A Carbon Cycle Science Update Since IPCC AR-4

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Abstract We review important advances in our understanding of the global carbon cycle since the publication of the IPCC AR4. We conclude that: the anthropogenic emissions of CO₂ due to fossil fuel burning have increased up through 2008 at a rate near to the high end of the IPCC emission scenarios; there are contradictory analyses whether an increase in atmospheric fraction, that might indicate a declining sink strength of ocean and/or land, exists; methane emissions are increasing, possibly through enhanced natural emission from northern wetland, methane emissions from dry plants are negligible; old-growth forest take up more carbon than expected from ecological equilibrium reasoning; tropical forest also take up more carbon than previously thought, however, for the global budget to balance, this would imply a smaller uptake in the northern forest; the exchange fluxes between the atmosphere and ocean are increasingly better understood and bottom up and observation-based top down estimates are getting closer to each other; the North Atlantic and Southern ocean take up less CO₂, but it is unclear whether this is part of the ‘natural’ decadal scale variability; large-scale fires and droughts, for instance in Amazonia, but also at Northern latitudes, have lead to significant decreases in carbon uptake on annual timescales; the extra uptake of CO₂ stimulated by increased N-deposition is, from a greenhouse gas forcing perspective, counterbalanced by the related additional N₂O emissions; the amount of carbon stored in permafrost areas appears much (two times) larger than previously thought; preservation of existing marine ecosystems could require a CO₂ stabilization as low as 450 ppm; Dynamic Vegetation Models show a wide divergence for future carbon trajectories, uncertainty in the process description, lack of understanding of the CO₂ fertilization effect and nitrogen–carbon interaction are major uncertainties.

Keywords Global carbon cycle · Terrestrial uptake · Ocean acidification · Carbon budgets · Carbon-climate feedback

INTRODUCTION

The amount of carbon dioxide in the atmosphere is determined by the emissions from fossil fuel, deforestation, and cement production, the natural uptake and release of oceans and terrestrial surfaces and by agricultural activities and management of (semi) agricultural land. Since the uptake and release processes are climate and temperature dependent (e.g., Friedlingstein et al. 2006), this creates potential for feedback. The Fourth Assessment Report of IPCC (AR-4) has identified those feedbacks as important to be built into models (Denman et al. 2007) because they lead to net higher CO₂ concentrations in the atmosphere than in the absence of feedbacks. The carbon cycle feedback has important implications for estimating and establishing required emission reduction scenarios (e.g. Meinshausen et al. 2009). At the same time, reliable estimates of sources and sinks are needed at increasingly high resolution to serve as potential input and validation tools in the (post) Kyoto process. Better understanding of feedbacks and source/sink regions formed the focus of a considerable amount of research on carbon cycle-climate studies since the publication of the AR-4. This review attempts to identify the important findings since the publication of AR-4 in relation to the carbon cycle on land, atmosphere and in the ocean. We first identify the developments in observational studies, particularly in relation to the growth rate of CO₂ and CH₄. We then review recent developments in estimating the current sinks and sources both for land and oceans. Vulnerable carbon pools

potentially signify important feedbacks in the climate-carbon coupling and understanding how carbon uptake changes with disturbances, for instance fires, drought or increased nitrogen availability, is critical in assessing its future behaviour. We thus review our current understanding of the carbon budget and the most important of these vulnerabilities and then review our capability to make reliable projections for terrestrial and oceanic carbon uptake in the future. We finish this review by identifying a number of areas where uncertainties are large and further study is needed.

OBSERVATIONS

CO₂ Emissions and Atmospheric Concentration

The increase in emissions increases as reported in AR-4 has continued (Canadell et al. 2007; le Quéré et al. 2009). The average growth rate of the atmospheric CO₂ concentration from 2000 to 2008 was observed at 1.93 ppm/year (4.1 PgC/year), compared to 1.60 and 1.46 ppm/year in the 1980s and 1990s. Growth rates in 2008 and 2009 were at 1.79 and 1.86 ppm/year, respectively, while in 2007 the growth rate was 2.13 ppm/year.¹ The relative decline in 2008 and 2009 can be attributed partly to the impact of the financial crisis on the fossil fuel use and associated emissions. The growth rate in the period 2000–2008 was 21% higher than that in the period 1980–2000. The average proportional growth rate of fossil fuel emissions and small other contributions increased from 1.0% per year for 1990–1999 to 3.4% for 2000–2008 (le Quéré et al. 2009). The increase in emissions puts the current emission trajectory at the high end of the average of the family of high emission scenarios as developed by IPCC (2000). Van Vuuren and Riahi (2008), however, point out that they still are below some of the highest individual scenarios. Canadell et al. (2007), van Vuuren and Riahi (2008) and le Quéré et al. 2009 also suggest that the increase in emissions is caused by growth of the world economy, until the financial crisis, combined with an increase in global carbon intensity, i.e. the CO₂ emission per unit of economic activity. The latter is related to the increasing contribution to the overall emissions of the strongest growing economies such as India and China, both having above average carbon intensity levels (Raupach et al. 2007; le Quéré et al. 2009).

