The prospects for reversing dangerous global warming by directly capturing CO_2 from the atmosphere

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Abstract

There is now little doubt that anthropogenic greenhouse gas emissions are causing the global temperature to rise and if emissions continue to grow at their current rate, the consequences for humanity could be catastrophic. The international community appears to be reaching agreement on the importance of taking action to limit the global temperature rise to 2°C above the pre-industrial level and have acknowledged that failing to do so will risk potentially irreversible damage to the environment and the climatic system.

Evidence suggests that even with a determined effort to meet this 2°C target, it will be hard to achieve without seriously impairing global economic growth. This is something the international community is unlikely to agree to. If the global temperature exceeds the 2°C target, models of the climate system predict that natural processes will not significantly lower the temperature for thousands of years. On this timescale, slower climate feedback processes like the melting of the planet's ice sheets will come into play, possibly causing the global temperature to rise further. Under these circumstances even 2°C of warming may not be safe.

It is argued that the only safe and permanent option available to reverse a dangerous increase in the global temperature is the direct capture of CO_2 from the atmosphere. If the atmospheric CO_2 concentration is reduced quickly once it has peaked, the oceans will act as a huge heat reservoir, cooling the atmosphere and causing the global temperature to fall. To ensure that the direct CO_2 capture process brings about this rapid decline in the global temperature the atmospheric CO_2 concentration will have to be reduced within a relatively short timeframe, perhaps by the end of the century.

Biological direct capture relies on plants or algae to capture CO_2 from the atmosphere by photosynthesis and then store it, usually as biomass. It is estimated that combining all of the available methods of biological direct capture, a CO_2 drawdown of between 50ppm and 100ppm could be achieved by the end of the century.

Chemical direct capture would involve building a man-made device to chemically capture CO_2 from the atmosphere. This technology is still in the development phase, but it is estimated that, with a successful research program, it could achieve a CO_2 drawdown of around 100ppm by the end of the century. However, this option may be prohibitively expensive.

Combining all of the available methods of direct CO_2 capture and using them in conjunction with a strict emissions reduction regime, it may be possible to return the atmospheric CO_2 concentration to 350ppm by the end of the century. If only biological direct capture methods are used, this reduction is likely to take until the middle or end of the next century. If used proactively, a program of direct CO_2 capture has the potential to prevent warming and help make the 2°C target more achievable.

Contents

1. Introduction

Starting around the time of the industrial revolution in the 1700s, the combined effects of deforestation and the burning of fossil fuels have increased the atmospheric carbon dioxide (CO_2) concentration from the pre-industrial level of 280ppm to the current level of 386ppm [1]. The present atmospheric CO_2 concentration is higher than at any time during the last 650,000 years [2] and probably during the last 20 million years [3]. The increase in the level of atmospheric CO_2 is of great concern because CO_2 is a greenhouse gas (GHG) that traps solar energy. As the CO_2 concentration increases, more of the Sun’s energy is trapped in the atmosphere, which causes the Earth’s surface temperature to increase. CO_2 is not the only atmospheric GHG, but it is the most important because it is the main contributor to global warming, currently being responsible for 63% of the total warming caused by GHGs [4]. CO_2 also remains in the atmosphere for a much longer time period than any of the other GHGs, so it has a long-term impact on the climate [5].

Since the beginning of the instrumental temperature record in 1880, an increase in the global surface temperature of around 0.8°C has been observed. The rate of the observed increase is also gathering pace, with a rise of 0.6°C occurring in the last 30 years [6]. At what point should this rise in the global temperature be considered dangerous?

Hansen et al. (2006) made a comparison of measured sea surface temperatures in the Western Pacific with paleoclimatic data. This comparison suggests that the planet as a whole is approximately as warm now as at the Holocene maximum and it is within 1°C of the maximum temperature of the past million years. Hansen concludes that an additional increase in the global temperature of approximately 1°C relative to 2000 will constitute a dangerous change in the Earth’s climate system that could result in significant sea level rise and expose the climate to runaway feedback processes [6]. Hansen suggests that to keep the Earth’s surface temperature within this limit, the atmospheric CO_2 concentration must peak no higher than 450ppm [7] and every effort should be made to return the atmospheric CO_2 concentration to a level below 350ppm as quickly as possible if we are to avoid slow climate feedback processes and preserve a climate similar to that in which civilization developed [8].

In a statement issued at the 2009 G8 summit, the eight member nations acknowledged that GHG emissions, caused by human activity, are causing global warming. The member nations stated their commitment to reducing their GHG emissions by 80% or more by 2050, relative to 1990 levels. They also recognised the importance of limiting the rise in the global temperature to 2°C (above pre-industrial levels), in order to avoid the risk of serious economic consequences and irreversible damage to the environment and the climatic system [9]. As the Earth has already warmed by 0.8°C over the pre-industrial temperature, this limit is very close to that suggested by Hansen.

The United Nations Secretary General, Ban Ki-moon, has welcomed the commitment made by the G8, but also stated that it is not enough. He believes the industrialized nations must make ambitious and binding mid-term (by 2020) emissions reduction targets and the developing nations must also take action to reduce growth in their emissions substantially below business as usual [10].

The European Union (EU) first established the 2°C limit as a target in 1996 during preparations for the Kyoto negotiations. However, the EU has stated that even this temperature increase cannot be considered entirely safe and that very urgent action is required if the 2°C target is to be achieved [11].

Even though the international community has acknowledged the dangers of GHG emissions, the rate of increase of anthropogenic CO_2 emissions is continuing to accelerate on a global scale. The main source of CO_2 emissions is fossil fuel burning and industrial processes. CO_2 emissions have increased from an average growth rate of 1.1% per year between 1990 and 1999, to an average growth rate of 3% per year between 2000 and 2004 [12]. The main driver of this increase in emissions is global economic development coupled with population growth. Economic development stimulates an increasing demand for cheap energy, which is mostly being satisfied by power stations that burn fossil fuels. In the period 2000 to 2004, every region of the world increased its use of fossil fuels. More recent figures for global CO_2 emissions show that this rate of growth continues, with both 2006 and 2007 having a growth rate over 3% and with the global consumption of coal increasing by 4.5% in 2007 [13].

The aim of this dissertation is to consider whether international efforts to reduce emissions are likely to be effective at stabilizing the global temperature below the 2°C target, and if the target is missed and the global temperature becomes dangerously high, can the warming be reversed and the global temperature be returned to a safe level?

It is argued that the only safe and permanent option available to reverse a dangerous increase in the global temperature is the direct capture of CO_2 from the atmosphere. Not only can direct CO_2 capture reverse global warming that has already occurred but, if implemented proactively, it has the potential to prevent warming and help make the 2°C target more achievable.

The argument is presented in four main sections. Section 2 examines the prospects for keeping global warming below the 2°C target. Section 3 argues that if the 2°C target is missed, natural processes are unlikely to reduce the global temperature for thousands of years and the only safe and permanent option for quickly reversing a dangerous increase in the global temperature is the direct capture of CO_2 from the atmosphere. In Section 4, the options for direct CO_2 capture are assessed and their potential for CO_2 drawdown examined in order to determine if it would be possible to implement them quickly enough and on a scale large enough to help bring global warming under control. Discussion and conclusions are presented in Section 5.

2. The prospects for keeping global warming below 2°C

2.1 International consensus on the 2°C target

The international community appears to be reaching a consensus on the importance of limiting the global temperature rise to 2°C above the pre-industrial level. The G8 and the European Union have stated clearly that, in order to avoid serious environmental and economic consequences, it will be important to limit global warming to 2°C. With this as a target, both groups have committed to cutting their GHG emissions by 80% by 2050 [9]. The Major Economies Forum on Energy and Climate, which includes both India and China [14], has stated that its members recognize the importance of limiting global temperature rise to 2°C above the pre-industrial level, however many of the 17 members of the forum have yet to commit to explicit emissions reduction targets [15].

