The Anthropogenic Perturbation of Atmospheric CO_2 and the Climate System

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ABSTRACT

Deep cuts in carbon dioxide (CO_2) emissions are warranted to stabilize the concentration of atmospheric CO_2. The increasing trend in CO_2 emission must be reversed and, on the long-term, emissions must fall well below the present level. Global warming-carbon cycle feedbacks tend to reduce the uptake of excess carbon from the atmosphere by the land biosphere and the ocean. The climate-carbon cycle system has a long memory such that if adverse climate trends indeed materialize, they are likely to be long lasting. Unlike other anthropogenic forcing agents, anthropogenic CO_2 is not destroyed by oxidation or deposition, but is redistributed between the major carbon reservoirs. The consequence is that today's CO_2 emissions will affect the atmospheric composition and climate over many millennia.

1 INTRODUCTION

The man-made increase in atmospheric CO_2 and the resulting climatic changes pose a serious challenge to human society [1]. Slowing man-made global climate change requires an understanding of the carbon cycle and how emissions of carbon dioxide (CO_2), a powerful greenhouse gas (GHG), are redistributed within the climate system.

This article provides an overview of the main carbon reservoirs, discusses the interactions of the carbon cycle and the climate system, addresses time scales in the climate-carbon cycle system in the context of the anthropogenic perturbation, and presents projections for the recent IPCC non-intervention emission scenarios and for pathways leading to stabilization of atmospheric CO_2.

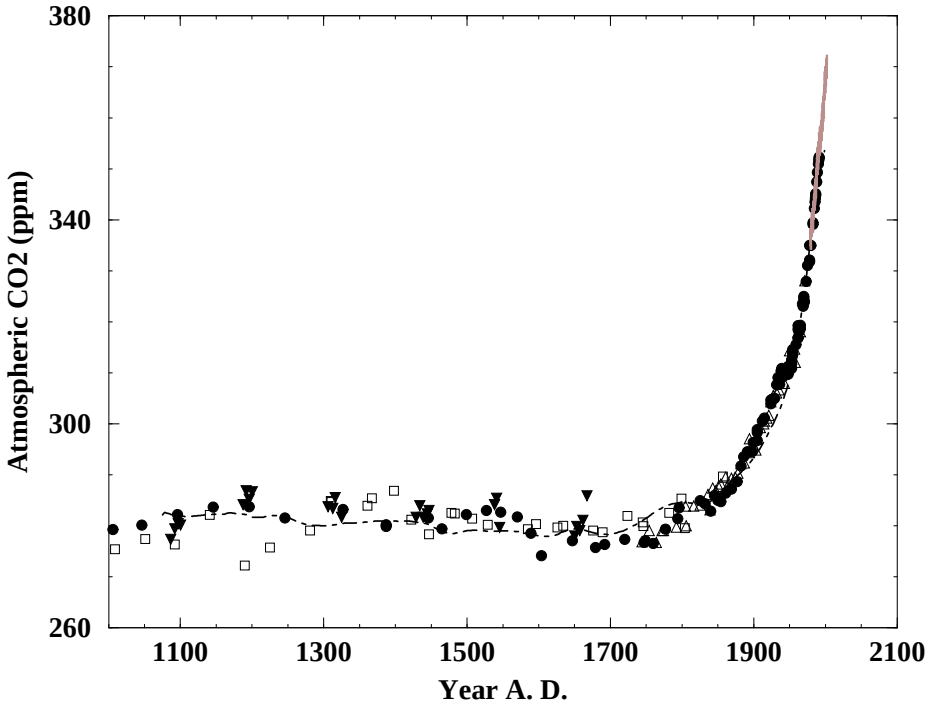

Figure 1: The evolution of atmospheric CO_2 during the last millennium. The data points are measurements on air bubbles entrapped in Antarctic ice cores [2, 3, 4, 5, 6]. The gray solid line represents the global mean atmospheric concentration from data of the global network of the National Oceanographic and Atmospheric Administration over the period 1979 to 2001 (courtesy of Tom Conway, NOAA). Modelled atmospheric CO_2 (dot-dash) is comparable to the observed evolution: the Bern Carbon Cycle-Climate Model has been forced with anthropogenic carbon emissions (fossil and land use) and radiative forcing from anthropogenic agents and from changes in solar irradiance and explosive volcanic eruptions [7].

The atmospheric concentration of CO_2 has increased by 30% above preindustrial values (Figure 1). Today's concentration of 370 ppm is higher than observed at any time within the last 400,000 years, the period spanned by ice core records [8]. Measurements on air entrapped in polar ice demonstrate the unprecedented rapid increase of CO_2 during the industrial period [9]. Previous atmospheric CO_2 variations of comparable magnitude have occurred only slowly, over many millennia [10, 11]. Atmospheric CO_2 varied, in pace with global surface temperature changes, between roughly 200 ppm during glacial times and 280 ppm during interglacials. Today, atmospheric CO_2 is projected to rise two to four times above the preindustrial level by the end of this century if anthropogenic emissions continue unabated [12, 9].

Changes in CO_2 and other GHGs affect the radiation balance of the Earth [13]. GHGs absorb and re-emit part of the infrared radiation emitted toward space from the Earth's surface and lower air masses, while allowing solar radiation with its maximum energy in the visible wavelength band to penetrate the atmosphere almost unhindered. Without this naturally occuring greenhouse effect surface temperature would be much cooler and not very suitable for life.

Carbon dioxide is the most important of a variety of anthropogenically-emitted climate forcing agents [14]. It contributes about 60% to total radiative forcing by well-mixed anthropogenic GHGs (CO_2, methane, nitrous oxide, halocarbons) and its share is projected to increase in future. The increase in tropospheric ozone, an air pollutant with large spatio-temporal variability in concentration, also contributes to a positive forcing (surface warming), whereas the decrease in stratospheric ozone tends to cool the Earth's surface. Short-lived aerosols such as sulfate particles, soot, and particles of organic carbon affect the radiation balance, and the radiative properties and life-time of clouds. Overall, they are thought to offset a substantial part of the GHG forcing regionally and globally. Due to their high spatio-temporal variability and their complex interactions with radiation and clouds, global aerosol forcing is not well quantified. Natural radiative forcing caused by changes in solar irradiance and explosive volcanic eruptions have likely been negative over the past two decades and probably over the past five.

