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A Review of the Contemporary Global Carbon Cycle and as Seen a Century Ago by Arrhenius and Högblom

The agenda of global carbon cycle research features two fundamental problems. The first concerns the direct response of the carbon system to the anthropogenic perturbation, i.e. how is the excess carbon dioxide emitted by fossil fuel burning and from changes in land use (i.e. deforestation) distributed between atmosphere, land and the ocean, and how is this distribution changing as a function of time? The second problem addresses the feedbacks, i.e. how do changes in climate feedback on the natural carbon cycle and may thus lead to variations in the atmospheric CO2 concentration? This paper reviews some of the observational constraints to addressing these problems: (i) The direct atmospheric observations and the ice-core measurements which document the CO2 increase during the last 100 years; (ii) the role of the ocean in the current atmospheric CO2 budget as determined from model simulations and by new methods based on observations of oxygen and carbon isotopes; and (iii) the spatial information revealed by the global CO2 monitoring networks. One hundred years ago, Arrhenius and his geologist colleague Högblom were both aware of the major processes which control the atmospheric CO2 concentration, however, they were more interested in the long-term aspects and did not perceive the industrial emissions as an immediate threat to the global climate. Today, we can quantify and model the direct response to anthropogenic perturbation, although important uncertainties still exist, in particular with respect to terrestrial biospheric processes. However, our understanding of the multitude of climatic feedbacks on the carbon cycle is very limited. This problem constitutes a challenge that will remain on the scientific agenda for the next decades.

INTRODUCTION

Honoring the work of Svante Arrhenius certainly would not be complete without an appraisal of his insights into the workings of the global carbon cycle. It must be stated at the outset, however, that Arrhenius’ comments and speculations about processes and possible changes in the global carbon cycle draw heavily on the work of his colleague, Professor Högblom, a geologist, to whom he gives due credit. What were Högblom’s and Arrhenius’ interests and how do we perceive the global carbon cycle today? In this paper I outline some of the key issues of current carbon cycle research and confront them to what was known 100 years ago (1–3). Clearly, such a review cannot be comprehensive because the carbon cycle represents a vast, interdisciplinary field and much work has been performed, especially during the last 40 years. Therefore, I make a subjective selection which centers around large-scale observational constraints on the workings of the carbon cycle as revealed by atmospheric and oceanic measurement programs.

Figure 1 shows, schematically, the global carbon cycle, its major interaction pathways with the physical climate system and, on the right-hand side, present-day direct anthropogenic impacts, i.e. the emissions of CO2 from fossil fuel burning and from changes in land use. Both, the climate system and the anthropogenic impacts primarily affect the carbon reservoirs that rapidly exchange carbon on timescales of up to a few thousand years: (i) the atmosphere, where carbon exists primarily in the form of the chemically inert carbon dioxide gas; (ii) the ocean, which contains carbon in dissolved inorganic forms and as organic matter; and (iii) the terrestrial biosphere, holding organic carbon in living and dead vegetation and in soils. Exchanges with the lithosphere by weathering, sedimentation and volcanism are important only on timescales beyond several thousand years.

A multitude of interaction pathways exist between the physical climate system and the different carbon reservoirs. The most prominent which is the concentration of CO2, an atmospheric trace gas, which through its physical properties influences the radiation balance of the Earth. Therefore, variations of the atmospheric concentration of CO2 may lead to climate changes. It is this link which was Arrhenius’ primary interest, and which is covered extensively in other contributions of this volume. Contrary to how we pose the CO2-climate problem today, Arrhenius addressed it in the reverse order: Firstly he derived an estimate of the climate sensitivity, i.e. the magnitude of the global average surface temperature as a function of the atmospheric CO2 concentration. Based on this, he subsequently inferred the needed CO2 concentration variations in order to explain past climate changes, such as the glacial-interglacial cycles. He then speculated whether changes in the natural global carbon cycle may indeed involve atmospheric CO2 fluctuations of the required magnitude.