The UN Climate Conference, set to take place in Copenhagen in December 2009, aims to secure international agreement on global GHG emissions reduction targets for post 2012, when the Kyoto agreement lapses [16]. The 2°C target is likely to form the backbone of these negotiations. Unfortunately, determining how much atmospheric CO_2 will cause the global temperature to increase beyond the 2°C target is not straightforward. This question sits at the centre of current climate debate, as the answer will determine the emissions reduction targets that will be needed to ensure the 2°C target is not exceeded.

2.2 Determining climate sensitivity to an increased CO_2 concentration

In trying to determine the likely global temperature response to an increase in the atmospheric CO_2 concentration, scientists define the term “climate sensitivity”. Climate sensitivity is defined as the amount by which the global mean surface temperature would change, once the system has reached equilibrium, following a doubling of the pre-industrial CO_2 concentration. To estimate the climate sensitivity, scientists must consider two principle factors. The first is the radiative forcing caused by the enhanced CO_2 concentration. The radiative forcing is a measure of the difference between the incoming radiation energy and the outgoing radiation energy in the lower atmosphere. The second is the effect of any climate feedback systems. In the absence of any feedback systems, a doubling of atmospheric CO_2 would result in ~1°C of global warming, a figure that can be easily calculated [17]. The uncertainty comes when estimating the effect of the climate feedback systems.

As the climate warms in response to the elevated CO_2 concentration, feedback processes can be caused by,

1) Changes in the water vapor amount and distribution
2) Changes in cloud cover, height and optical depth
3) Changes in surface albedo, e.g. disappearing snow and ice cover
4) Changes in advected energy transports.

All of these processes can contribute to the total change in global temperature, and the complex interaction between the processes makes their overall contribution very difficult to estimate or predict [18].

Scientists have used a wide range of methods to estimate the climate sensitivity, including the use of ice core data to look back at past variations of CO_2 and temperature, and the use of complex computer models to simulate how the oceans and atmosphere respond to an increased CO_2 concentration.

The IPCC has reviewed a wide range of these estimates and have concluded that climate sensitivity is,

“*Likely [66%-90% probability]* to be in the range of 2 to 4.5°C with a best estimate of about **3°C**, and is *very unlikely [<10% probability]* to be less than 1.5°C. Values substantially higher than 4.5°C cannot be excluded, but agreement of models with observations is not as good for those values.” [19]

Simplistically, this means a CO_2 concentration of 560ppm is likely to result in a 3°C rise in the global temperature once the climate system has reached equilibrium. In reality, there is also warming and cooling caused by other GHGs and aerosols and this must be accounted for. It is usual when considering the overall GHG concentration to express it in terms of CO_2 equivalence (CO_2eq); this measure combines the warming and cooling effect of all the GHGs and aerosols being considered and expresses it as the equivalent concentration of CO_2. So, from the IPCC best estimate of climate sensitivity, it is likely that a 3°C rise in global temperature will occur if the atmospheric GHG concentration reaches 560ppm CO_2eq.

2.3 What GHG concentration is likely to lead to 2°C of warming?

There are many uncertainties in trying to predict what concentration of GHG will lead to 2°C of warming. Figure 2.1, published by the EU Climate Change Expert Group, shows a summary of a number of different models that estimate the probability of exceeding the 2°C target across a range of GHG stabilization levels. They conclude from this research that, if the world is to meet the 2°C target with at least a 50% probability, the atmospheric GHG concentration would need to be stabilized at approximately 450ppm CO_2eq or lower. Stabilization at 400ppm CO_2eq or lower would raise the probability of keeping the temperature increase below 2°C to above 66%. Stabilization at 500ppm CO_2eq or above will make it unlikely or very unlikely that the target will be met [11].

Estimating the overall CO_2 equivalent warming effect of the various GHGs and aerosols is not straightforward. The overall concentration of the six Kyoto GHGs (CO_2, CH_4, N_2O, HFC, PFC, SF_6) reached 436 CO_2eq in 2007. Considering all long-lived GHGs, (the Kyoto GHGs plus the CFCs and HCFCs that are included in the Montreal Protocol), a level of 463ppm CO_2eq was reached in 2007. Finally, including ozone, the various aerosols and black carbon, the net warming effect reached an equivalent concentration of 396ppm CO_2eq in 2007 [20].

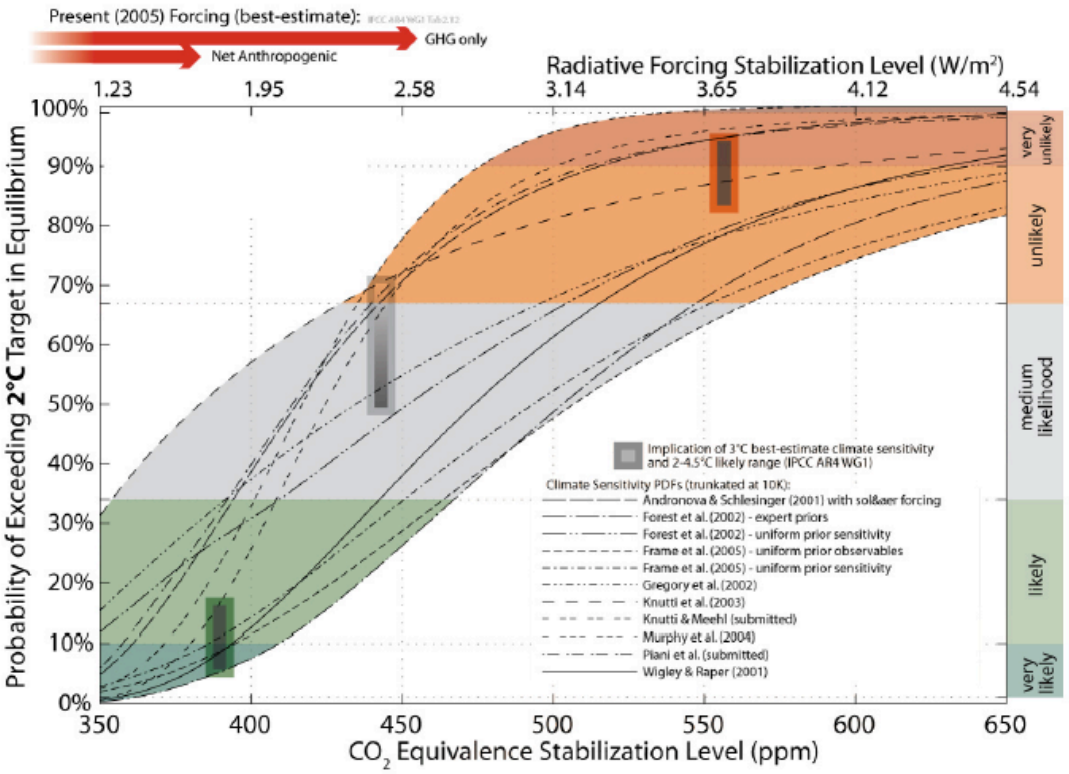

Figure 2.1: The probability of exceeding 2°C warming at various stabilization levels. At stabilization levels around 400ppm or below, global mean temperatures are likely to stay below 2°C. There is a 50% probability of exceeding a 2°C temperature increase at levels of around 450ppm CO_2eq. The target is unlikely or very unlikely to be achieved at stabilization levels above approximately 500ppm CO_2eq [11].

Aerosols are important for the global climate as they have in general a strong cooling effect, although some aerosols enhance the warming. Aerosols have a relatively short lifetime and pollution policy measures are expected to reduce aerosol emissions, consequently their influence on the climate is expected to diminish. Likewise, the Montreal Protocol gases as a group contributed about 18% to the current warming, but their contribution is also likely to decrease in the near future due to policy measures.