Evidence strongly suggests that the rise of CO_2 and other anthropogenic GHGs causes climate to change [15]. The observed climatic changes are consistent with the picture of a warming world. Global mean surface temperature has increased by 0.6 K during the 20th century; heat content has increased in all ocean basins to gave a total global increase in ocean heat storage of around $2\ 10^{23}$ Joules over the period from 1955 to 1995 [16]; sea level has risen; total precipitation in mid- and high-northern latitudes has increased, as have the number of heavy rainfall events; alpine-type glaciers have experienced a dramatic retreat worldwide; late summer extent and thickness of Arctic sea ice has decreased, plant growing season length has extended, and the distribution of flora and fauna has changed. It has also been suggested that gradients in the atmospheric distribution of anthropogenic aerosols

modify rainfall patterns, e.g. in the Sahel or monsoon regions. Reconstructions of Northern Hemisphere surface temperature show that the recent years were the warmest, or at least among the warmest of the past millennium [17, 18].

Studies aimed to detect and attribute anthropogenic climate change consistently find that more than half of the observed warming during the past five decades is man-made [19]. The rise in global mean temperature and associated spatial temperature patterns are quantitatively explained by climate models that include the effects of GHGs, aerosols and solar and volcanic changes. Natural variability contributes to the observed climatic changes. For example, the observed warming in the early part of the 20th century is partly attributed to an increase in solar energy output [19].

Climate change poses a significant risk for us [1, 20]. The impact of climate change on the socio-economic system are manifold. They include impacts on human infrastructure, on health, food and fiber production, on the availability of water, and on forests, mountain, aquatic and coastal ecosystems. Economic losses associated with a doubling of atmospheric CO_2 compared to pre-industrial levels are estimated to be a few percent of the national gross domestic product annually. In the past few decades, storms, floods, drought and other severe weather events have been responsible for many deaths and caused hardship worldwide. While individual extreme events can not be attributed to anthropogenic activities, they are projected to be more likely in a warmer and wetter climate. Anthropogenic GHG emissions may trigger non-linear and rapid climate changes, of the type observed in the paleo record. The North Atlantic thermohaline (density driven) circulation, responsible for a vast amount of heat transport from the tropics to northern mid-latitudes, is subject to instabilities and can collapse [21].

Many scientists have focused on the study of the carbon cycle as understanding the changes in atmospheric CO_2 is of prime importance for the understanding of future climate change. The carbon cycle involves all the major components of the Earth system including the atmosphere, oceans, biosphere (both on land and in the ocean), the sediments, and the socio-economic system and is closely linked to other biogeochemical cycles. This complexity means that a variety of measurements performed on the archives of the earth system such as ice cores, ocean and lacustrine sediments and in situ measurements of a range of different moleculess and their isotopic composition can be used to infer past, present, and future states of the climate-carbon cycle system. It is the combination of observational evidence and the synthesis of the observations provided by models that allows us to draw a reasonably accurate picture of the carbon cycle.

2 THE MAJOR CARBON RESERVOIRS: TIME SCALES AND INTERACTIONS BETWEEN THE PHYSICAL, BIOGEOCHEMICAL AND SOCIO-ECONOMIC SYSTEMS

Interactions between the climate system and the socio-economic system play an important role in determining today's atmospheric CO_2 loading. Figure 2 shows a schematic view the global carbon cycle [22] and its major interactions with the physical climate system [23] and the socio-economic system [24, 25].

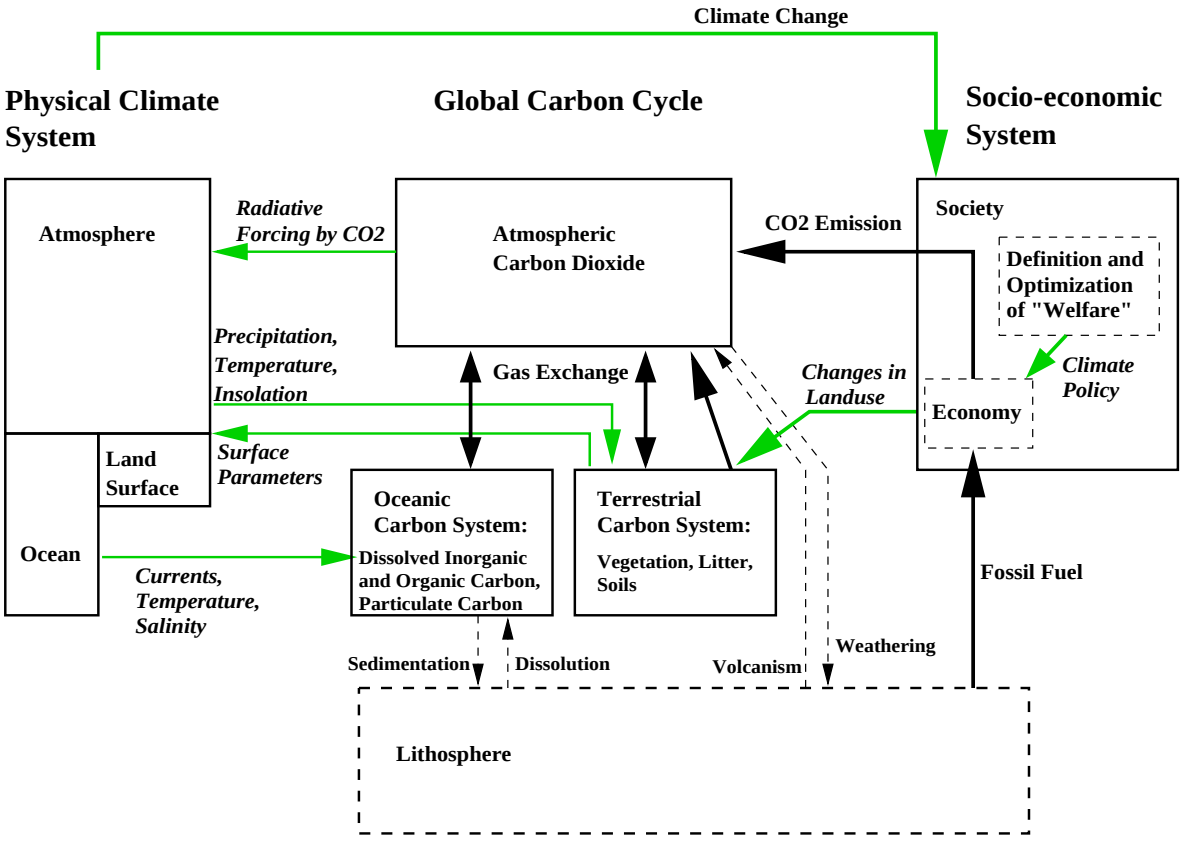

Figure 2: Sketch of the global carbon cycle and its interaction with the physical climate system and the socio-economic system. Black arrows indicate carbon flows, gray arrows indicate interaction pathways.