Arrhenius was aware of possible anthropogenic influences on the carbon cycle, too. However, as discussed below, the relatively modest CO2 emissions from fossil fuel burning in his time made him overlook these as an immediate threat to the climate system. Arrhenius’ interest was more directed to long time scales, such as the glacial cycles, and he and Högblom primarily analyzed the various interactions between the carbon cycle and the lithosphere (Fig. 1).

In the context of “global change” our present-day interest is strongly focussed on the consequences of the various anthropogenic impacts on the global carbon cycle and on time scales relevant to our societies which are less than a few hundred years. In this perspective, we have to investigate, quantify and eventually model the processes that control the exchanges of CO2 among the fast cycling carbon pools, i.e. the atmosphere and the oceans and terrestrial biosphere.

In analyzing the system (Fig. 1) it is useful to distinguish between two key questions:

i) What is the direct response of the carbon cycle to the anthropogenic emissions of CO2, i.e. how will the atmospheric CO2 concentration evolve given prescribed scenarios of past and future CO2 emissions?

ii) How will changes in the physical climate system feed back on the oceanic and terrestrial carbon systems and, through modified sources and sinks induce changes in the atmospheric CO2 concentration?

Our understanding regarding the direct response has considerably advanced, and it is possible today to provide credible sce-
nario calculations of future CO₂ concentrations. On the other hand, feedback effects are still poorly understood.

CHANGES IN THE ATMOSPHERIC CO₂ CONCENTRATION

In his book Arrhenius (2) describes measurements of the atmospheric CO₂ from several locations around the globe. However, the cited values exhibit considerable scatter and it is clear that long-term time series would not have revealed significant trends. Indeed, variations of the atmospheric CO₂ content were not very well known until the late 1950s when accurate measurements of the atmospheric CO₂ content became available (4). It became soon evident, that the atmospheric CO₂ concentration is indeed increasing. Figure 2 shows the longest direct atmospheric records obtained so far at the Mauna Loa (Hawaii) and at the South Pole station (5).

Many interesting features are present in the records shown in Figure 2. Most prominent are the seasonal cycles with opposite phase and larger amplitude in the Northern compared to the Southern Hemisphere, which are superimposed on a longer term rising trend.

During the 1970s and 1980s several global CO₂ monitoring station networks have been established, which give us a much more detailed picture of the atmospheric CO₂ concentration variations. The largest of these programs, run by the US National Oceano-

graphic and Atmospheric Administration (NOAA) routinely processes flask measurements from more than 32 stations distributed all over the globe (7). All of these stations confirm the globally rising trend of the CO₂ concentration. However, as is discussed below in more detail, the main value of the global station networks is that they allow the detection of the small spatial concentration gradients between different sites, which are caused by the nonuniform distribution of sources and sinks at the surface of the earth.

An extension of the atmospheric record to preindustrial times became available in the late 1980s with measurements of air bubbles enclosed in polar ice (8, 9). The most accurate record from ice cores obtained so far is shown in Figure 3 (10). This record is believed to be accurate to better than 1.3 ppmv. The increase in the atmospheric CO₂ concentration after the beginning of the industrial revolution is seen to be without any precedent over the prior 400 years. The extension of the ice-core record further back in time, however, confirmed Arrhenius’ speculations that major changes in the atmospheric CO₂ content, caused by natural processes, can indeed occur: As determined from several ice-cores the atmospheric CO₂ concentration was substantially lower (180–200 ppmv) during the last and the penultimate glacial maximum (11–13). Whether this lower CO₂ concentration contributed substantially to climatic cooling over that period, however, is still a controversial subject. Conversely, the mechanism in the carbon cycle responsible for the glacial lowering of the atmospheric CO₂ concentration is not yet understood (14). In any case, the synchronous changes in temperature and the CO₂ concentration clearly document a close link between the global carbon cycle and the physical climate system.