Accounting for the influences and different lifetimes of the various GHGs and aerosols is not easy, but the European Environment Agency estimates that the net warming effect, expressed as a CO_2 equivalent concentration, may exceed 450ppm CO_2eq sometime between 2015 and 2030 [20].

2.4 Calculating the available carbon budget for the 2°C target

In studies of future warming, research tends to focus specifically on changes in the atmospheric CO_2 concentration. There are a number of reasons for this. Firstly, CO_2 is by far the main contributor to global warming, currently being responsible for 63% of the total warming caused by GHGs [5]. Secondly, CO_2 remains in the atmosphere for a much longer time period than any of the other GHGs, so it has a long-term impact on the climate. Thirdly, the atmospheric CO_2 concentration is growing rapidly because of human activity and therefore controlling this growth in CO_2 emissions offers the best chance for humanity to prevent dangerous warming. The contribution to warming from the other

GHGs is generally included in the climate models used by researchers and the uncertainties in the GHG projections are included in their final results. For this reason, this study will be concerned mainly with the atmospheric CO_2 concentration. If referring to the overall GHG concentration, this will be stated explicitly and it will be expressed as a CO_2 equivalent (CO_2eq) concentration.

Allen et al. (2009) suggest that it would be better to base CO_2 emissions targets on a carbon budget that limits the overall cumulative CO_2 emissions rather than focusing on staying below a specific atmospheric CO_2 concentration or a stabilization scenario. They used models to simulate the temperature response to a broad range of CO_2 emissions pathways and found that the peak warming depends mainly on the total amount of CO_2 emitted and is remarkably insensitive to the specific timing or profile of the emissions. Therefore, targets that limit the total amount of CO_2 emitted will allow a more accurate prediction of the resulting warming response than targets that aim to limit the peak atmospheric CO_2 concentration, as the peak CO_2 concentration is influenced by both the amount of CO_2 emitted and the emissions pathway [21].

In a related study, Meinhausen et al. (2009) use this approach and estimate the carbon budget that is available between 2000 and 2050, if the 2°C target is to be achieved. For a given carbon budget, they calculated the probability of meeting the 2°C target using a range of climate sensitivity values, in line with the IPCC estimates. The study found that if cumulative CO_2 emissions over the period 2000 to 2050 are limited to 1000Gt CO_2, there is a 75% probability of warming remaining below 2°C. If the CO_2 emissions over this period add up to 1440Gt CO_2, this drops to a 50% probability of warming remaining below 2°C. CO_2 emissions in the period 2000 to 2006 add up to approximately 234Gt CO_2, that is almost a quarter of the lower 1000Gt CO_2 budget used in the first six years of the century. Since 2006 global CO_2 emissions have continued to grow rapidly (Section 2.5), but even if we assume they are frozen at the 2000 to 2006 level, the budget for a 50% probability of exceeding 2°C of warming will still be exhausted within 30 years [22].

In calculating the available carbon budget, it is necessary to account for the fraction of the emitted CO_2 that is absorbed by natural carbon sinks. Currently, about 45% of the CO_2 emitted remains in the atmosphere to cause warming; natural carbon sinks, like the oceans and the forests, absorb the rest. There is evidence that the airborne fraction of CO_2 emissions has been increasing steadily since 1959, when records of atmospheric CO_2 began. This suggests a decline in the efficiency of natural carbon sinks in absorbing anthropogenic emissions. Most climate models predict a decline in the airborne fraction over the period 1959 to 2006, so the behaviour of the carbon sinks is not well understood [23]. If the airborne fraction continues to increase at a rate not predicted by the climate models, the carbon budget for 2000 to 2050 will be even smaller than that calculated by Meinhausen et al. because a larger fraction of the emitted CO_2 will remain in the atmosphere to cause warming.

2.5 The current growth in global CO_2 emissions

Efforts so far to tackle the problem of climate change have had no apparent impact on global emissions. Climate change has been on the international communities agenda since the UN Earth Summit in Rio in 1992, yet global CO_2 emissions have continued to increase rapidly since that time.

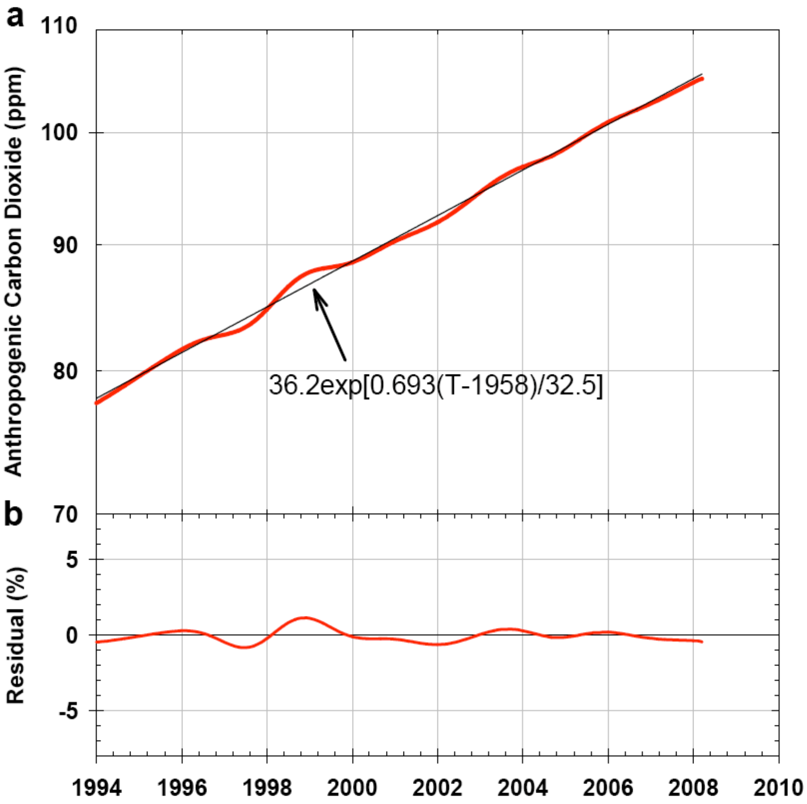

Figure 2.2: a) Exponential fit to the Mauna Loa observatory anthropogenic CO_2 data (CO_2 measurement – 280ppm) from 1994 to 2008 and **b)** percentage difference between the observations and the exponential function [24].

Research by David Hoffman (2009) from the National Oceanic and Atmospheric Administration has shown that the anthropogenic component of atmospheric CO_2 (the difference between the measured CO_2 level and the pre-industrial level of 280ppm) has been increasing exponentially since the beginning of the nineteenth century. Figure 2.2 shows an exponential function fitted to the anthropogenic component of CO_2 measurements made directly from the atmosphere between 1994 and 2008. The exponential function is an excellent fit to the data and at this rate of growth, the anthropogenic component of atmospheric CO_2 would double every 32 years. This would mean the atmospheric CO_2 concentration reaching 500ppm by 2040 [24].

One property of exponential growth is the growth rate doubles in the same time period as the function itself. The growth rate of global average atmospheric CO_2 in the 1980s was 1.49ppm/year, in the 1990s it increased to an average of 1.58ppm/year. The average growth rate between 2000 and 2006 was 1.93ppm/year. The current rate of growth is the highest since the beginning of continuous monitoring in 1959 [23].

A study by Raupach et al. (2007) looked at growth in emissions by using data collected by the Energy Information Administration (EIA) and the Carbon Dioxide Information and Analysis Center (CDIAC) on the consumption of fossil fuels in different regions of the world [12].