The direct anthropogenic impact on the carbon cycle is dominated by CO_2 emission from fossil fuel burning and from deforestation and other forms of land use change. Fossil fuel burning and land use change occur to a large degree to satisfy demands for energy, food, wood products, and other products that are essential for our present-day society and economy.

The anthropogenic emissions, as well as the interaction with the physical part of the climate system mainly affect the three relatively rapidly (< 1000 years) exchanging carbon reservoirs - the atmosphere, the oceans, and the land biosphere (including soils). In the atmosphere, carbon is stored mainly in the form of the chemically inert carbon dioxide gas. The ocean contains about 50 times more carbon than the present atmosphere, mostly in dissolved inorganic forms and as organic matter. Terrestrial carbon stocks in living and dead vegetation and in soils are about three times larger than the atmospheric inventory. Exchanges with the lithosphere, the far largest carbon reservoir, by sedimentation, dissolution of sediments, by volcanism, and weathering are governed by processes with typical time scales of several thousands to hundreds of thousands of years.

A multitude of interactions exist between the physical part of the climate system and the carbon cycle. The most prominent is the change in radiative forcing due to changes in the atmospheric CO_2 concentration. These changes can substantially alter the radiative balance of the earth surface and the atmosphere, and thereby, lead to climate changes. Changes in precipitation, temperature, and insolation modify the vegetation and the terrestrial carbon inventories. Changes in sea surface temperature and salinity modify ocean currents, the marine biospheric carbon cycle, and aquatic carbon chemistry. Changes in vegetation cover modify surface roughness, surface albedo and the storage and evaporation of water, thereby also modifying local energy balances and local climate.

Natural atmospheric CO_2 concentrations are controlled by different processes operating on a range of time scales [26]. The total amount of carbon in the relatively fast-exchanging reservoirs (ocean, land biosphere and atmosphere) is governed by the weathering-sedimentation cycle on very long geological time scales. Primarily the ocean carbon cycle and ocean-sediment interactions set the atmospheric CO_2 concentration on time scales of centuries to millennia. Typical time scales of surface-to-deep ocean exchange are centuries, and it takes millennia to equilibrate ocean water and ocean sediments after a perturbation in oceanic carbon content. Changes in the land biosphere and in the upper ocean influence atmospheric CO_2 concentrations on seasonal to decadal to century time scales.

The time scales for the redistribution of anthropogenically emitted CO_2 in the climate system are linked to the time scales of the natural carbon cycle (Figure 3). The upper ocean and the land biosphere are, at present and in the coming decades, the dominant sinks for excess carbon. The ocean's uptake capacity is only reached after several centuries, the time scale of deep ocean ventilation. Figure 3 shows the response of the Bern Carbon Cycle-Climate (Bern CC) model [12] to a pulse-like carbon input into the atmosphere. More than 50% of the initial input has been removed from the atmosphere within two decades after emissions through uptake by the upper ocean and the fast overturning reservoirs of the land biosphere. However, around 30% of the input is still air-borne after 100 years, and 15% is still found in the atmosphere after one thousand years. This fraction is only very slowly reduced further by ocean-sediment interaction and the weathering cycle [26].

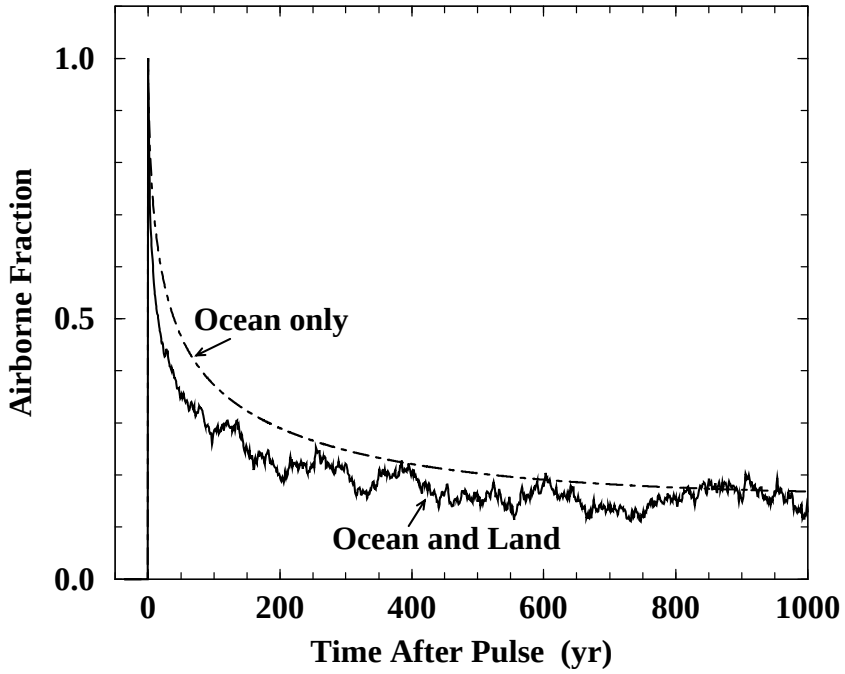

Figure 3: The response of atmospheric CO_2 to a pulse like injection of 40 GtC into a preindustrial atmosphere (CO_2= 280 ppm) at time 0 as simulated with the Bern Carbon Cycle-Climate (Bern CC) model (thick solid line) [12] and with the oceanic component of the Bern CC model alone (dot-dash). Terrestrial and oceanic uptake contribute significantly to the initial response and about 50% of the initial emission is removed from the atmosphere in less than two decades. The century-to millennium scale response is dominated by the ocean and around 15% are still air-borne at year 1000 when the ocean is close to a new equilibrium with the atmosphere.