However, van Vuuren and Riahi (2008) also suggest that there may be reasons to assume that the rise in emissions in the long term may be less rapid than in recent years. These relate to the quality of emissions data for the period of 2000–2006, in particularly the fossil fuel use data of China. Gregg et al. (2008) suggest uncertainties (reported as two

standard deviations) in the Chinese fossil fuel use of 15–20%, compared to 3–5% for the US. Further uncertainties with respect to the underlying driving forces such as the future development of China, global oil prices and the long-term economic prospects affect the robustness of the long-term evolution of emission trends. Van Vuuren and Riahi (2008) suggest that the current emission trajectory nears the high-end scenarios in the short term, but that it is too early to state unequivocally how this trend will behave in the longer term (50 years or more). In any case, there are several implications of the short-term increase in growth rate for policy negotiations, but these refer primarily to the strongly uneven regional development of the emissions (e.g. Raupach et al. 2007) and this aspect is surfacing regularly in the negotiations of the Conference of the Parties, such as recently in Copenhagen in December 2009.

Methane Emissions and Atmospheric Concentrations

Rigby et al. (2008) show that after a decade of no growth in CH₄ concentration, in 2007 and 2008 the concentration of methane in the atmosphere increased again. They attribute this increase to increased emissions from Northern Hemispheric sources. It is important to put this finding in the perspective of Bousquet et al. (2006) who suggested that atmospheric methane levels could increase in the near future, after a period of stabilization, if wetland emissions return to their mean 1990s levels. It is unknown if this is now indeed the case. Paleoclimatology studies (Petrenko et al. 2008; Fischer et al. 2008) furthermore suggest that the last glacial termination was likely to have been caused more by increased methane emissions from boreal wetlands rather than by emissions stemming from methane hydrate instability. In general, these results point to the very strong role of Northern Hemispheric wetland emissions in the variations of the methane budget. Uncertainty in these estimates is, however, still very large (Petrescu et al. 2010; Ringeval et al. 2010).

The idea that there exist large, hitherto unknown sources of methane from dry plant origin (Keppler et al. 2006) was disproved by Dueck et al. (2007). They showed conclusively, that there is no evidence for substantial aerobic methane emission by terrestrial plants. They put this to maximally 0.3% of the previously published values. Additional evidence for a strong reduction in the potential source from tropical plants as originally suggested comes from Frankenberg et al. (2008) who use inversions based on revised satellite retrieval from SCIAMACHY, and reduce annual tropical emission from 260 to about 201 Tg CH₄. The active contribution of terrestrial plants to global methane emission is thus very small at best, making it unnecessary to take this into account in (post) Kyoto land-use emissions.

¹ See <http://www.esrl.noaa.gov/gmd/ccgg/trends/>.

Airborne Fraction of CO₂ Emissions

While both land and ocean continue to accumulate carbon at an average rate of $5 (\pm 0.6)$ PgC/year, Canadell et al. (2007) and le Quéré et al. (2009) suggest evidence for a long-term (50 year) increase in the airborne fraction (AF) of CO₂ emissions. This implies a decline in the efficiency of the CO₂ sinks on land and/or ocean in absorbing anthropogenic emissions. The atmospheric fraction also shows strong interannual variability caused by for instance the effects of El Niño's and volcanic eruptions. While the analysis of le Quéré et al. (2009) uses nine different estimates of land-use change, four land vegetation and three ocean models, and would appear to be robust, Knorr (2009) concludes, using a more detailed analysis including uncertainties in the atmospheric observations that it is still unclear whether the calculated increase in AF is statistically significant.

An increase in the AF implies carbon emissions that have grown faster than the CO₂ sinks. There is, however, no a priori reason to assume that emission rate and sink strength are coupled though, with the latter primarily responding to the concentration of atmospheric CO₂ (e.g. Knorr 2009). Since the land and oceans are both mosaics of regions that are gaining and regions that are losing carbon, a possible trend in AF could arise from sink regions having weakened, either absolutely or relative to growing emissions; source regions could have intensified or finally sink regions could even have changed into source regions. Furthermore, the trend in AF depends on the magnitude and trend of the deforestation flux, which is still highly uncertain (van der Werf et al. 2009) and may need downward adjustment to values as low as 1.2 Gton C/year over the period 1997–2006, with a quarter on top of that (0.3 Gton C/year) coming from peat land degradation and peat fires in South East Asia. Satellite-based estimates of this flux are in general lower than estimates based on book-keeping methods, and using the lower estimates result in a more constant AF over time. It would thus appear too early to draw firm conclusions about trends in the AF.