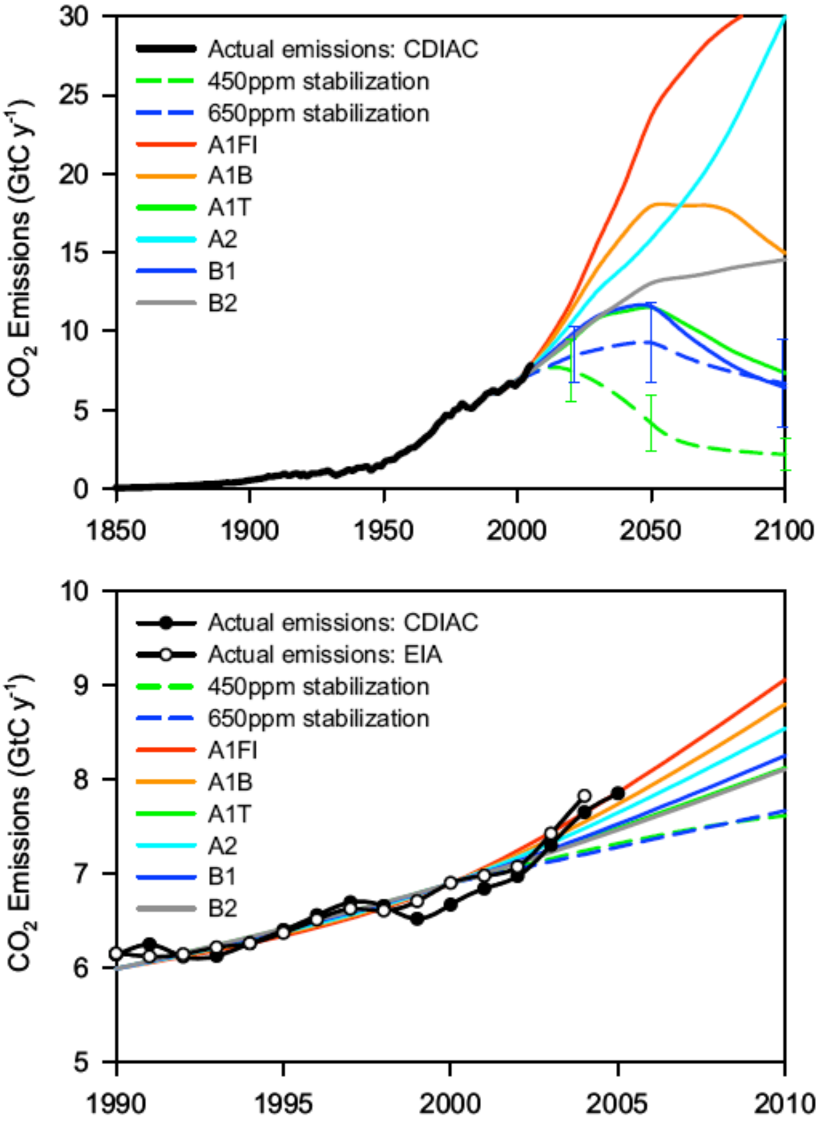

Figure 2.3: Estimated global CO_2 emissions from fossil fuel combustion. [Upper] global CDIAC data 1851 to 2005 and [lower] CDIAC data and EIA data 1990 to 2004. Both panels also show a number of the IPCC future emissions scenarios and stabilization trajectories [12].

Figure 2.3 shows the estimated CO_2 emissions from fossil fuel combustion for 1850 to 2005 (upper panel) and 1990 to 2005 (lower panel), plotted along with a number of the emissions scenarios published by the IPCC in the year 2000. The dip in emissions seen between 1997 and 1999 is thought to be largely due to China, which implemented economic reforms and restructured its power industry in this period. It is followed, from 1999, by a rapid acceleration in global emissions. The rapid increase in emissions since 1999 is largely due to economic growth in the developing and least developed economies, which accounted for 73% of global emissions growth in 2004. Whilst these regions are the main source of the recent growth in emissions, it should be noted that they represent 80% of the world's population and they still accounted for only 41% of the total global emissions in 2004, and only 23% of global cumulative emissions since the start of the industrial revolution [12].

Figure 2.3 also shows the emissions trajectories recommended by the IPCC for stabilization of CO_2 levels at 450ppm and 650ppm. Emissions since 2002 are far above the mean stabilization trajectories for both 450ppm and 650ppm and more recent measurements since 2005 show this trend has continued. The red line shows the A1FI emissions scenario, this is the IPCC scenario for a world that maintains an intensive dependence on fossil fuels. Clearly global CO_2 emissions are currently growing at a rate that is even greater than this "worst-case" scenario [13, 25].

2.6 Meeting the projected growth in world energy consumption

Global CO_2 emissions are coupled to the growth in world energy consumption, which is being driven by global economic growth and an increasing world population. In their report, International Energy Outlook 2009, the EIA made projections for the growth in world energy consumption up to 2030. Figure 2.4 shows both the historical and projected growth in world energy consumption between 1990 and 2030. World energy consumption is expected to have grown by 44% by 2030, over the 2006 level. Much of this growth will happen in the developing economies, the biggest of which are China and India (shown in red in figure 2.4) [26].

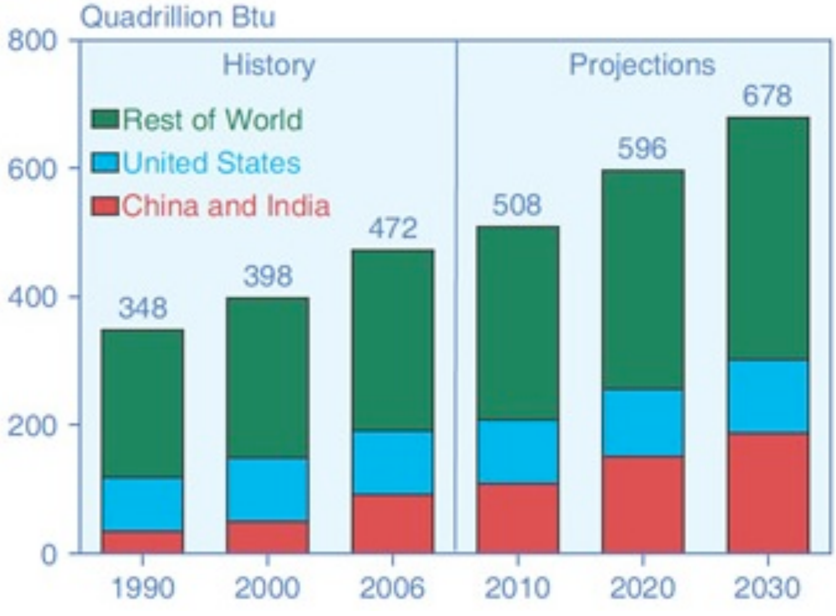

Figure 2.4: Historic and projected world energy consumption by region 1990 to 2030 [26].

Energy consumption in both China and India has increased significantly over the past few decades. In 1990 the two countries accounted for about 10 percent of the world's total energy consumption, by 2006 that had increased to 19 percent. Strong economic growth in both countries is expected to continue, with their combined energy use nearly doubling by 2030, growing to make up 28 percent of total world energy consumption.