3 ANTHROPOGENIC CARBON EMISSIONS AND THE ATMOSPHERIC CARBON BALANCE

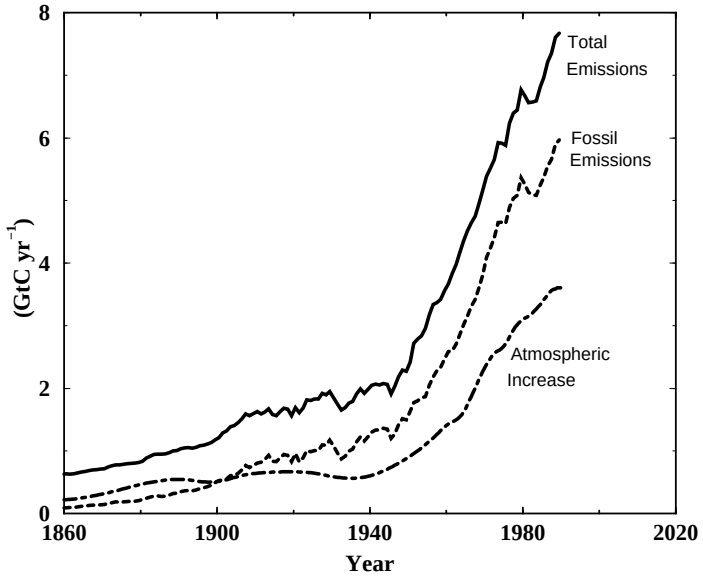

Figure 4: A comparison between the annual atmospheric growth rate in CO_2 and the anthropogenic emissions reveals that anthropogenic emissions were a factor of 2-3 larger than the increase in atmospheric carbon storage. The atmospheric growth rate is deduced from ice core data and direct observations as shown in Fig. 1. Fossil emissions are compiled based on trade statistics [27, 28]. The difference between fossil emissions and total anthropogenic emissions corresponds to the estimated carbon release due to land use changes and deforestation [29].

In less than two centuries, burning of fossil fuels has added 280 GtC (1 gigaton of carbon = 10^{12} kg C = 3.7 10^{12} kg CO_2) to the atmosphere [27]. This is only a small fraction of the total carbon in fossil fuel reserves, estimated to be around 5,000 GtC [30]. Over the same period, another 150 GtC are estimated to have been release during land use changes and by deforestation [29]. Today, more than 6 GtC per year are released into the air due to burning of fossil fuels, such as coal, gasoline, and gas, as documented by trade statistics. Human induced land use changes and deforestation, mainly in the tropics, cause an additional release of 1 to 2 GtC per year.

The observed increase in atmosheric CO_2 is explained by anthropogenic emissions. Only about 44% of the 430 GtC emitted by anthropogenic activities are still found in the atmosphere; the rest has been taken up by the ocean and the land biosphere. CO_2 emissions (Figure 4) have been larger than the atmospheric CO_2 increase during each decade since the begining of the emission record. Emissions from fossil fuel burning have been larger than

The Atmospheric Carbon Budget

	1980 to 1989	1990 to 1999
Atmospheric increase	3.3±0.1	3.2±0.1
Fossil emissions	5.4±0.3	6.3±0.4
Ocean-atmosphere flux	-1.7±0.6	-2.4±0.7
Land-atmosphere flux	-0.4±0.7	-0.7±0.8
Land use change	2.0±0.8	2.2±0.8
Residual terrestrial sink	-2.4±1.1	-2.9±1.1

Table 1: Global CO_2 budgets (in GtC yr^{-1}) based on measurements of atmospheric CO_2 and O_2 and estimated ocean outgassing of O_2 due to surface ocean warming, circulation changes and changes in the marine biological cycle [35]. The atmospheric increase and fossil emissions are from [9], the oceanic and terrestrial carbon uptake fluxes are from [35], and the land use change fluxes are from [36]. The land-atmosphere flux represents the balance of a positive term due to land use change and a residual terrestrial sink. The two terms can not be separated on the basis of current atmospheric measurements. The residual terrestrial sink is inferred by difference using independent analyses of the land use change term.

the atmospheric increase since the beginning of the 20^{th} century. Besides the constancy in pre-industrial CO_2 concentrations and the large anthropogenic emissions, other evidence demonstrates 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 [22, 31]. (2) Carbon of fossil origin has low concentrations of the stable carbon isotope ^{13}C and is free of the radioisotope ^{14}C, which has radioactively decayed over time since deposition in geological reserves. The atmospheric concentration of both isotopes has decreased in parallel with fossil emissions [32, 33]. (3) The observed decrease in atmospheric oxygen of a few ppm per year can be quantitatively linked with the anthropogenic CO_2 perturbation [34]. Oxygen is consumed when fossil fuel is burned or organic matter is decomposed. Oxygen is produced when carbon is assimilated.

The global atmospheric carbon balance for the 1980s and 1990s is inferred from measurements of atmospheric CO_2 and O_2, taking into account ocean outgassing of O_2 due to sea surface warming, changes in circulation, and changes in the marine biological cycle [35, 9] (Table 1). During the 1990s, slightly more than 2 GtC per year were, on average, sequestered by the ocean. The land biosphere acted overall as a small sink. This means that carbon emissions from deforestation and land use changes are more than offset by a terrestrial carbon sink. The size of this residual sink can only be determined by difference between the estimated anthropogenic land use emission and the net land-atmosphere flux determined from the atmospheric measurements. Current estimates of land use emissions are highly uncertain and so is the residual sink. If land use emissions are as high as 2 GtC per year as suggested

by [36], then the residual sink may be up to 3 GtC per year. Otherwise, if land use emissions are lower, as suggested recently [37], then the residual terrestrial sink may be closer to 1 to 2 GtC per year.

The regional distribution of the terrestrial sinks is also under debate [38, 39]. Inverse studies deducing unknown carbon sources and sinks from the observed spatial distribution of atmospheric CO_2 by applying atmospheric transport models yield a wide range of estimates of regional terrestrial sinks. A large terrestrial sink is often inferred in the Northern Hemisphere mid latitudes [38]. However, estimates obtained from atmospheric inverse studies must be treated with caution due to uncertainties in the preindustrial latitudinal gradient in CO_2, in the magnitude of interhemispheric carbon transport by the ocean, in the interaction between the seasonal terrestrial fluxes and atmospheric transport, and in riverine carbon transport. Forest inventories in northern mid-latitudes generally yield a smaller carbon sink than inverse studies suggest [36, 40].