Current CO₂ Sink Strength of the Biosphere

Contradictory results were often found when comparing estimates of biospheric uptake from measurements in forests and grasslands at the regional scale with estimates inferred from atmospheric CO₂, the latter known as the 'inverse' approach² (Pacala et al. 2001; Janssens et al.

2003). In order to get these different approaches to converge, care must be taken to account for all components of carbon exchange between the land and the atmosphere, and the movement of carbon in and out of the region in question (e.g. Schulze et al. 2009). This requires exhaustively cataloguing data from all of the major vegetation and soil categories in a region through the use of inventories, field measurements, surveys and remote sensing. In addition to this 'bottom-up' estimate, process-based ecosystem models and ensembles of atmospheric inversions are needed to arrive at a convergent estimate.

Piao et al. (2009a, b) and Schulze et al. (2009) show how this methodology is now increasingly mature to confidently estimate the carbon balance of large regions like China and Europe, respectively. Piao et al. (2009a, b) estimate a net carbon sink for China in the range of 0.19–0.26 PgC/year, smaller than that in the conterminous United States but comparable to that in geographic Europe. This was sufficient to offset 28–37% of the fossil fuel emissions of China in the 1980s and 1990s. Schulze et al. (2009) in a very comprehensive study, exploiting the full benefits of both a top down estimate from inverse models and bottom up estimates from models and observations, provide not only the carbon balance but also the first complete GHG balance of Europe. This allows them to conclude that the overall GHG balance of Europe is nearly neutral, with emissions of N₂O and CH₄ caused largely by agriculture in the west, balanced by uptake of CO₂ by forest and grasslands in east Europe.

Luyssaert et al. (2008) report that old-growth forests can continue to accumulate carbon, in contrast to the long-standing view that they are carbon neutral. This would apply to over 30% of the global forest area that is still unmanaged primary forest. Half of the primary forests (600 million ha) are located in the boreal and temperate regions of the Northern Hemisphere. These forests alone sequester about 1.3 ± 0.5 PgC/year. These findings suggest that 15% of the global forest area, previously considered to be non-contributing to net uptake, provides at least 10% of the global net ecosystem productivity (NEP). In Europe, conservative forest management strategies have not kept pace with increasing woody biomass production, thus creating a net sink (Ciais et al. 2008).

Observations show that, at least over recent decades, long-term monitoring plots of old-growth forest across Amazonia (Phillips et al. 2008) are a sink of 0.62 ± 0.23 MgC/ha/year adding up to 0.5–0.8 PgC/year for the whole Amazonian region. Stephens et al. (2007) using global measurements of vertical atmospheric CO₂ distributions, reveal annual-mean vertical CO₂ gradients that are inconsistent with a set of atmospheric inverse models that estimate a large transfer of terrestrial carbon from tropical to northern latitudes. This suggests that these models may

² Our ability to diagnose the fate of anthropogenic carbon emissions depends critically on interpreting spatial and temporal gradients of atmospheric CO₂. The state of the art methodology to achieve this is to back-calculate, from observed concentrations with the help of a transport model, the areas where the sources or sinks are located. This technique is also called inverse modeling.

have overestimated the contribution of northern latitude sinks compared to tropical ones. The three inverse models that most closely reproduce the observed annual-mean vertical CO₂ gradients estimate weaker northern uptake of 1.5 PgC/year and weaker net tropical emissions (i.e. uptake minus deforestation loss) of 0.1 PgC/year compared with the estimates from the average of twelve inverse models (an uptake of 2.4 and net emissions of 1.8 PgC/year, respectively). Note that the tropical emissions are net results, subtracting this from the estimated land-use change (1.5 PgC/year, le Quéré et al. 2009), yields the uptake from tropical forests. This suggests that northern terrestrial uptake of CO₂ plays a smaller role in the global carbon budget than previously thought and that, after subtracting land-use emissions, tropical ecosystems may currently be stronger sinks for CO₂.

For Africa, based on data from a ten-country network of long-term monitoring plots in tropical forests, Lewis et al. (2009) suggest that above-ground carbon storage in live trees increased by about 0.6 MgC/ha/year between 1968 and 2007. Extrapolation to unmeasured forest components (live roots, small trees and necromass) and scaling to the continent of these numbers implies a total increase in carbon storage in African tropical forest trees of 0.34 PgC/year. These reported changes in carbon storage are similar to those reported for Amazonian forests per unit area, providing evidence that increasing carbon storage in old-growth forests is a pan-tropical phenomenon. Indeed, combining all standardized inventory data from this study and from tropical America and Asia together yields a comparable figure of 0.49 MgC/ha/year over the interval, 1987–1997. This indicates a carbon sink of 1.3 PgC/year (0.8–1.6) across all tropical forests during recent decades, corroborating the estimate of Stephens et al. (2007) discussed above. Changes in resource availability such as increasing atmospheric carbon dioxide concentrations, may be the cause of this increase in carbon stock, in line with modelling studies (Sitch et al. 2008). Mercado et al. (2009) present modelling evidence that a late twentieth century increase in diffuse radiation may have enhanced the terrestrial C sink by about 25%. The precise causes of the increase in tropical forest biomass are thus not yet clear.