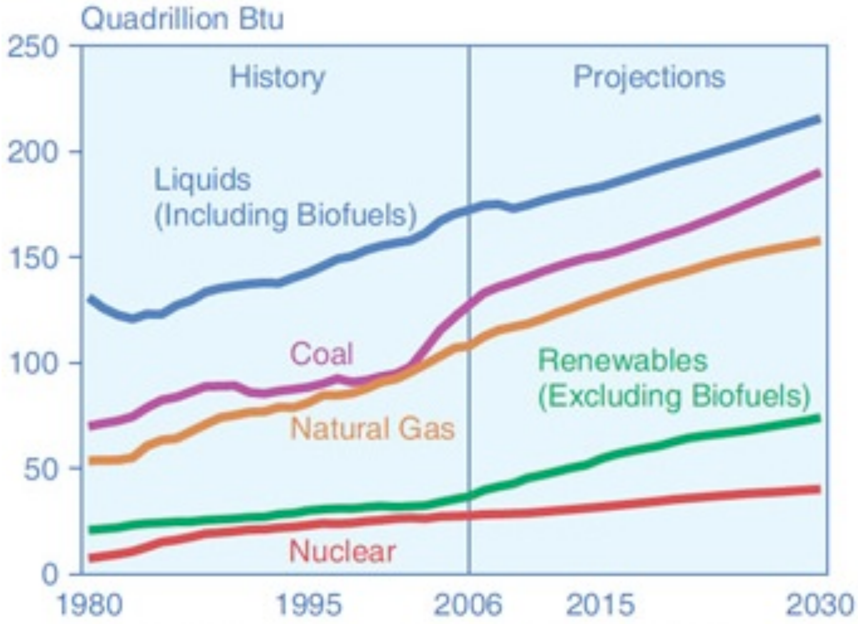

Figure 2.5: Historical and projected world energy consumption by fuel type 1980 to 2030 [26].

To date, this rapid growth in energy consumption has been supported by the increased use of fossil fuels, which has led to the rapid increase in CO_2 emissions seen in figure 2.3. Figure 2.5 shows both the historical and projected World energy consumption by fuel type. The rapid increase in the use of coal as a fuel from 2000 is clear to see. The EIA project that this trend will continue as energy consumption continues to grow through to 2030. Even though the EIA expect renewable energy to be the fastest growing source for world electricity generation, more than doubling between 2006 and 2030, that growth in supply will be outstripped by the increase in demand for energy and fossil fuels are expected to remain the dominant source of energy over this period [26].

New initiatives and financial incentives could encourage the renewable energy sector to grow even more quickly than in the EIA projection, but there are practical limits to this growth because moving energy generation from fossil fuels to renewable sources is inherently complex and time-consuming. Renewable energy sources tend to have a low energy density when compared to fossil fuels, so harnessing them requires engineering solutions on an enormous scale. An example of this is the planned London Array wind farm in the UK. Extensive environmental studies for the wind farm began in 2001, planning consents and licenses were applied for in 2005 and the project is expected to be fully operational by 2015. The wind farm will have 341 large wind turbines that cover an area of $230km^2$ and when complete, it will have a generating capacity of 1GW [27]. That is comparable to just one of the UK's smaller coal power stations [28]. The European Union, which is currently leading the world in its efforts to reduce emissions, has set itself the target of increasing the share of its energy consumption that comes from renewable sources to 20% by 2020, but even this is considered to be an "extremely challenging" target by The European Union Committee of the House of Lords [29].

The IPCC have also stated that in most scenarios the supply of primary energy will continue to be dominated by fossil fuels until at least the middle of the century [30]. This suggests that, unless there is a significant reduction in world energy consumption, global efforts to reduce CO_2 emissions over the next few decades are likely to rest in the main part on the success of carbon capture and storage (CCS) technologies that capture CO_2 from fossil fuels before it is released into the atmosphere. CCS is still in the development phase and has yet to be implemented on a large, commercial scale. In their 2005 report on CCS [30], the IPCC state that for the development and deployment of CCS to become a reality, international policies that place a sufficiently high price on CO_2 emissions will be required. Their economic models suggest CCS is unlikely to have a significant role in global CO_2 mitigation until after 2035 and the majority of CCS deployment will occur in the second half of this century.

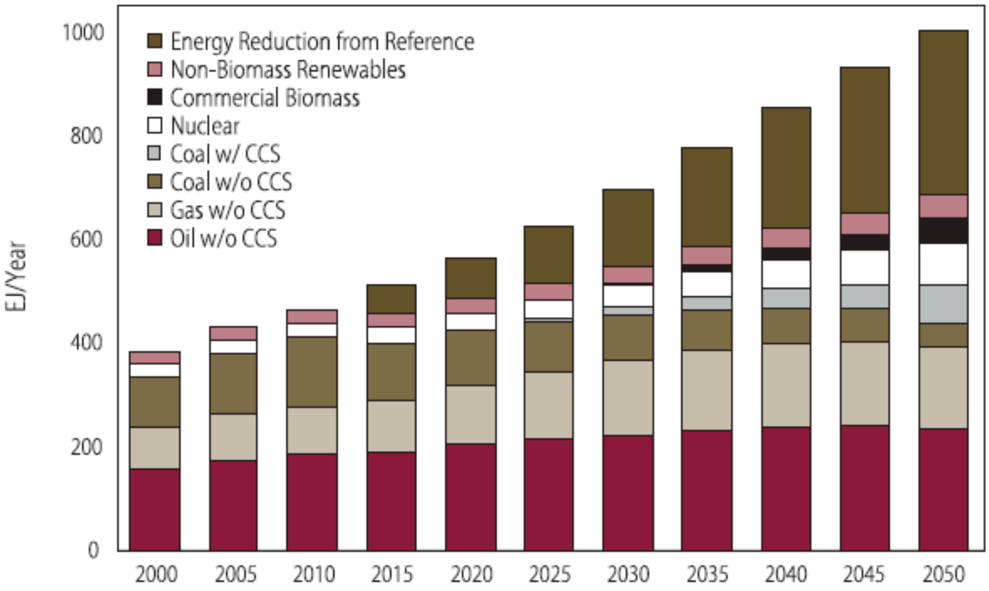

Figure 2.6: Global primary energy consumption by supply type. This forecast assumes a high CO_2 price, starting at \$25/tCO_2 in 2015 and increasing at a rate of 4% per year to around \$100/tCO_2 by 2050. This measure would create a favourable economic environment for the development and deployment of a low carbon energy supply. The reference case is business as usual [31].

In a 2007 study published by the Massachusetts Institute of Technology, the contribution made by coal with CCS to the world energy supply was predicted assuming a global agreement to place a high financial penalty on CO_2 emissions, starting at \$25/tCO_2 in 2015 and increasing at a rate of 4% per year to around \$100/tCO_2 by 2050. Figure 2.6 shows that this measure is likely to have a significant impact on global economic development, with a significant expansion in the low carbon energy supply by 2050 and a reduction in world energy consumption relative to the “business as usual” reference case. However, even in this severely carbon constrained energy market, coal with CCS (shown in grey) is unlikely to contribute significantly until after 2030 and global CO_2 emissions are likely to remain at or above the current level until at least the middle of the century [31]. Using the carbon budget calculated by Meinhausen et al. (Section 2.4), this forecast would mean reaching a 50% probability for exceeding 2°C of warming soon after 2030 and CO_2 emissions are not likely to fall significantly for decades after this date [22].

The coming UN Climate Conference, to be held in Copenhagen in December 2009, will aim to get international agreement on a global strategy for reducing GHG emissions. Hopefully this will be more successful at reducing emissions than the efforts made to date. However, even if international agreement on emissions reduction measures can be achieved, the current growth rate in energy consumption and the time it will take to implement low carbon alternatives for energy production and transport, mean that emissions are likely to continue growing for decades and global warming that exceeds 2°C over the pre-industrial temperature is going to be very difficult to avoid without seriously impairing global economic growth.

3. The prospects for reversing dangerous global warming

3.1 Natural processes will not reverse global warming for millennia

If measures to reduce CO_2 emissions do not succeed in keeping global warming below the 2°C target, how long will it take for the temperature to drop once emissions have been significantly reduced?

Scientific and policy research often considers the mitigation efforts that will be required to stabilize the atmospheric CO_2 concentration at an appropriate level. This approach would allow CO_2 emissions to continue at a reduced rate after they have peaked because the oceans will continue absorbing CO_2 from the atmosphere for at least a century. However, research published by Matthews and Caldeira (2008) suggests that stabilizing the atmospheric CO_2 concentration would not be enough to stop the global temperature from increasing. They argue that if the global temperature is to be stabilized quickly, it will be necessary for humanity to reduce their CO_2 emissions to a near-zero level as soon as possible after they have peaked. For example, they found that to stabilize the global temperature at its current level, CO_2 emissions would have to be reduced to almost zero within a decade [32].