THE OCEANIC RESPONSE TO THE RISING ATMOSPHERIC PARTIAL PRESSURE OF CO₂

Arrhenius (2) believed that the anthropogenic impact on the atmospheric CO₂ concentration would be relatively minor. Based on an estimate of fossil fuel CO₂ emissions of 0.7 GtC yr⁻¹ for the year 1900, he correctly inferred that this corresponds to about 1/900 of the atmospheric CO₂ content, or 0.33 ppmv if distributed.
over the whole globe. He then realized that the ocean will moderate to a large extent this increase. He deduced that 5/6 of the emitted CO₂ would be absorbed by the ocean and only 1/6, i.e. a mere 0.055 ppmv of the excess CO₂ would actually accumulate annually in the atmosphere. Based on this Arrhenius calculated that within 54 years such an increase would correspond to approximately 3 ppmv, or 1% of the atmospheric CO₂ content. Clearly, such a small annual increment would be difficult to observe even with present day measuring techniques.

Arrhenius’ computation of the so-called airborne fraction with respect to ocean uptake was correct. Indeed, considering the response of an idealized atmosphere-ocean system to an initial unit pulse input, it can be readily computed that about 1/6 will remain in the atmosphere forever. The numerical value of 1/6 is based on the well known carbonate chemistry of seawater (15, 16) and reflects the buffering effect of the ocean carbonate system.

Arrhenius’ calculation pertains to the long-term equilibrium response of the air-sea system. The time required to establish this equilibrium, however, depends crucially on the internal mixing time of the ocean, which is on the order of several hundred to a few thousand years. Arrhenius did not foresee the more than 10-fold, almost exponential increase in CO₂ emission rates over the last 100 years and that on short time scales the airborne fraction is determined to a large extent by the volume of the ocean that mixes rapidly enough to “see” the atmospheric perturbation. The present-day anthropogenic perturbation proceeds with a time constant (e-folding time) of about 30 years. Based on this, it can be shown that on average only the upper 500 m of the ocean are available for storage of excess carbon (17). It is easy to show, that in this case the airborne fraction with respect to ocean uptake is about 60%, i.e. substantially larger than the long-term equilibrium value.

An accurate computation of the oceanic uptake of excess CO₂ requires the knowledge of oceanic mixing which necessitates the use of realistic ocean models. Early computations made use of models consisting of a few “boxes” which are connected by water-flows, the magnitude of which was determined either from auxiliary oceanographic knowledge or by optimizing the flows such that the modeled distribution of radioactive tracers (e.g. natural and bomb produced radiocarbon) fitted the observations (18–20). Today, most ocean carbon models are based on three-dimensional flowfields computed by global ocean general circulation models. In addition to the carbon compounds (dissolved CO₂, bicarbonate and carbonate ions), these models typically describe transport and transformation processes of additional oceanic biochemical tracers such as alkalinity, dissolved and particulate organic carbon, calcium carbonate, silicate, phosphorus, oxygen, etc. and include a simple representation of the marine biota (21–23). As an example, Figure 4 shows schematically and simplified the processes that are included in the Hamburg Model of the Oceanic Carbon Cycle (HAMOCC) (21). It must be stated, though, that the inclusion of the detailed biogeochemistry beyond the carbonate system is not very important for the determination of the oceanic uptake of excess CO₂. This is because it is generally believed (24, 25) that the marine biota is limited not by the abundant dissolved inorganic carbon, but by nutrients (e.g. nitrate and phosphate) and micronutrients such as iron (26, 27). An increase in the atmospheric CO₂ will lead to an increase in dissolved inorganic carbon but not to any changes in nutrients, and hence will not affect marine productivity.

The confidence in the ability of present state-of-the-art ocean carbon models to accurately compute the uptake of excess CO₂ stems from detailed validation simulation experiments with transient tracers such as bomb-radiocarbon, tritium and chlorofluorocarbons. Crucial contributions were the large observational programs of GEOSECS and TTO, which provided a first database with global coverage of the penetration of bomb radiocarbon (28, 29). This database is now routinely used to validate the decadal time-scale mixing properties of global ocean models (30), even though bomb-radiocarbon is not an exact analog to the excess CO₂ absorbed by the ocean (17).