Current CO₂ Sink Strength of the Ocean

Gruber et al. (2009) synthesize estimates of the contemporary net air-sea CO₂ flux on the basis of a set inversion models using ocean carbon observations. They use 10 ocean general circulation models (Mikaloff Fletcher et al. 2007) and compare these to estimates of a new climatology of the air-sea difference of the partial pressure of CO₂ (pCO₂) (Takahashi et al. 2008). The two independent flux

estimates yield a largely consistent description of the regional distribution of annual-mean oceanic sources and sinks for the decade of the 1990s and the early 2000s. Differences at the regional level are generally less than 0.1 PgC/year. This good agreement between inversions and other flux estimates mirrors similar progress made in narrowing down uncertainties between models and observations on the land.

The distribution of fluxes from the ocean obtained by inverse models consists of outgassing in the tropics, uptake in midlatitudes, and comparatively small net fluxes in the high latitudes. Both the inversion and climatology-based estimates suggest a relatively small (0.3 PgC/year) contemporary CO₂ sink in the Southern Ocean (south of 44°S) as a result of the near cancellation of a substantial outgassing of natural CO₂ and a strong uptake of anthropogenic CO₂. In the Southern Ocean, the ocean inversions suggest a relatively uniform uptake, while the pCO₂-based estimate suggests strong uptake in the region between 58°S and 44°S, and a source in the region south of 58°S. Globally, for 1995–2000, the net air-sea flux of CO₂ is estimated at 1.7 ± 0.4 PgC/year for the inversions and at 1.4 ± 0.7 PgC/year based on the pCO₂-climatology, respectively. This is composed of an outgassing flux of river-derived carbon of $0.5 \text{ PgC year}^{-1}$, and an uptake flux of anthropogenic carbon of 2.2 ± 0.3 PgC/year (inversion) and 1.9 ± 0.7 PgC/year (pCO₂-climatology). As mentioned, the convergence of these two independent estimates is encouraging as it suggests that it is now possible, as on the land, to provide relatively tight constraints for the net air-sea CO₂ fluxes at the regional basis. However, both studies are still limited by their lack of consideration of long-term changes in the ocean carbon cycle, such as the recent possible stalling in the expected growth of the Southern Ocean and Atlantic Ocean carbon sink.

In the Southern Ocean, poleward displacement and intensification of westerly winds caused by human activities have appeared to enhance the ventilation of carbon-rich waters normally isolated from the atmosphere at least since 1980 (le Quéré et al. 2007, 2008), but it remains probably too early to robustly attribute this to a pertinent change in the circulation or to multidecadal or interannual variability (Zickfeld et al. 2008).

In the North Atlantic, Schuster and Watson (2007) show that the sink for atmospheric CO₂ exhibits significant interannual variability. They also observe an interdecadal decline, evident throughout the North Atlantic that is significant in the northeast of the area but not in the western subtropical areas. They found that the overall sink reduced by more than 50% from the mid-1990s to the period 2002–2005. They estimate that the uptake of the region between 20°N and 65°N declined by 0.24 PgC/year from 1994–1995 to 2002–2005. An unresolved question is still

whether this decline is due to a rearrangement of the ocean part of the global carbon cycle in response to climate change or part of ‘natural’ fluctuations in the basin caused by the North Atlantic Oscillation (e.g. Gruber 2009).

VULNERABILITY: FACTORS INFLUENCING THE CARBON EXCHANGE WITH THE BIOSPHERE

Vulnerability of carbon stocks is the critical unknown in coupled carbon-climate models. Increased realism in these models relies on adequate understanding of the size and sensitivity of the ocean and terrestrial carbon stocks. We review here the most important developments in this area since AR-4.

Droughts and Fires

On land, a number of major droughts in mid latitude regions in 2002–2005 appear to have contributed to a decrease in the terrestrial carbon sinks in these regions over that period. Peters et al. (2007) using the NOAA advanced Carbon Tracker assimilation scheme find that terrestrial uptake in the US fell to 0.32 PgC/year during the large-scale drought of 2002, compared to an average uptake of 0.62 PgC/year over the period 2001–2005. This was also suggested by Ciais et al. (2005) who found a reduction in European uptake in the dry and hot summer of 2003 that offset 4 previous years of uptake. The sensitivity of carbon uptake and release to climate perturbations is non-linear and there is large potential for extreme climate events to significantly disturb the annual average sink behaviour.