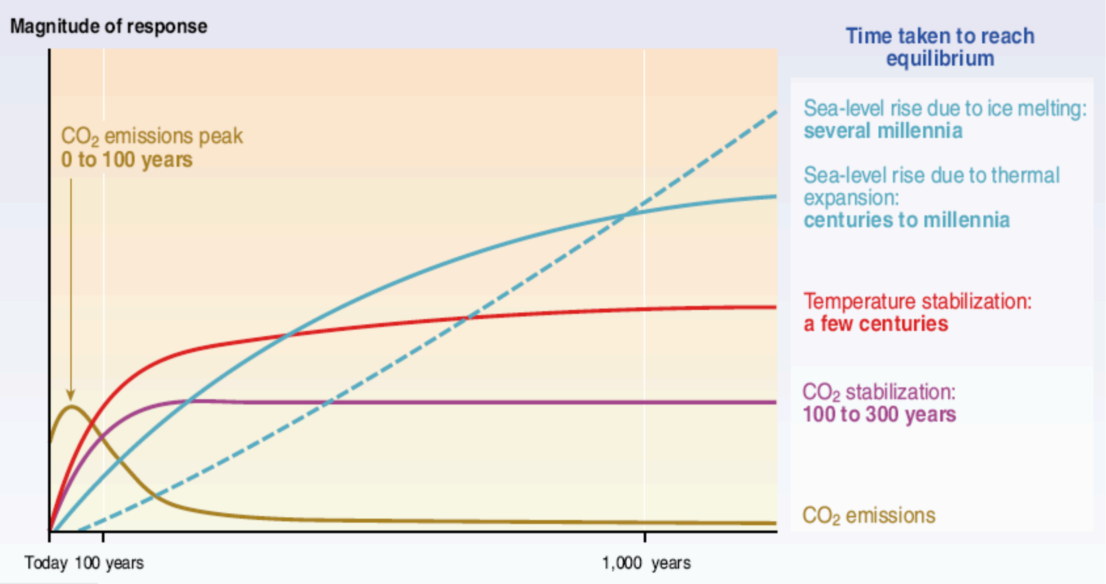

Figure 3.1: A generic picture for CO_2 stabilization anywhere between 450 and 1000ppm showing that the temperature and sea level will continue to rise after the CO_2 concentration has been stabilized [33].

Figure 3.1, published by the IPCC (2001), shows a generic picture of what is expected to happen once CO_2 emissions have been reduced, and the CO_2 concentration has been stabilized anywhere between 450ppm and 1000ppm. The global temperature is projected to continue to rise for a century or more before it eventually stabilizes and it will then remain elevated for thousands of years. In response to this long-term temperature increase, the sea level also continues to rise due to thermal expansion and, on a timescale of many centuries, the contribution to sea level rise from melting ice becomes steadily more significant [33].

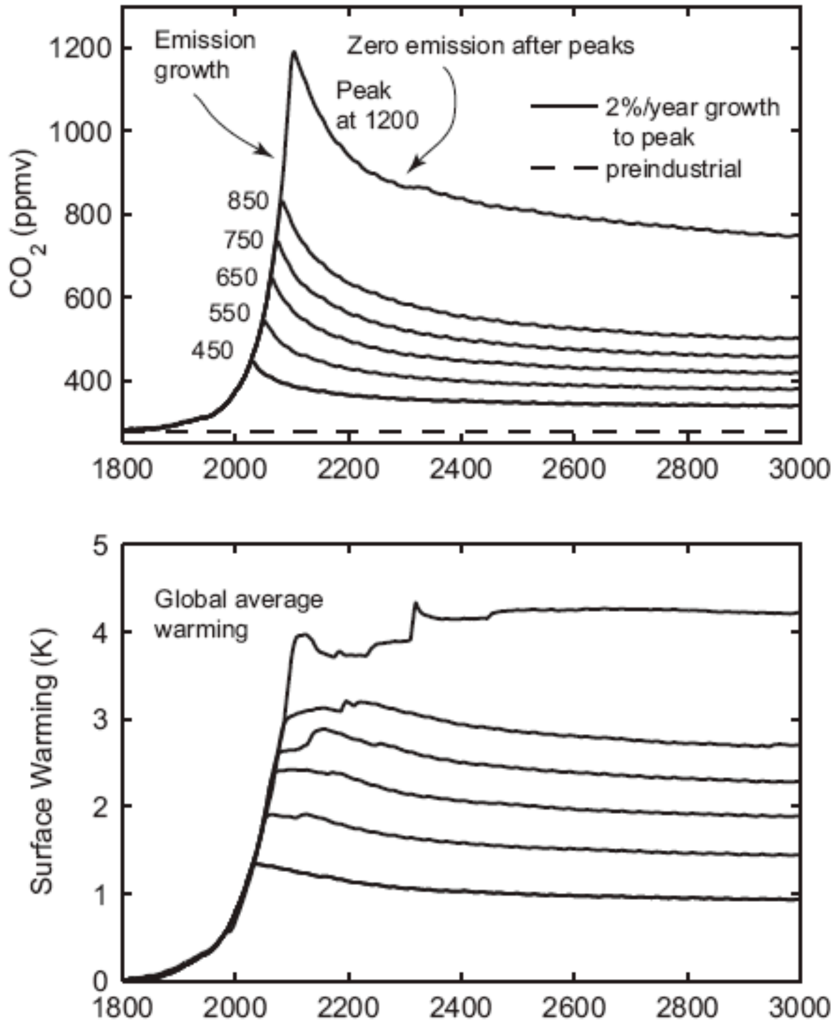

Figure 3.2: [upper] Model predictions for the natural decline in the atmospheric CO_2 concentration for various peak CO_2 levels, assuming a 2% per year rise, followed by zero emissions from peak and [lower] global average temperature response for each of these emission scenarios [34].

Solomon et al. (2009) provide independent verification of Matthews and Caldeira's result. Solomon et al. used detailed models of the atmosphere and oceans to investigate the long-term response of the atmospheric CO_2 concentration and the global average temperature to CO_2 emissions that are reduced to zero instantly after a period of steady growth. Figure 3.2 [upper] shows the model results assuming CO_2 emissions increase at a rate of 2% per year to peak CO_2 values of 450, 550, 650, 750, 850 and 1200ppm, followed immediately by zero emissions. These are not meant to be realistic emissions scenarios but they provide an illustrative example of what would happen to the CO_2 concentration and temperature in the best case, if emissions could be stopped instantaneously. The results show that the CO_2 concentration initially declines quite rapidly from its peak value but then, after a century or more, it stabilizes at an elevated level where it remains, probably for many thousands of years. This pattern is easy to explain, the initial drop from the peak concentration happens as the oceans absorb CO_2 from the atmosphere, but once the climate system approaches a new equilibrium state, this process slows and the atmospheric CO_2 concentration stabilizes. A more realistic emissions profile would peak much less sharply because global emissions will not stop instantaneously. Still, qualitatively the profile will be similar; as the CO_2 emissions slow down, the atmospheric CO_2 concentration will peak and then stabilize at an elevated value from which it will not fall significantly for thousands of years [34].

Figure 3.2 [lower] shows how the global temperature changes in response to the different CO_2 emission scenarios shown in figure 3.2 [upper]. In each case, the global temperature continues to increase until the emissions are reduced to zero, at which point the temperature stabilizes and remains constant within ±0.5°C of its peak value for thousands of years. This is because immediately after emissions have ceased, the climate system is out of equilibrium. The atmosphere continues to absorb heat energy from the sun because of the enhanced CO_2 concentration, but at the same time both heat energy and CO_2 are absorbed from the atmosphere by the oceans. The combined effect of the two processes holds the atmospheric temperature constant. Once the climate system reaches its new equilibrium state the global temperature will remain stable for thousands of years [34]. This process is explained in more detail in Section 3.3.

