO₂ 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 CO₂ 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 CO₂, a global warming, changes in the hydrological cycle and a consequent decrease in the oceanic transport rates. This yields a large reduction in oceanic CO₂ uptake, - hence more CO₂ 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 CO₂ 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 CO₂ levels and nitrogen input still...
The atmospheric concentration of CO₂ 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 CO₂ will double (=500 ppm) in the middle of the next century (fig. 6). If emissions are stabilized at 1990 levels, atmospheric CO₂ will continue to grow 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 CO₂ only, global mean surface temperature is modelled to increase in the range between 1.5 to 4.5 degree Celsius at equilibrium. Besides CO₂ 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 CO₂ 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 CO₂, 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ must probably be stabilized at levels below 500 ppm. Economic cost-benefit calculations suggest that measures to mitigate CO₂ 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 CO₂ 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. CO₂ 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 geo-
physical experiment of a kind that could not have hap-
pened 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 sedi-
mentary rocks over hundreds of millions of years.*

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Why remains the budget of anthropogenic CO\textsubscript{2} uncertain? The difficulties arise both from the spatial and temporal scales involved. The dimensions of our planet 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\textsubscript{2}. Thus, oxygen decreases in parallel to the increase in atmospheric CO\textsubscript{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 Gt C yr\textsuperscript{-1} and into the biota of 1.8 \pm 0.7 Gt C yr\textsuperscript{-1} during 1989 to 1994.

2. The atmospheric as well as the oceanic distribution of the isotope \textsuperscript{13}C (Fig. 9) provides a further constraint. Fossil and plant material is tagged by a lower \textsuperscript{13}C/\textsuperscript{12}C isotope ratio than atmospheric and oceanic carbon. This allowed Heimann and Maier-Reimer to estimate the ocean uptake of 2.2 \pm 0.8 Gt C yr\textsuperscript{-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 methods. The three 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 Gt C yr\textsuperscript{-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\textsubscript{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 these 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\textsubscript{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.