Large uncertainties are still associated with the response of tropical vegetation to drought and boreal ecosystems to elevated temperatures and changing soil moisture status. For boreal zones, Piao et al. (2009a, b) show that temperature changes before the 1970s had a limited influence on the current pattern of net carbon sequestration, and that the impact of recent temperature changes within the last decade are not strong enough to be observable. Changes in the seasonal patterns of temperature, however, are one of the important drivers of today’s forest carbon balance in the Northern Hemisphere. At long time scales, our ability to accurately model carbon fluxes is thus constrained by our limited understanding of how seasonal temperature might vary over time.

Phillips et al. (2009) used records from multiple long-term monitoring plots across Amazonia to assess forest responses to the intense 2005 Amazon drought. The forest affected by the drought lost biomass, and this loss reversed a large long-term carbon sink. The greatest impacts were observed where the dry season was unusually intense. The drought had a total (committed) biomass carbon loss

impact of 1.2–1.6 PgC. Amazon forests thus appear particularly vulnerable to increasing moisture stress, with the potential for large carbon losses to exert feedback on climate change. It is, however, unclear what the long-term response of the forest to such a disturbance is. Focussing on single year events may overemphasize the effects, as trees could die in later years and dead trees may give space for new species at increased rates. It is further worth emphasizing that in the analysis of Friedlingstein et al. (2006) the role of the tropical forest is critical in determining the carbon-climate sensitivity.

The fastest way in which drought can lead to carbon losses (or, to a reduction in the sink strength) is through fire. Fires were recently identified as one of the main features lacking in global models, even though (deforestation) fires not only influence CO₂ concentrations but also seven other radiative forcing components (Bowman et al. 2009). According to Nepstad and Stickler (2008), increased vulnerability of Amazon forests due to drought may expose more than 50% of the Amazon to fires and logging. In Indonesia where carbon-rich peat soils are burned during the dry season, fires have been known to be a large emissions source. Only recently reliable estimates of emissions have been made, turning out to be comparable to Indonesian fossil fuel emissions (van der Werf et al. 2008). Moreover, these fires have been amplified by human interference and are strongly dependent on seasonal droughts governed by El Niño or positive phases of the Indian Ocean Dipole (Field et al. 2009). The strong non-linear relation between droughts and fires versus carbon emissions and deforestation highlights a climate-carbon feedback that may lead to higher CO₂ concentrations if droughts become more frequent in the future (Li et al. 2007)

Interaction with the Nitrogen Cycle

Since industrialization, N-deposition has increased, particularly in the Eastern US, Europe and in South and East Asia. There is growing evidence that this increase may also be responsible (Magnani et al. 2007; de Vries et al. 2008; Reay et al. 2008; Janssen and Luyssaert 2009) for maintaining at least part of the current terrestrial sink. The estimates of C sink strength per deposited kilogram of nitrogen vary from 70 to 400 kgC per kgN deposition (Magnani et al. 2007), depending on the estimate of the total N-deposition. Due to an increase of fossil fuel combustion for energy, industry and traffic and of fertilizer and manure use for food and biomass production, the deposition rates are likely to become even larger and wider spread (Galloway et al. 2008). The acceleration of the natural N-cycle as a consequence of global warming is another mechanism to increase N availability to the vegetation. Several authors have evaluated the effect of including C–N

coupling in carbon and/or climate models (Sokolov et al. 2008; Xu-Ri and Prentice 2008). In response to a 2°C warming, simulated Net Primary Production (NPP)³ decreased when the C- and N-cycles were uncoupled, an effect largely due to higher plant respiration. Simulated NPP increased when they were coupled, because the higher decomposition rates and associated N availability offset the cost of plant respiration (Sokolov et al., 2008). Janssens et al. (2010) note how increased N-deposition may decrease heterotrophic respiration, thus enhancing, at least for some time, the apparent sink at ecosystem level.

The responses of net land carbon exchange at global level to variation in temperature and precipitation are significantly damped by C–N-cycle coupling (Thornton et al. 2007). These coupled C and N modeling studies suggest that the likelihood of greatly enhanced global CO₂ sequestration resulting from future changes in N-deposition is low. Even if N emissions were to follow the more pessimistic IPCC emission scenarios these models show a decline in the terrestrial sink compared to models that have no N-cycle. Several processes are not yet fully integrated into the coupled C–N modelling, including the effect of climate change on the C–N coupling, influence of anthropogenic N-deposition, biological nitrogen fixation, reallocation of nitrogen between vegetation and soil and between labile and recalcitrant pools and the redistribution of plant species in response to disturbance or climate change (Bonan 2008; Janssens et al. 2010).