Uncertainties in global and regional estimates of the strengths of the present oceanic and terrestrial carbon sinks will not be easily reduced. The anthropogenic perturbation comes on top of a huge and complicated natural cycle. Spatio-temporal fluctuations in the globally large and nearly balanced fluxes of the carbon cycle make it difficult to measure directly the uptake of excess carbon by the land biota and by the ocean. Globally, the net fluxes between the atmosphere, the ocean, and the biosphere are only a few percent of the total exchange fluxes, e.g., primary production and respiration of organic matter. Large regional differences exist. For example, the upwelling of cold, carbon rich deep water leads to oceanic outgassing in the tropics, whereas CO_2 is taken up in mid and high-latitudes. The estimated 100 GtC of carbon that have accumulated in the land biota over the past 200 year, partly offsetting deforestation emissions, are small compared to the total standing stocks of living vegetation and in soils of about 2200 GtC. Similarly, estimated ocean uptake of about 140 GtC is only a minor fraction of the total ocean carbon inventory of 40,000 Gt C. The anthropogenic component of oceanic carbon has been determined from data of dissolved inorganic carbon and other tracers [41]. Despite these difficulties, a wealth of observations and tracer-evaluated models consistently show that the ocean is presently taking up carbon by about 2 GtC per year and that the terrestrial biosphere is taking up somewhat more carbon than is released by land use changes.

4 UPTAKE OF ANTHROPOGENIC CO_2 BY THE OCEAN AND THE LAND BIOSPHERE

The oceanic uptake of excess CO_2 is dictated by three processes [42, 43, 44, 45, 46, 47]: (i) the air-sea exchange of CO_2 gas that is a function of the air-sea CO_2 partial pressure difference [48]; (ii) the dissolution of CO_2 to aquatic $[CO_2]$ and its transformation to bi-carbonate $[HCO_3^-]$, and carbonate ions $[CO_3^{--}]$ [49]; and (iii) the transport of carbon from the surface to the deep by the oceanic circulation. The ocean's uptake capacity for anthropogenic carbon is determined by ocean volume and sea water chemistry, whereas the time scales to approach the uptake capacity are governed by surface-to-deep exchange, the rate limiting step. These chemico-physically based mechanisms are relatively well understood and quantified. In addition, climate change is expected to influence the natural oceanic carbon cycle and future oceanic carbon uptake.

The ocean plays an unusual and dominant role in the fate of emitted carbon dioxide over the next millennium. About 65 times more carbon was in the ocean than in the atmosphere at preindustrial times. Without further understanding of 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. However, the chemical capacity of seawater to take up anthropogenic carbon is substantially less than what might be expected from the relative size of the atmospheric and oceanic inventories. Chemical equilibrium models [49], tested by thousands of seawater measurements [50], demonstrate that the ocean is only able to absorb up to 85% of the emissions into the atmosphere-ocean system. The fraction remaining air-borne increases with the emission amount due to the non-linear nature of aquatic carbon chemistry. The chemical reaction pathway leads to acidification and to a decrease in the pH of seawater. The potentially negative consequences of this acidification for marine ecosystems are not well understood.

The ocean's uptake capacity is approached only several centuries after emissions. Radiocarbon measurements demonstrate that the "oldest" water masses found in the deep North Pacific have been isolated from the air-sea interface for more than a thousand years [51]. Cosmogenically-produced radiocarbon enters the ocean through gas exchange and is mixed towards the abyss, while its concentration continuously decreases by radioactive decay. The mapped penetration of anthropogenic tracers into the upper ocean shows that it takes about a decade for a tracer to penetrate the uppermost 300 meters (e-folding depth scale). Particularly valuable information about the time scales of upper ocean mixing, most relevant for today's uptake rate of excess carbon, stems from the observed oceanic distributions of radiocarbon produced by the atomic bomb-tests in the fifties and early sixties [52], and CFC-11 and CFC-12 [53]; two tracers with only anthropogenic sources. The present suite of ocean carbon models, evaluated against a range of observed oceanic tracer distributions, are in

agreement with data-based estimates that slightly more than 2 GtC per year are taken up by the ocean today [54, 9].

Next, terrestrial carbon uptake is addressed. The mechanisms responsible for terrestrial carbon uptake are under debate and quantitatively not well understood. The complex interactions between land use changes, increasing atmospheric CO_2 and nutrient availability, climate change, fires and other disturbances, forest encroachment, species composition feedbacks, edaphic controls, and other factors modify terrestrial carbon storage [9, 55, 56]. Experiments exposing plants and even forest stands to higher CO_2 concentrations yield an increase in photosynthesis and water use efficiency in agreement with biochemical models of CO_2 assimilation by leaves [57, 58]. However, limited availability of phosphate, nitrate, or other nutrients, and the adaption of plants to the new environmental conditions may down-regulate long-term carbon uptake by this so-called CO_2 fertilization mechanism [59]. The burning of fossil fuel and the use of fertilizer has enhanced the nitrogen cycle. Nitrogen input into the world's ecosystem has increased and has potentially stimulated additional carbon storage [60, 61]. Regrowth of previously cleared forest in northern mid-latitudes, woody encroachment into non-forested areas [62], and forest thickening due to fire suppression or other changes in management practices are also thought to contribute to the ongoing terrestrial carbon sequestration.

The potential of deliberate management options to stimulate terrestrial and ocean uptake appears to be limited. It has been estimated that if all of the carbon released by historic land use change could be restored to the terrestrial biosphere over the course of the century, CO_2 concentration, projected to double or quadruple without policy measures by the end of the century, would be reduced by only 40 to 70 ppm [9]. Similarly, it has been shown that stimulating biological production in the vast and nutrient rich areas of the Southern Ocean would reduce atmospheric CO_2 by a relatively small amount if emissions continue unabated [63].

It has been suggested to capture CO_2 from flue gas and dump it into the ocean to avoid a direct release into the atmosphere. The time scales of ocean overturning by advection, diffusion, and convection also govern the rate at which carbon artificially injected into the deep ocean will escape back to the atmosphere once it moves away from the injection site [64]. Measurement of the helium isotope ^{3}He, naturally released at mid-ocean ridges within the ocean, reveal that the water in the deep ocean is stirred. CO_2 that is artificially released into the deep ocean will be distributed over a basin-wide scale, together with accompanying changes in pH and injected impurities.