Despite different grid resolutions, numerics and subgrid-scale parameterizations the few existing 3d global ocean models com-

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Figure 3. Variations of the atmospheric CO₂ concentration during the last 800 years as reconstructed from measurements on air enclosed in Antarctic ice (10).
pute a surprisingly similar ocean uptake of excess CO$_2$ when run through the industrial period with the observed atmospheric CO$_2$ concentration history as a prescribed upper boundary condition. As summarized in the 1994 IPCC report (31) the predicted global uptake for the 1980–1989 time period is $1.8 \pm 0.5$ GtC yr$^{-1}$ (The error reflects the 90% confidence interval). This agreement might be fortuitous, since all existing models employ a relatively coarse grid (equivalent to 2–4 degrees in latitude and longitude and 10–20 layers in the vertical dimension), and are not able to resolve crucial small-scale features of the oceanic circulation, such as mesoscale eddies or convective processes in high latitudes. But also the resolved oceanic circulation is different among the models. Indeed, first results from the ongoing Ocean Carbon Model Intercomparison Project (OCMIP), an activity of the Global Analysis, Interpretation and Modelling (GAIM) task force of the International Geosphere Biosphere Programme (IGBP), reveal substantial differences in the spatial patterns of the computed oceanic uptake of excess CO$_2$.

Even if interactions with the oceanic biogeochemistry and the marine biota are not very important for the passive oceanic uptake of excess CO$_2$, these processes are nevertheless crucial when the climate-carbon cycle feedback problem is addressed; i.e. when possible changes in the oceanic circulation are to be taken into account. In this case, the ocean carbon cycle model must be coupled to the ocean general circulation model. The first, pioneering study performed with the Hamburg coupled models (32) using a standard global warming scenario revealed only a modest feedback effect, at least in comparison to the direct increases in atmospheric CO$_2$ due to the projected future CO$_2$ emissions from fossil fuels. This study, however, was confined to a simulation of the next century only. If longer timescales and more drastic scenarios are considered then substantial feedback effects may indeed occur (33).

On timescales beyond several hundred years, interactions between ocean biochemistry and the sediments (e.g. sedimentation, carbonate dissolution) become important. If these are taken into account, the equilibrium response of the atmosphere-ocean system after a unit CO$_2$ input is no longer governed by Arrhenius' equilibrium airborne fraction. Due to carbonate dissolution the ocean can absorb about a factor of 2 more of the excess CO$_2$ (25).

THE GLOBAL BUDGETS OF CARBON AND OXYGEN

A crucial test of our understanding of the global carbon cycle is provided by the current atmospheric carbon budget. The recent assessment by the Intergovernmental Panel on Climate Change (IPCC) 1994 (31) of the different budget terms and their uncertainties (estimated 90% confidence intervals) is given in Table 1. The listed numbers represent averages over the 1980–1989 time period. Compared to the IPCC budget, Table 1 has been reorganized to more clearly reflect how the different terms have been determined. Accordingly, CO$_2$ emissions from fossil fuel use, as determined from energy use statistics amount to 5.5 GtC yr$^{-1}$. This number includes a small contribution (~2%) of CO$_2$ released by the production of cement. The atmospheric increase 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 GtC yr$^{-1}$ is based on detailed ocean model calculations. Table 1 also lists two additional, essentially model independent, estimates of the oceanic uptake rate obtained from observations of the $^{13}$C/$^{12}$C ratio in the atmosphere and the ocean (17, 34, 35), and from observations of the temporal trend in the O$_2$/N$_2$ ratio in atmospheric air (6, 36, 37, 67), which confirm the model-based estimates albeit with substantial error margins. 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.