A recent review (Reay et al. 2008) also indicates that the enhanced global CO₂ sequestration resulting from future changes in N-deposition may be relatively low and probably compensated by emissions of N₂O Dentener et al. 2006 estimated that the current N-deposition is about 4 kg/ha on the Northern Hemisphere and is greatly varying. If half of this is of anthropogenic origin, the additional carbon stored is about 0.2 MgC/ha. If local variations in nitrogen deposition are taken into account this can be higher. Even if N emissions were to follow the more pessimistic IPCC emissions scenarios (Erisman et al. 2008) and large increases in the strengths of the terrestrial and oceanic carbon sinks were achieved, this may be off-set by any simultaneous enhancement of N₂O emissions. A doubling of the year 2000 N emissions by 2030 may achieve 3 Pg of additional CO₂ sequestration in northern and tropical forests each year, but it would also induce global annual emissions of between 0.54 and 2.7 Pg of CO₂ equivalent, in the form of N₂O, via increased nitrification and denitrification on land and in the

oceans. Such ‘pollution swapping’ would greatly off-set any net climate change mitigation benefits.

Permafrost Decomposition

Tarnocai et al. (2009) show that accounting for C stored deep in the permafrost more than doubles previous high-latitude inventory estimates of carbon stocks. This new estimate puts the permafrost carbon stock to an equivalent of twice the atmospheric C pool. Thawing of permafrost with warming occurs both gradually and catastrophically, exposing organic C to microbial decomposition. Growing season length, plant growth rates and species composition and ecosystem energy exchange may balance those losses. However, these processes may ultimately not be able to compensate for C release from thawing permafrost. Schuur et al. (2009) found that areas that thawed over the past 15 years had 40% more annual losses of old carbon than less-thawed areas, but still had an overall net ecosystem carbon uptake as increased plant growth offset these losses. In contrast, areas that thawed decades earlier lost even more old carbon, this constituted a 78% increase over the less-thawed areas. This old carbon loss contributed to overall net ecosystem carbon release despite increased plant growth. They conclude that over decadal timescales, the losses overwhelmed increased plant carbon uptake at rates and that this could make permafrost a large biospheric carbon source in a warmer world of the order of 1 PgC/year. Dorrepaal et al. (2009), using data from long-term ecosystem manipulation experiments, found that respiration rates through warming of sub arctic soil increased by almost 70%, particularly from the layer from 25–50 cm below the surface. These effects were sustained for 8 years. If these results can be extrapolated globally, an additional 38–100 PgC could be released per degree warming. It has to be emphasized that both these estimates of future behaviour are based on relative simple upscaling principles and do not take into account negative feedback mechanisms that may decrease carbon loss. Nevertheless, they indicate the potential significance of the carbon climate feedback at Northern latitudes.

Ocean Acidification

Oceanic uptake of anthropogenic carbon dioxide (CO₂) is altering the seawater chemistry of the world’s oceans with consequences for marine biota. Elevated partial pressure of CO₂ is causing the calcium carbonate saturation horizon to shoal in many regions, particularly in high latitudes and regions that intersect with pronounced hypoxic zones as the result of increased nitrogen run-off and deposition. The ability of marine animals, most importantly pteropod molluscs, foraminifera and some benthic invertebrates, to

³ NPP is the rate at which plants in an ecosystem produce net useful chemical energy. It is equal to the difference between the rate at which the plants in an ecosystem produce useful chemical energy (GPP) and the rate at which they use some of that energy through cellular respiration.

produce calcareous skeletal structures is directly affected by seawater CO₂ chemistry. CO₂ influences the physiology of marine organisms as well through acid-based imbalance and reduced oxygen transport capacity. The few studies at relevant pCO₂ levels limit our ability to predict future impacts on foodweb dynamics and other ecosystem processes. Fabry et al. (2008) present new observations, review available databases on regions, ecosystems, taxa and physiological processes believed to be most vulnerable to ocean acidification. They conclude that ocean acidification and the synergistic impacts of other anthropogenic stressors provide great potential for widespread changes to marine ecosystems.

Silverman et al. (2009) show that by the time atmospheric partial pressure of CO₂ will reach 560 ppm all coral reefs (more than 9,000 reef locations) will cease to grow and start to dissolve as result of ocean acidification. Cao and Caldeira (2008) using a coupled climate-carbon model, conclude similarly that ocean chemistry will be significantly perturbed even if atmospheric CO₂ can be stabilized at low to modest levels. At stabilization levels as low as 450 ppm, some parts of the high-latitude ocean would become undersaturated with respect to aragonite and experience a decrease in pH by more than 0.2 units. They find at stabilization levels of 550 ppm, there will be no water left in the open ocean with the kind of chemistry (aragonite saturation levels) experienced by more than 98% of shallow-water coral reefs before the advent of the industrial revolution. Silverman et al. (2009) suggest that preservation of existing marine ecosystems could require a CO₂ stabilization level that is lower than what might be chosen based on climate considerations alone.