The research work of Matthews and Caldeira (2008) and Solomon et al. (2009) suggests that, even if it were possible to cut CO_2 emissions instantaneously, natural processes will not significantly reduce the global temperature for thousands of years and any increase in the global temperature that occurs as a result of the anthropogenic CO_2 emissions will be effectively irreversible without human intervention [32, 34].

3.2 Reconsidering what level of global warming is dangerous

It is clear that, even if emissions cuts are successful at keeping the global temperature rise within the 2°C target, the new, elevated global temperature will endure for thousands of years. Most studies that look at the consequences of an increased global temperature only consider the impact over the next century and do not consider possible slow feedback processes or impacts that become important over a timescale of many centuries or thousands of years. The most obvious long-term danger from an elevated global temperature is the loss of the planet's ice sheets. Loss of land ice from mountain glaciers, Greenland and Antarctica could result in significant increases in sea level. Loss of ice more generally could also create a runaway positive feedback, as the Earth's albedo increases and causes further warming [8].

Rohling et al. (2009) made an estimate of the sea level for the Middle Pliocene epoch, around 3 million years ago. This was a period when the climate system was in equilibrium with an atmospheric CO_2 concentration similar to that found today. They estimated that sea level at that time was 25±5m above the present level, a result that is in agreement with independent sea level data [35]. It is generally considered that such a change in sea level will take thousands of years to be realized, but there is evidence that such slow climate feedback processes may come into play much sooner than expected and that the long-term consequences of even today's atmospheric CO_2 concentration may be dramatic [36, 37].

A recent report published by the World Wildlife Fund (2009) reviews an array of recent scientific research concerning climate feedback systems in the Arctic region. The report's authors believe there is emerging evidence that these feedbacks are already beginning to accelerate global warming significantly beyond the projections currently being considered by policymakers and recent observations strongly suggest that climate change may soon push some systems past tipping points, with global implications [38].

Hansen et al. (2008) argue that the 2°C target, and the associated atmospheric CO_2 concentration, can no longer be considered safe in the longer term. Paleoclimatic data shows that, if slower climate feedback processes are included, climate sensitivity is around 6°C, not the 3°C suggested by the IPCC. Hansen et al. argue that the present Antarctic ice sheet formed about 34 million years ago as a consequence of global cooling caused by the falling atmospheric CO_2 concentration and estimate that large scale glaciation occurred when the atmospheric CO_2 concentration fell below 425±75ppm. They suggest that, in order to prevent the large-scale loss of ice and avoid possible runaway positive feedback processes, the atmospheric CO_2 concentration will need to be reduced to at most 350ppm as soon as possible after it has peaked [8]. The currently observed rapid break down of the planet's ice sheets [37], accelerating glacial retreat in Greenland [39] and the release of previously frozen methane from the seabed near Norway [40] all provide further evidence that today's atmospheric CO_2 concentration may already be too high.

As evidence of the reality of climate change becomes more apparent, there is growing support for the idea that returning the atmospheric CO_2 concentration back to below 350ppm may be the only safe option [41]. In August 2009, Rajendra Pachauri, the chairman of the IPCC personally endorsed the 350ppm target, saying in an interview,

"As chairman of the Intergovernmental Panel on Climate Change I cannot take a position because we do not make recommendations, but as a human being I am fully supportive of that goal. What is happening, and what is likely to happen, convinces me that the world must be really ambitious and very determined at moving toward a 350 target." [42]

Eighty of the world's most vulnerable countries have also expressed their support for this lower target. The Least Developed Countries (LDCs) and the Alliance of Small Islands States (AOSIS) issued a joint press release at the UN climate talks, held in Bonn in August 2009. In the press release, they requested that much deeper emissions targets be set so it will be possible to quickly return the atmospheric CO_2 level back to 350ppm once the atmospheric CO_2 concentration has peaked [43].

3.3 The direct capture of atmospheric CO_2 can reverse global warming

Even if the atmospheric CO_2 concentration peaks as low as 450ppm, natural processes will not return it to 350ppm for many centuries. For peak CO_2 concentrations above 500ppm it is not likely to return to 350ppm for thousands of years. The only way the atmospheric CO_2 concentration can be quickly returned to 350ppm, once it has peaked, is by directly capturing the CO_2 from the atmosphere.

While natural processes will reduce the atmospheric CO_2 concentration to some extent once emissions have stopped, this will not significantly reduce the global temperature (Section 3.1). However, it can be argued that enhancing the natural decline in atmospheric CO_2 by directly capturing CO_2 from the atmosphere does have the potential to quickly reverse global warming, although there is a limited timeframe in which this can be effective and the sooner it is implemented the more potential there is for both preventing and reversing the increase in the global temperature.

Figure 3.3 [upper] shows a range of CO_2 emissions profiles modelled by Solomon et al. (2009) and discussed in Section 3.1. The profiles show CO_2 emissions that increase at a rate of 2% per year to peak CO_2 values of 450, 550, 650, 750, 850 and 1200ppm, followed immediately by zero emissions. In figure 3.3 [lower], the green lines show the expected global temperature if the climate system were in equilibrium with the CO_2 enhancements shown in figure 3.3 [upper]. In reality, the climate system remains in disequilibrium for a period of a few centuries after emissions have ceased because water has a high heat capacity and the oceans warm up much more slowly than the atmosphere. The red lines in figure 3.3 [lower] show model predictions for the actual global temperature in this period of disequilibrium. The global temperature is expected to stop increasing and remain largely stable after emissions cease because competing processes cause similar amounts of heat energy to flow in and out of the atmosphere. The radiative forcing, which results from the enhanced atmospheric CO_2 concentration, causes heat energy from the sun to be trapped in the atmosphere. At the same time, the oceans absorb both heat energy and CO_2 from the atmosphere as the climate system moves towards its new equilibrium state. The rate at which heat energy flows from the atmosphere into the oceans decreases as the oceans warm, but at the same time the oceans also reduce the atmospheric CO_2 concentration, which decreases the rate at which heat is trapped in the atmosphere by radiative forcing. As the uptake of both heat energy and CO_2 by the oceans depends on the same process of deep-ocean mixing, the heat flowing in and out of the atmosphere is moderated at the same rate. Consequently, the net heat flow from the atmosphere remains close to zero and the global temperature remains largely constant until the new equilibrium state is reached [32, 34].

Solomon et al. use the temperature profiles in figure 3.3 [lower] to argue that any increase in the global temperature caused by anthropogenic CO_2 emissions is effectively irreversible [34]. In their study they only consider natural processes, so do not include the potential for reducing the global temperature by directly capturing CO_2 from the atmosphere.