5 CLIMATE FEEDBACKS ON CARBON UPTAKE

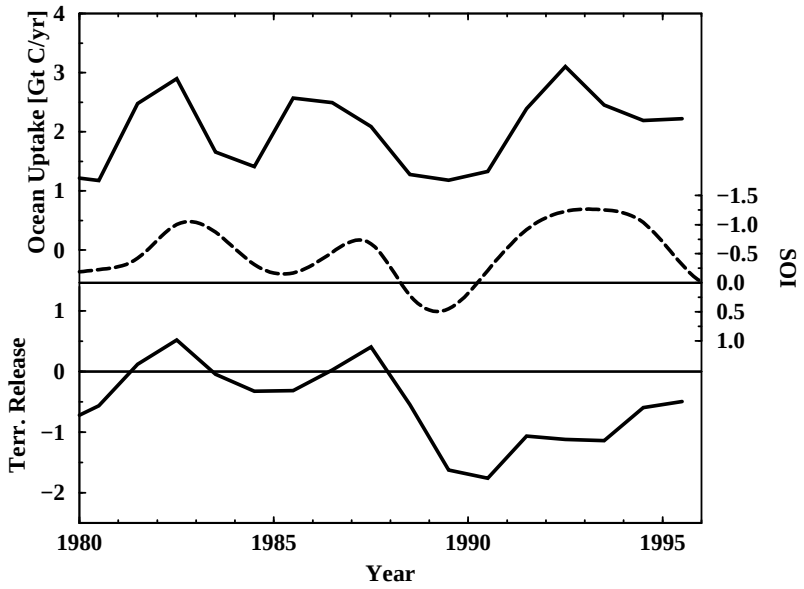

Figure 5: Interannual variations in ocean uptake and terrestrial release of carbon compared to the Southern Oscillation Index (SOI). The carbon fluxes have been reconstructed by inverting the observed atmospheric CO_2 and $\delta^{13}C$ histories [65].

Climate change will affect future carbon uptake by land and ocean. Interannual variations in the atmospheric CO_2 growth rate and in terrestrial and oceanic carbon storage already reveal a highly dynamic system. Interannual climate variability has a considerable impact on carbon fluxes (Figure 5). Large feedbacks between climate and the carbon cycle are also expected on decadal-to-century time scales relevant to the anthropogenic perturbation [66, 67, 12].

The present terrestrial carbon sink may turn into a carbon source. Higher temperatures lead to an increase in plant and soil respiration; changes in temperature, precipitation, water availability, and disturbance regimes may either enhance or decrease the productivity of individual plants and ecosystems; future climatic changes may induce substantial shifts in the species composition of a particular area and may cause forest dieback. Our present understanding suggests that the importance of terrestrial sink fluxes, whether stimulated by increasing atmospheric CO_2, enhanced nitrogen deposition or forest regrowth, will diminish in the future. On the other hand, carbon release from soils, the dominant reservoir of the land biosphere, is expected to further increase with continued soil warming. Conditions favoring a future carbon source are high emissions of GHGs and a high relative share of non-CO_2 GHGs that do not contribute to CO_2 fertilization but contribute to high warming rates [12] (Figure 6).

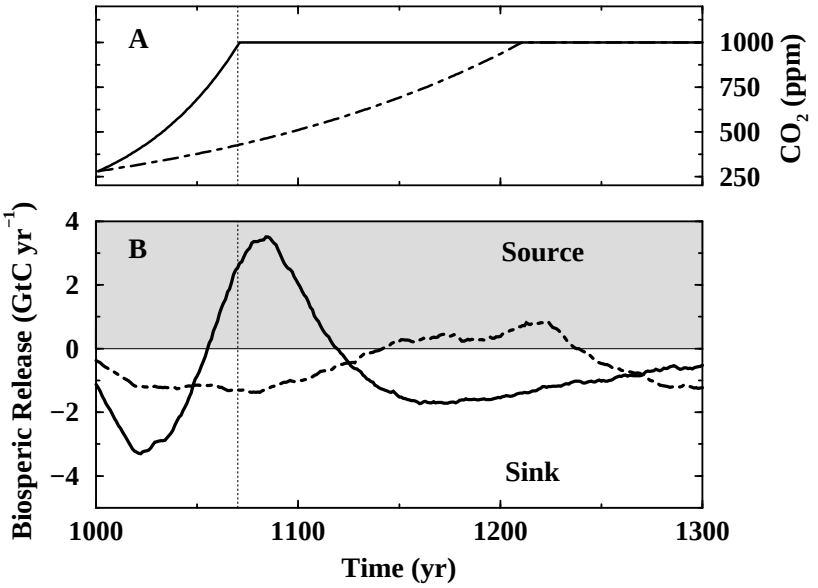

Figure 6: (A) In transient simulations with the Bern Carbon Cycle-Climate model, atmospheric CO_2 is prescribed to increase exponentially within 70 and 210 years to a level of 1000 ppm and kept constant afterward. (B) Simulated terrestrial carbon release for the profiles shown in (A). Non-CO_2 radiative forcing is set to 25% of the CO_2 radiative forcing and the model's climate sensitivity is set to 4.5 K for a nominal doubling of atmospheric CO_2. The land biosphere component of the Bern CC model is the Lund-Potsdam-Dynamic Global Vegetation model [68]. The terrestrial biosphere becomes a temporary CO_2 source either when atmospheric CO_2 increases rapidly or when non-CO_2 radiative forcing is large. In this case, the carbon loss due to climate change dominates for a few decades over the carbon gain by CO_2 fertilization [12]. Data are smoothed.

Global warming-carbon cycle feedbacks tend to reduce ocean uptake [69, 70, 71, 72]. CO_2 is less soluble in warm water than in cold water. The transport of excess CO_2 is slowed as ocean warming and changes in the hydrological cycle lead to a more stratified ocean and a reduced circulation. Climate-induced changes in marine ecosystem structure and biogenic fluxes are expected to further modify carbon uptake.

A low-order physical-biogeochemical climate model has been applied to investigate these feedbacks [72, 73]. For a range of carbon emission or CO_2 scenarios, ocean uptake is reduced by about 10% in global warming simulations as compared to baseline simulations without global warming. The projected atmospheric CO_2 increase up to year 2100 is a few percent higher in model simulations including climate-ocean carbon cycle interactions than that in simulations neglecting global warming. This finding is consistent with palaeo data that show only minor changes in atmospheric CO_2 during the Younger Dryas cold spell 12,000 years before present [74] or other abrupt climate changes during the last glacial period [75].