The fossil fuel CO$_2$ emissions, together with the atmospheric and oceanic CO$_2$ uptake imply by the conservation of carbon that during 1980–1989 the terrestrial biosphere as a whole must have been a very small net sink (0.3 ± 1.0 GtC yr$^{-1}$) or effectively be almost in balance. However, from the analysis of statistics of land-use changes (e.g. deforestation) a substantial terrestrial CO$_2$ source of 1.6 ± 1.0 GtC yr$^{-1}$ can be deduced (38). In order to achieve the inferred net balance of the terrestrial biosphere, additional terrestrial sink processes must operate. From forest statistics regrowing temperate latitude forests have been identified as a potential sink which might sequester currently up to 0.5 GtC yr$^{-1}$. The closing of the budget, however, requires still additional terrestrial sink processes which, as a whole, must amount to 1.4 ± 1.5 GtC yr$^{-1}$. Potential candidates are the fertilization effects due to the increasing CO$_2$ concentration and/or from increased nitrogen deposition. It must be realized though, that the budget as portrayed in Table 1 does not only reflect the direct response of the carbon cycle to the anthropogenic perturbation, but that the observed atmospheric increase might also reflect temporary fluxes driven by interannual and longer-term climate anomalies (39).

One of the most significant advances in the last few years has been the development of a measurement method to determine, with high-precision, changes in atmospheric oxygen (5, 36, 37). 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 over 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 during photosynthesis O$_2$ is produced and during any oxidation process O$_2$ is consumed 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 two gases behave dynamically different and measurements of the two gases are therefore not redundant.

Figure 2 shows for the time period after 1989 the longest available O$_2$ record from the La Jolla station (R. Keeling, unpubl. data, and 6) (right-hand scale). The measurements are expressed as ppmv deviations from a standard, which corresponds to approximately 209 500 ppmv. It can be seen that the oxygen con-
centration is diminishing at a slightly faster rate than the increase of the CO$_2$ concentration. This reflects on the one hand the stoichiometric relation between O$_2$ and CO$_2$ in burning of fossil fuels of about -1.4:1 (40) 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$_2$ thus provide two budget equations, which allow a discrimination of global oceanic and biospheric contributions in the global CO$_2$ balance. Graphically the two equations can be displayed in an O$_2$/N$_2$-CO$_2$ vector diagram (Fig. 5) (6). In such a graph, because of the different geochemistry of the two gases, oceanic uptake or release changes the state vector in the horizontal direction since there is no associated O$_2$ change, while biospheric uptake or release follows along a diagonal line with a slope defined by the stoichiometric relation for biospheric carbon. It is seen that the burning of fossil fuels during the three years 1991–1994 alone would have moved the state vector along the long arrow to the lower right, increasing atmospheric CO$_2$ by 8.9 ppmv and lowering the O$_2$/N$_2$ ratio by 60.4 per meq. The observed change is less, both in CO$_2$ and oxygen. As seen in the vector diagram, the observations can only be explained by a particular combination of oceanic and terrestrial uptake vectors. Performing the analysis over the slightly longer La Jolla record (1989–1994) the analysis yields an average oceanic sink of 1.9 ± 0.8 GtC yr$^{-1}$ (the error is the estimated 90% confidence interval). The oxygen technique thus provides a new means to cross-check the global rates computed by ocean carbon models. 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 further decrease substantially. The oxygen analysis (Fig. 5) yields also an estimate of the global net terrestrial balance over the 1991–1994 time period amounting to 2.0 ± 1.5 GtC yr$^{-1}$. This is much larger than during the IPCC base period as listed in Table 1. The reason is that during the early 1990s the atmospheric CO$_2$ growth rate was much smaller than during the 1980s.

**SPATIAL INFORMATION: THE MERIDIONAL CONCENTRATION GRADIENT**

A close inspection of the Mauna Loa and the South Pole station records (Fig. 2) reveals that the concentration difference between the two stations, on annual average, increases with time: in the late 1950s the South Pole and the Mauna Loa record are almost at the same level, while in the early 1990s the difference between the two stations has increased to almost 3 ppmv. The increase of this concentration difference documents the increasing CO$_2$ emissions from fossil fuel use, which takes place primarily in the Northern Hemisphere. Indeed, it is easy to show, that under the assumption of no interannual variations in atmospheric transport the concentration difference between the two hemispheres should, on annual average, be linearly related to the difference in the net CO$_2$ sources in the two hemispheres (41, 42). A regression between the concentration difference Mauna Loa-South Pole and the total CO$_2$ emissions from fossil fuel use shows that the change in emissions alone can explain most of the observed features in the difference record (Fig. 6). This provides one of the most compelling pieces of evidence that the observed concentration increase must be directly related to anthropogenic influences.