PROJECTIONS OF CARBON REMOVAL

Since IPCC-AR, the carbon cycle feedback has received much attention and modelling groups have been active to incorporate this feedback into their models (e.g. Boer and Arora 2009, for an example and analysis of this feedback). However, since the range in carbon sensitivity is large between the models used in the IPCC 2007 reporting (Denman et al. 2007) it remains important to determine how well our land and atmosphere models capture all relevant processes. Intercomparison studies are critical in this respect.

Terrestrial Carbon Uptake

In a recent modelling study (Sitch et al. 2008), five Dynamic Global Vegetation Models (DGVMs)⁴ were

⁴ A DGVM simulates (shifts in) potential vegetation and its associated biogeochemical and hydrological cycles as a response to (shifts in) climate.

compared with global land carbon budgets for the 1980s and 1990s. Their results show that all DGVMs are consistent with the global budgets and in agreement with earlier modelling studies on cumulative land uptake over the last 50 years (e.g. Friedlingstein et al. 2006). The study went beyond earlier intercomparisons by including and diagnosing climate-carbon cycle feedbacks, and by spanning a wide range of emission scenarios. The five models were run with observed climatologies and atmospheric CO₂ and with future ones derived from four IPCC scenario's (IPCC 2000) and from a simple climate model and ocean carbon cycle model. The DGVMs are able to simulate the correct sign of the global land carbon response to ENSO, but, importantly, still with differing magnitudes of response. All models show cumulative net uptake in the twenty-first century, but the land uptake varies markedly among DGVMs. This indicates large uncertainties in future atmospheric CO₂ concentration associated with uncertainties in the terrestrial biosphere response to changing climatic conditions. It is likely that part of this uncertainty is caused by poor and different representation of the interactions with nitrogen. The DGVMs show more divergence in their response to regional changes in climate than to increases in atmospheric CO₂ content. All models simulate a release of land carbon in response to climate change, when physiological effects of elevated atmospheric CO₂ on plant production are not considered, implying a positive terrestrial climate-carbon cycle feedback. All DGVMs simulate a reduction in global Net Primary Production (NPP) (see Footnote 3) and a decrease in soil residence time of carbon in the tropics and extra-tropics in response to future climate. When both counteracting effects of climate and atmospheric CO₂ on ecosystem function are considered, all the DGVMs simulate cumulative net land carbon uptake over the twenty-first century for the four SRES emission scenarios. However, for the most extreme A1FI emissions scenario, three out of five DGVMs simulate an annual net source of CO₂ from the land to the atmosphere in the final decades of the twenty-first century. For this scenario, cumulative land uptake differs by 494 PgC among DGVMs; equivalent to about 50 years of anthropogenic emissions at current levels.

Oceanic Carbon Uptake

Previously, ocean models suggested that the interannual variability in the global sink is relatively small, while new estimates based on atmospheric inversions (see 'Current CO₂ Sink Strength of the Biosphere' section) indicate a year-to-year variability that is substantial. IPCC AR4 projections (Denman et al. 2007) suggest that the sink should increase as atmospheric CO₂ continues to rise, but that under anthropogenically induced climate change,

increasing stratification⁵ and a slowing overturning circulation decrease rates of ventilation and tend to slow the uptake. Thomas et al. (2008) propose that the interpretation of a reduced sink may need to be viewed with great caution. Using a global model of the ocean carbon cycle, forced with observed atmospheric conditions they investigated how variations and trends in the North Atlantic Oscillation (NAO)⁶ have affected the North Atlantic carbon sink since 1979. They argue that the observed trends instead reflect fluctuations on a decadal timescale that are a response to climate variability in the North Atlantic region and find substantial year-to-year changes in the surface-ocean carbon cycle, with an overall tendency for increased uptake in the temperate North Atlantic.

The Southern Ocean stands out with its large uptake of anthropogenic CO₂ and with its substantial outgassing of natural CO₂. This region reacts with relatively high sensitivity to climate variations over the last 50 years as well as to future climate change, because of the interaction of sea-ice, upwelling and convection with changes in heat and freshwater. Given the large exchange fluxes of the two CO₂ components, relatively small changes in the Southern Ocean could lead to large changes in the net atmosphere–ocean balance of CO₂ (Gruber et al. 2009, le Quéré et al. 2008; le Quéré et al. 2009).