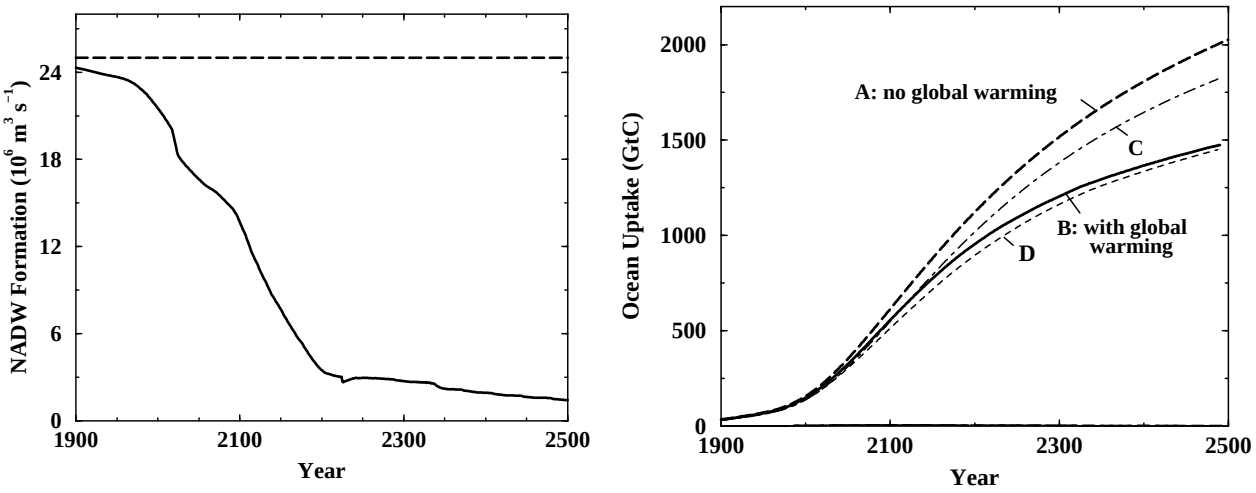

Figure 7: Reduction in the formation rate of North Atlantic Deep Water (NADW) (left, solid) and cumulative oceanic carbon uptake (right) obtained by applying a low-order physical-biogeochemical climate model [72]. Atmospheric CO_2 has been prescribed in the model according to a profile leading to stabilization at 1000 ppm. Ocean uptake has been calculated for different model setups (Simulations A-D). Simulation A (long dash) is the control run where climate is kept constant. Simulation B (solid) is the standard simulation where global warming feedbacks are included. The difference between simulation A and B is the reduction in ocean uptake due to global warming feedbacks. The difference between A and C (dot-dash) is the reduction due to the influence of sea surface warming on the aquatic CO_2 chemistry only. The difference between C and D (dash) is the additional reduction due to the slowdown of the downward transport of anthropogenic CO_2. The latter reduction is partly compensated by an increased uptake mediated by changes in the marine biological cycle that is the difference between simulation D and B.

The importance of different oceanic processes for the reduction in CO_2 uptake was estimated by running the model in different setups. It was found that both a decrease in the CO_2 solubility caused by increasing sea surface temperature and the reduction in surface-to-deep transport of anthropogenic carbon decreases oceanic uptake, whereas changes in the cycling of marine organic material and $CaCO_3$ partly compensate the reduction. Sea surface warming is by far the most dominant feedback with respect to CO_2 uptake in our model, except when North Atlantic Deep Water formation stops (Figure 7).

6 WHAT DOES THE FUTURE HOLD?

Without a doubt, atmospheric CO_2 will continue to rise as carbon emissions continue and global warming will progress. The question is not whether man's activities will affect the climate-carbon cycle system, but to what extent and at what rate. The answer depends largely on how much GHGs people will release.