A quantitative analysis of the interhemispheric concentration difference and of the more detailed spatio-temporal structures revealed by the records from the global monitoring station networks since the late 1970s requires a model which accurately describes the mixing of air in the global troposphere. Studies employed simple box-models or one-dimensional, meridional eddy-diffusion models (43–46) to describe meridional transport.

These studies have now been superseded by calculations with three-dimensional models of atmospheric transport based on meteorology from either climate or weather forecast models (47, 48), and recently by online calculations of transport within atmospheric general circulation models (49, 50). The realism of these models to describe the global-scale atmospheric mixing, typically, is assessed by means of simulations of tracers with known source-sink configurations, such as Krypton-85, CFC-11 or SF6 (51) and comparing with observations. Nevertheless, the existing models display a significant variance in large-scale and interhemispheric transport, as witnessed in a recent international model intercomparison (52).

The inversion of the spatial concentration patterns in order to deduce magnitude and locations of surface sources and sinks is a very difficult problem because of the strongly diffusive nature of oceanic uptake and release (100). The problem of linear inversions is simplified if the sink conditions are known from the analysis of tracers (52). The standard method of the inversion is the inverse method (53) (which is also known as the Kalman filter (54) in the domain of linear dynamic systems), which is an iterative method for deducing the state vector from measurements. The method is very general and can be used to estimate any state vector from measurements of the state vector itself and of the error in the measurements. It is an extremely accurate method, not only in the domain of linear dynamic systems, but also in the domain of nonlinear dynamic systems (52). The standard method of the inversion is the inverse method (53) (which is also known as the Kalman filter (54) in the domain of linear dynamic systems), which is an iterative method for deducing the state vector from measurements. The method is very general and can be used to estimate any state vector from measurements of the state vector itself and of the error in the measurements. It is an extremely accurate method, not only in the domain of linear dynamic systems, but also in the domain of nonlinear dynamic systems (52).

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**Figure 5.** Globally and annually averaged oxygen versus CO$_2$ concentration over the time period 1991–1994. The oxygen concentration is displayed as the measured O$_2$/N$_2$ ratio and expressed in “per meq” which denote the ppm deviation from a standard ratio. The inset shows the directions of the state vector expected for terrestrial and oceanic uptake. The long arrow shows the expected atmospheric trend from fossil fuel burning alone if there were no oceanic and terrestrial exchanges (6).

**Figure 6.** Annually averaged concentration difference between the Mauna Loa and South Pole station (black dots, left axis) and the emissions of CO$_2$ from fossil fuel use (solid line, right axis). The scales have been linearly adjusted such that an optimal fit is achieved according to CMLO - CSEP = -0.794 ± 0.510 Qfoss. (Note that there remains a negative concentration offset between the two stations even in the absence of fossil fuel CO$_2$ emissions).
of atmospheric transport (53, 54). Nevertheless, the most conspicuous result from these studies was the inference of a strong, presumably natural, CO$_2$ sink in the Northern Hemisphere (55, 56). The evidence is shown in Figure 7, where the mean annual concentration observed at various stations of the NOAA and SIO networks is plotted as a difference from the South Pole value versus latitude. The data reflect averages over the 1980–1987 time period. An interhemispheric concentration gradient of about 3 ppvm is clearly discernible. Also shown is the zonally averaged meridional concentration profile predicted by a three-dimensional model of atmospheric transport (48) in which only the fossil fuel CO$_2$ is prescribed as a surface source and which is allowed to mix and accumulate in the atmosphere.