CONCLUSIONS AND DISCUSSION

There is no doubt that understanding the future behaviour of the carbon cycle is critical in making realistic mitigation plans for the near and far future (Meinshausen et al. 2009). In that sense, the uncertainty that still exist in our understanding of key processes is worrying, although the basic message that we have experienced a free discount of about 40–50% on our fossil fuel emissions through the uptake of excess carbon by land and ocean is indisputable. How long this discount will continue to operate is uncertain (Le Quéré et al. 2009; Knorr 2009). We have reviewed advances in our understanding of the carbon cycle since the publication of the IPCC Fourth Assessment Report (Denneman et al. 2007). While the choice of subjects of this is arguably somewhat arbitrary and limited in scope, we believe that our choice of developments covers the most

important areas of progress and the most important areas of uncertainty. We conclude:

- The anthropogenic emissions of CO₂ due to fossil fuel burning have increased through 2008 at a rate close to the high end of the IPCC emission scenarios;
- There are contradictory analyses whether an increase in atmospheric fraction, that might indicate a declining sink strength of ocean and/or land, exists;
- Methane emissions are increasing, possibly through enhanced natural emission from northern wetland, methane emissions from dry plants are negligible;
- Old-growth forest take up more carbon than expected from ecological equilibrium reasoning;
- Tropical forest also take up more carbon than previously thought, however, for the global budget to balance, this would imply a smaller uptake in the northern forest;
- The exchange fluxes between the atmosphere and ocean are increasingly better understood and bottom up and observation based top down estimates are getting closer to each other;
- The North Atlantic and Southern ocean take up less CO₂, but it is unclear whether this is still part of the ‘natural’ decadal scale variability;
- Large-scale fires and droughts, for instance in Amazonia, but also at Northern latitudes, have lead to significant decreases in carbon uptake on annual timescales;
- The extra uptake of CO₂ stimulated by increased N-deposition is, from a greenhouse gas forcing perspective, counterbalanced by the related additional N₂O emissions;
- The amount of carbon stored in permafrost areas appears much (two times) larger than previously thought;
- Preservation of existing marine ecosystems could require a CO₂ stabilization as low as 450 ppmv;
- Dynamic Vegetation Models show a wide divergence for future carbon trajectories, uncertainty in the process description, lack of understanding of the CO₂ fertilization effect and nitrogen–carbon interaction are major uncertainties.

In general, a better understanding of the current land and ocean budgets has been achieved. Perhaps, more importantly for some regions consistency, and consequent reduction of uncertainty has been obtained by bringing top down and bottom up estimates closer together. This, however, requires for land budgets considerable effort in obtaining reliable bottom up estimates of biomass and soil carbon. In particular, the role of agriculture in both the current budget as well as increasing CO₂ uptake through management and reducing emissions of N₂O requires more work.

⁵ Water stratification occurs when water of high and low salinity (halocline), as well as cold and warm water (thermocline), forms layers that act as barriers to water mixing.

⁶ The NAO is a climatic phenomenon in the North Atlantic Ocean of fluctuations in the difference of atmospheric pressure at sea-level between the Icelandic Low and the Azores high. Through east–west oscillation motions of the Icelandic Low and the Azores high, it controls the strength and direction of westerly winds and storm tracks across the North Atlantic.

At the large scale, the sparseness of the CO₂ concentration network is still the main stumbling block for improving inversion-based estimates (Marquis and Tans 2008). With the recent loss of the Orbiting Carbon Observatory this situation has not improved, although the Japanese GOSAT mission and maybe the second OCO will hopefully provide useful data. However, to be able to study interannual variability and make comparisons with inventory data long time series of dense observations are needed.

Several studies, both on land and on ocean have highlighted critical vulnerabilities in the interaction between the carbon cycle and climate. In the ocean, the debate about interannual variability of the Northern Atlantic and potential decline of the Southern Ocean sink shows how difficult it still is to provide robust estimates about future behaviour. Again lack of data is a key issue, and land modelling studies (e.g. Sitch et al. 2008) show how similar carbon trajectories can be realized for the present, relatively well-constrained system, but how model divergence, or uncertainty, increases when the same models are used to predict future trajectories.

The current models for projections of carbon removal appear to lack key processes that are necessary to perform detailed assessments of carbon budgets. On a relatively high level of abstraction the models are in reasonable agreement, but for the sub-systems of the budgets, sensitivity to critical processes and on the regional scales the models are still too coarse. On land, these models will need to improve their parametrizations of the effect of increasing CO₂ levels on primary production and long-term carbon sequestration, the response of carbon uptake to disturbances in nutrient input (primarily N) and the interaction with the hydrological cycle (drought). A recent study (O'ishi et al. 2009) highlights the interaction between longer term vegetation change and positive effects from fertilization, while at the same time still predicting a conversion to a source of CO₂ for the land in the future. In the ocean the potential decline in sink strength, and its variability need to be better understood. Improving understanding the response of marine ecosystem and associated carbon cycle impact to acidification is of critical importance and, *inter alia*, shows how “secondary” effects of carbon uptake may have dramatic consequences for ecosystem functioning.

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