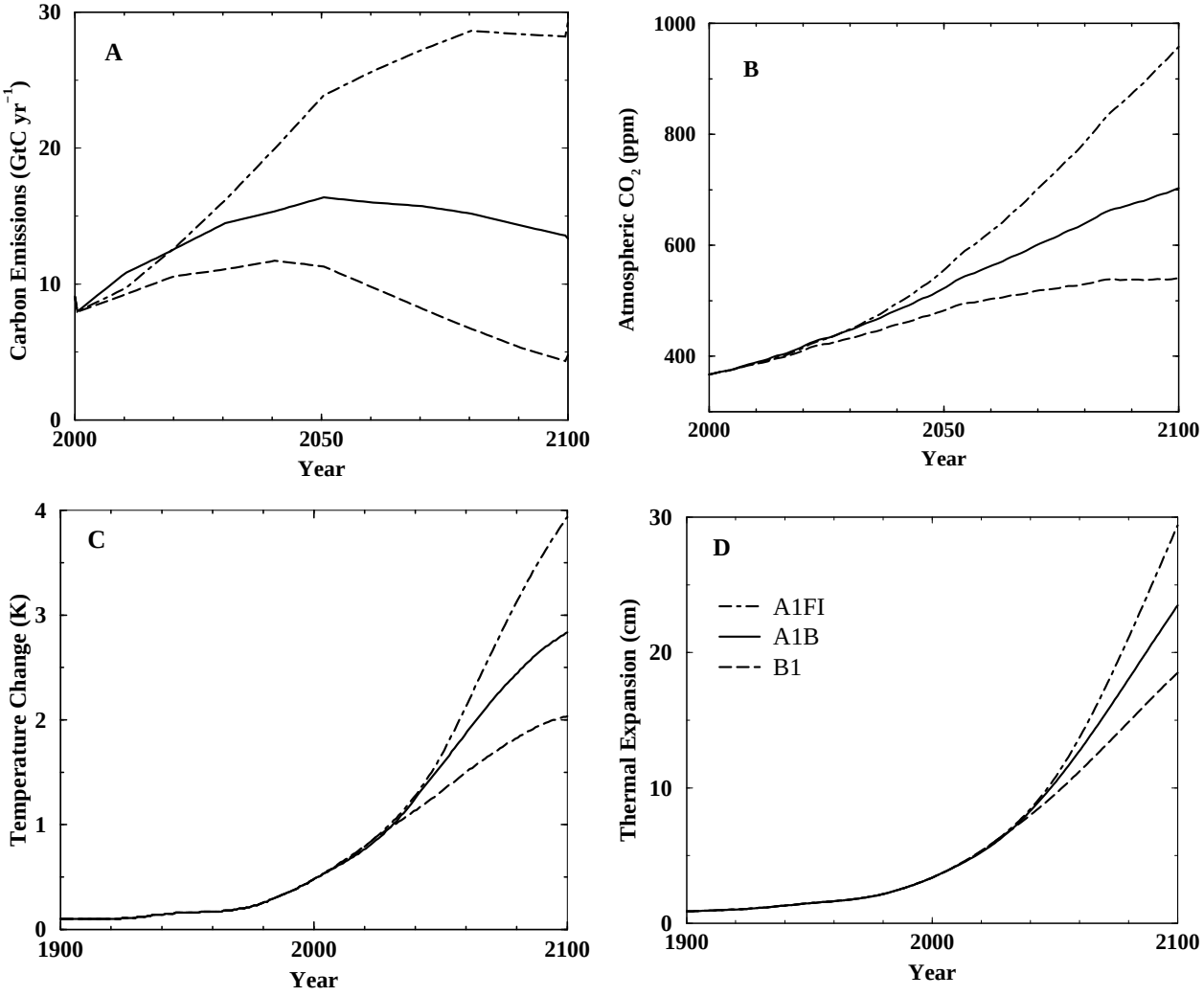

Figure 8: Anthropogenic carbon emissions (A) and emissions of other forcing agents have been prescribed in the Bern Carbon Cycle-Climate model according to a low (B1), medium (A1B), and high (A1FI) illustrative SRES scenario. Future atmospheric CO_2 (B), changes in global average surface Temperature (C), and sea level rise due to ocean thermal expansion (D) have been projected [12, 9]. Global warming and sea level continue to rise throughout the century even for emission scenario B1 where carbon emissions drop below the present level around year 2070.

Global average surface temperature is projected to rise between 2 and 4 K above preindustrial values for the six illustrative scenarios and for a mid-range climate sensitivity (Figure 8C). Global average surface temperature change is just one indicator. Associated with the projected changes in global mean temperature are regionally- and temporally- distinct changes in temperature, precipitation, frequency of extreme weather events, changes in drought and floods, the melting of permafrost, shrinking of alpine-type glaciers, the reduction in Arctic sea ice extent and thickness, and sea level rise (Figure 8D) [15]. These projected changes pose a significant risk for sustainable development and human well-being [20]. In conclusion, the SRES scenario results suggest that policy measures to limit carbon emissions are needed to stabilize atmospheric CO_2 concentrations on a century time scale and to limit future climate change and climate change impacts.

The United Nations Framework Convention on Climate Change calls for the stabilization of GHG concentrations to avoid dangerous anthropogenic climate interferences. Concentration profiles leading to stabilization of atmospheric CO_2 between levels of 450 and 1000 ppm have been prescribed in the Bern CC model (Fig. 9A). The anthropogenic emissions consistent with the profiles are calculated as the sum of prescribed atmospheric and modeled oceanic and terrestrial carbon inventory changes (Fig. 9B). It is not sufficient to keep carbon emissions at present day levels to achieve stabilization of atmospheric CO_2. Eventually, carbon emissions have to drop well below current levels.

Global warming will continue, albeit at a largely reduced rate, for several centuries after GHGs concentration and radiative forcing have been stabilized. The reason for continued warming is in the large thermal inertia of the ocean and its slow overturning. Sea level rise due to thermal expansion of ocean water will continue over millennia as the ocean continues to take up heat.

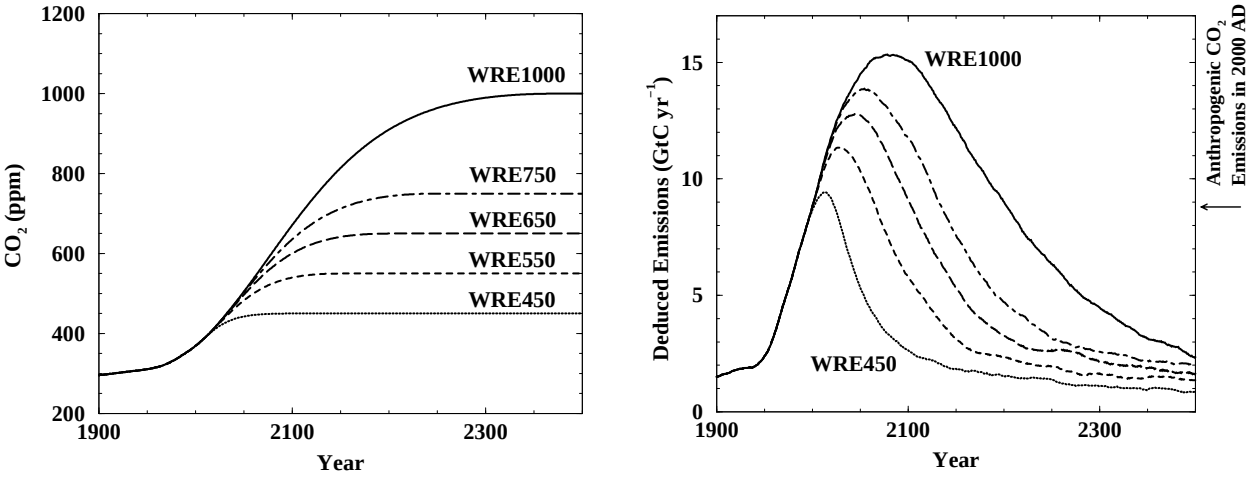

Figure 9: (A) Profiles leading to stabilization of atmospheric CO_2 in the range of 450 to 1000 ppm. (B) Inferred carbon emissions consistent with the concentration profiles shown in (A). Eventually, carbon emissions need to fall well below present levels to stabilize atmospheric CO_2.

7 CONCLUSIONS

The carbon cycle is an important part of the climate system. The forcing by increasing atmospheric CO_2 causes climate to change. A multitude of interaction pathways and feedbacks exists between the physical climate system and biogeochemical cycles. Global warming-carbon cycle feedbacks are likely to reduce the combined uptake by the ocean and terrestrial biosphere, thereby leading to higher atmospheric CO_2 and higher rates of warming as compared to a situation without such feedbacks. Fossil fuel emissions are the dominant control for atmospheric CO_2 over the next century, as illustrated by the SRES and stabilization scenario calculations.

Carbon emission control is crucial to abating global warming. Radiative forcing by CO_2 is projected to further increase as anthropogenic carbon continues to accumulate in the atmosphere. Stabilization of atmospheric CO_2 requires that the current trend in emissions be reversed and that emissions fall below present levels. Eventually, emissions need to be phased out. Anthropogenically emitted carbon is not destroyed but accumulates in the Earth system. Hence, a delay in emission reduction measures will require larger emission reductions at a later time to meet a certain stabilization target.

Anthropogenic GHG emissions and, in particular, emissions of carbon dioxide will affect the climate system over millennia. The long time scales in the carbon cycle-climate system imply that if adverse climatic trends become indeed reality, they are likely to be long lasting.

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