Clearly, most of the stations are located in remote areas dominated by oceanic air and will therefore not correctly reflect the zonally averaged concentration distribution. But even by correcting for this effect by sampling at the station locations does not remove the discrepancy between model and data that is evident in Figure 7. The modeled gradient due to fossil fuel CO$_2$ emissions of more than 5 ppvm has to be reduced to the observed approximately 3 ppvm. Since the atmospheric gradient is driven essentially by the differences in sources between the hemispheres, its magnitude can be reduced either by introducing a substantial sink in the temperate Northern Hemisphere, or by a corresponding source in the temperate Southern Hemisphere or by an appropriate combination of both. Whatever scenario is chosen, however, the global balance as inferred from the global budget must be ensured as well. Unfortunately, this second, global constraint does not pin down the magnitudes of the source/sinks in the respective hemispheres. This is because sources in the equatorial region are not reflected in the meridional gradient as they tend to be symmetric with respect to both hemispheres. Furthermore, the present station network is not very likely to capture spatial signatures of strong tropical sources or sinks because of three reasons: (i) the present network of stations is quite sparse in the tropics and confined primarily to the oceanic areas; (ii) the atmospheric circulation is much less zonal in the tropics as compared to higher latitudes; and (iii) the strong tropical convection tends to dilute any horizontal surface gradients by vertical mixing.

To first order we thus have three source regions (temperate latitudes in each hemisphere and the tropics) and only two atmospheric constraints: the global budget (i.e. the sum of all sources must equal the global CO$_2$ concentration increase) and the transport model inferred magnitude of the difference between the northern and southern temperate latitude source. Clearly, more information is needed to determine the system. For instance, some one would also like to distinguish between oceanic and terrestrial components in each source region. The studies conducted so far either rely on observed air-sea fluxes (56) or other information such as observations of the $^{13}$C/$^{12}$C ratio (42, 57).

Concurrent observations of the global Q$_2$ budget and of the interhemispheric gradient in the O$_2$/N$_2$ ratio provide two independent, additional constraints. The oxygen data allow a separation between oceanic and biospheric components, and, assuming that the Southern Hemisphere biosphere plays a negligible role in the global budget, these two additional constraints allow the determination of the net contributions from the terrestrial biosphere from the tropics and from the northern mid-latitude hemisphere. The analysis of the data for the time period 1991–1994 yields a biospheric sink of about 1.9 ± 1.5 GtC yr$^{-1}$ in the temperate latitudes of the Northern Hemisphere (6). This value, together with the global net biospheric balance of 2.0 GtC yr$^{-1}$ during the same time period, imply 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.

Variations in atmospheric oxygen can also be induced by changes in the marine biota which contributes substantially to the seasonal cycles of O$_2$/N$_2$ in the atmosphere and possibly also to interannual variations (37). However, it is unlikely that the long-term trends of O$_2$/N$_2$ analyzed here contain a significant component induced by sustained changes of the marine biosphere and can therefore be neglected in the present context.

THE ROLE OF THE TERRESTRIAL BIOSPHERE

The quantitative inferences on the global carbon cycle discussed earlier address the terrestrial biosphere from an external point of view. Nevertheless, the anthropogenic perturbation together with the evidence of carbon accumulation in the atmosphere and the oceans together with the “Northern Hemisphere sink” argument imply a significant role of the terrestrial biosphere in the global carbon cycle. Because of this, attempts to identify, to quantify, and eventually to model the relevant biospheric processes on a global scale have become a very important area of research. A full appraisal of the work performed in this domain is beyond the scope of this review. The interested reader is referred to the assessment of the IPCC 1994, and 1995 (31, 58).

The view that terrestrial biospheric processes matter significantly on the global scale, contrasts with the opinion of Högblom as cited by Arrhenius (1), who dismissed the role of the biosphere almost entirely by stating that both, the processes of photosynthesis and decomposition are very fast, have thus a short turnover and are therefore without any potential to substantially alter the atmospheric CO$_2$ concentration. In part, this contrasting view can be explained by the different timescales of interest. Indeed most of the inferential evidence for the importance of the terrestrial biosphere stems from short-term investigations based on observational data from mostly a few decades to 1000 years, whereas Arrhenius’ interest was directed primarily at the glacial-interglacial timescale. But even on these longer timescales, changes of carbon storage on land must have occurred as witnessed by changes in the global $^{13}$C/$^{12}$C ratio of oceanic carbon (59) and have to be taken into account when trying to explain changes of atmospheric CO$_2$ in the past (60).
At least over the last 45 years, where precise atmospheric observations are available, the terrestrial biosphere appears as a dynamic component in the global carbon balance. This is witnessed by the growth rate of atmospheric CO₂, which exhibits substantial fluctuations on interannual timescales (5). Figure 8 shows in the upper panel the seasonally adjusted average growth rate from the Mauna Loa and South Pole stations (solid line). The dashed line represents the corresponding change in the atmospheric CO₂ growth rate based on the balance of the inputs from fossil fuels (61) and changes in land use (38) and the oceanic and terrestrial uptake computed by carbon models based on constant climate, but driven by the observed atmospheric CO₂ concentration. Thereby, the biospheric model has been “tuned” by inclusion of a negative feedback such that during the 1980–1989 target period the average global carbon balance is achieved. The difference between the observed and modeled growth rate reflects a global net anomalous source (lower panel) which must be the result of climate driven fluctuations, since the anthropogenic direct effects have been subtracted out with this procedure. A close inspection of these anomalous fluctuations reveals that they are correlated to various climatic indices, such as ENSO (42, 62). A particularly conspicuous feature is the large negative anomaly in 1992 and 1993, after the Pinatubo volcanic eruption, which represents an additional temporary sink of more than 2 GtC yr⁻¹ sustained over two years. A more detailed analysis of the growth rate of the atmospheric CO₂ concentration based on the more comprehensive records from the NOAA station network (7) reveals also spatial signatures and indicates, that the recent anomaly must have its origin primarily in the Northern Hemisphere.

The nature of the anomalous source is still poorly understood. Attempts to separate oceanic from terrestrial contributions based on concurrent δ¹³C/δ¹²C isotopic ratios are contradictory (5, 63). It is clear, however, that a substantial fraction of these variations must be caused by the terrestrial biosphere, since it is difficult to conceive such large fluctuations from changes in oceanic circulations alone. A first modeling effort by means of coupled ocean carbon cycle-general ocean circulation model driven by observed climate failed to give a response of the required magnitude (64). Conversely, several modeling studies with terrestrial biogeochemical models driven by observed climate did show indeed a response of the required magnitude and phase—at least with respect to the ENSO type anomalous fluctuations (65, 66). None of the studies so far, however, have demonstrated a convincing response over the post-Pinatubo period. Clearly, modeling the response of the carbon cycle to climate fluctuations will remain one of the major challenges for the years to come.

CONCLUSIONS

The foregoing sections have outlined that the multitude of observational constraints obtained over the last decades have given us a much more detailed picture of the workings of the global carbon cycle, at least on shorter timescales, than was available in the time of Arrhenius and Högberg. These results are the fruits of many interdisciplinary investigations by means of process studies, global observation and modeling. Nevertheless, the blueprint of the global carbon cycle including the major processes and interaction pathways (Fig. 1) was already well outlined by Arrhenius and Högberg (1, 3).

Despite our improved qualitative and in part quantitative understanding of the global carbon cycle, there remain several challenging questions. Clearly, the response of the terrestrial systems to the rising atmospheric CO₂ and their interactions with the nutrient and water cycles are still very poorly understood. But also the study of the climate feedbacks between ocean circulation and marine biogeochemistry has only started. It is only by understanding and modeling these in a much more realistic way that we will be able to quantify the atmospheric budget on longer time scales, and which will allow us to solve the second problem posed in the introduction, i.e. the determination of the climatic sensitivity of the carbon cycle on timescales ranging from 1 to 1000 years and more.

In a historical perspective, it is sobering to note that Arrhenius did not perceive the anthropogenic perturbation of the carbon cycle as a potential global threat, primarily because he did not foresee the rapid growth of the global CO₂ emissions during the last century caused by the tremendous increases in population and industrial development. Today, we believe that we understand the problem better and we attempt to predict the system and how it responds to present and future perturbations. However, given our still limited knowledge, is it not possible that we might have overlooked something and are making under- or overestimates similar to Arrhenius 100 years ago?
References and Notes