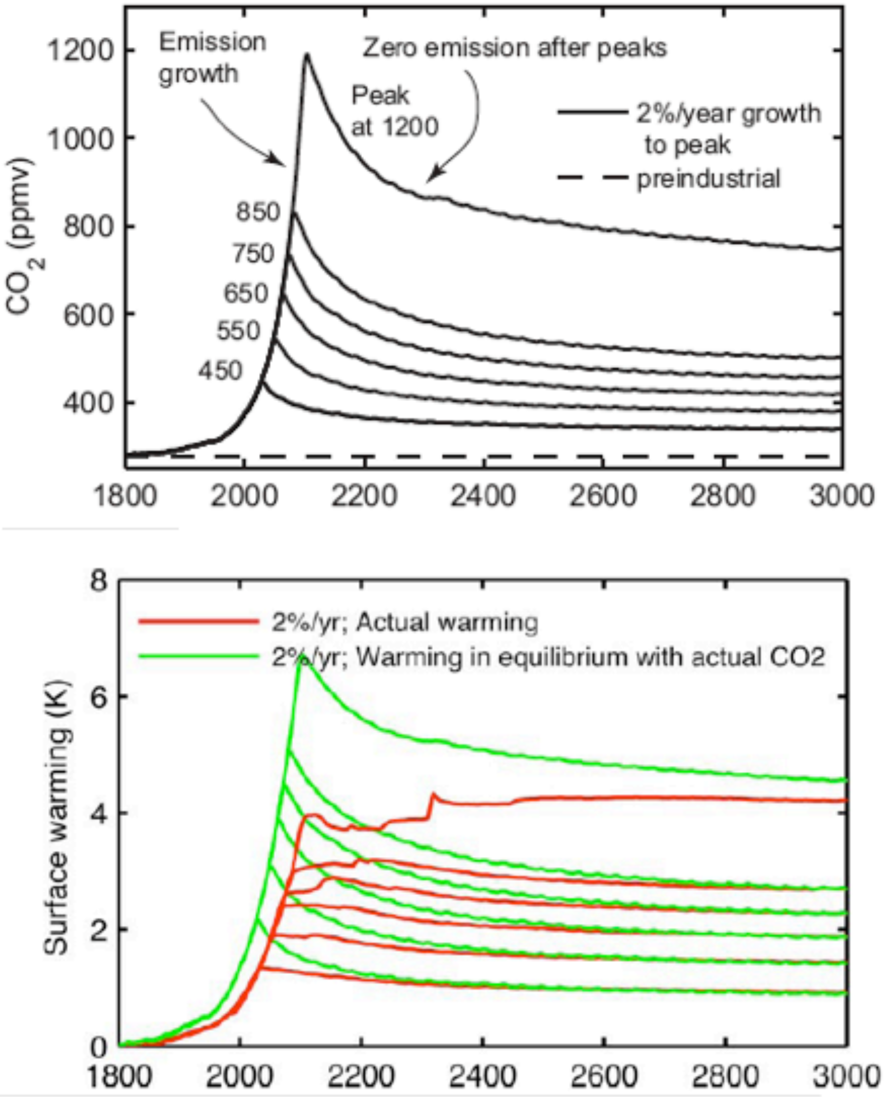

Figure 3.3: [upper] CO_2 emissions profiles for 2%/year emission increases to 450, 550, 650, 750, 850, and 1,200ppm followed by zero emissions at peak. [lower] Comparison between the actual global warming (red line) and the values that would be expected if temperatures were in equilibrium with respect to the CO_2 enhancements shown in upper panel (green line). The climate system has reach equilibrium when the red and green lines meet [34].

If CO_2 is directly captured from the atmosphere in the period of climatic disequilibrium, the rate at which heat energy flows into the atmosphere by radiative forcing will be reduced, leading to a net flow of heat energy from the atmosphere into the oceans. This will cause the global temperature to fall.

In effect, directly capturing CO_2 from the atmosphere in this period of climatic disequilibrium will allow the cooler oceans to reduce the temperature of the atmosphere, reversing some of the global warming that has already occurred.

In each of the cases shown in figure 3.3 [lower] the climate system reaches its new equilibrium state at the point where the green lines and the red lines meet. The CO_2 emissions profiles are idealized, but even for a more realistic profile, it is likely that there will be a period of at least 100 years before the climate system reaches its new equilibrium state once the atmospheric CO_2 concentration has peaked. This period is a window of opportunity in which it will be possible to quickly reduce the global temperature by directly removing CO_2 from the atmosphere. The earlier the direct capture process starts, the greater is the potential for reversing the global warming that has already occurred and the more quickly the global temperature will fall. This is because the oceans act as a huge heat reservoir, initially the temperature difference between the oceans and the atmosphere is large, so they have more potential to cool the atmosphere down. Once the climate system gets close to its new equilibrium state, the temperature difference between the oceans and the atmosphere is smaller and directly capturing CO_2 from the atmosphere will be much less effective. Once the oceans have reached their new equilibrium state they will act in the opposite sense, buffering against any reduction in the global temperature and the atmospheric CO_2 concentration by releasing both heat energy and CO_2 to atmosphere.

The direct capture of atmospheric CO_2 is the only permanent option available for reversing an increase in the global temperature. Other geoengineering proposals could help control the global temperature by reducing the absorption of incoming solar radiation, but they are only temporary measures and there is concern that they may have serious side effects. Two plausible proposals of this kind are the injection of sulphur aerosols into the stratosphere [44] and seeding clouds with seawater particles to increase their albedo and longevity [45, 46]. These proposals have the major benefit of being effective very quickly, working on a timescale of a year or so. However, they could also have serious and unpredictable side effects, like changing local climate and rainfall patterns, causing droughts, ozone depletion, affecting plant life and they would not resolve other problems associated with an elevated atmospheric CO_2 concentration, like ocean acidification [47, 48]. Such measures are generally regarded as a solution of last resort, to be used in case urgent action is required to slow down or prevent global warming that is occurring at a catastrophic rate. In such a situation, these measures may have to be used to bring global warming under control, preventing the oceans from heating up and buying enough time for direct capture to reduce the atmospheric CO_2 concentration and resolve the global warming problem permanently.

In addition to being the only permanent option for reversing global warming once it has occurred, a program of direct CO_2 capture could be implemented proactively, complimenting measures to reduce CO_2 emissions. Directly capturing CO_2 from the atmosphere would effectively increase the available carbon budget (Section 2.4), helping to reduce the risk of exceeding the 2°C target. It would also help to slow down the rate of increase in the global temperature, making it easier for ecosystems to adapt to the temperature change and reducing the risk of triggering events like the shutdown of the thermohaline circulation, which is sensitive to the rate at which the global temperature increases [49].

The direct capture of atmospheric CO_2 should be considered a compliment to emissions reduction measures, not an alternative. Reducing the atmospheric CO_2 concentration by just 1ppm equates to the direct capture and sequestration of about eight billion tons of CO_2. Therefore directly capturing enough CO_2 to significantly reduce the atmospheric concentration is an enormous undertaking that will probably require efforts on a global scale. CO_2 emissions reduction is vital to keep the atmospheric CO_2 concentration as low as possible so that direct CO_2 capture will have a chance to return both the atmospheric CO_2 concentration and the global temperature back to a safe level if the emissions reduction measures fail to prevent a dangerous increase in the global temperature.

In the next section we will look at what methods may be used to directly capture CO_2 from the atmosphere and we will assess if any of the available options could operate on the scale required to help reduce global warming or reverse a dangerous increase in the global temperature.

4. The prospects for the direct capture of atmospheric CO_2

4.1 The options for the direct capture of atmospheric CO_2

Even with a strong mitigation effort, it is probable that the atmospheric CO_2 concentration will peak above 500ppm. If emissions continue growing at their current exponential rate (Section 2.5), the atmospheric CO_2 concentration will exceed 1000ppm before the end of the century. In either case, it is likely that many hundreds of billions of tons of CO_2 will need to be captured from the atmosphere if the CO_2 concentration is to be returned to a safe level. To ensure that the capture process brings about a rapid decline in the global temperature, it is likely that the atmospheric CO_2 concentration will have to be reduced within a relatively short timeframe, perhaps by the end of the century (Section 3.3).

As a benchmark, we will consider if it is possible to return the atmospheric CO_2 concentration to 350ppm by 2100. We will assume that, in the absence of direct CO_2 capture, emissions cuts are capable of stabilizing the atmospheric CO_2 concentration at 500ppm by the end of the century. This would make it necessary to directly capture 150ppm over the next 90 years. Are there any options available for the direct capture of CO_2 that have the potential to operate on this scale?

Two recent reports, one by The Royal Society (2009) and one by Lenton et al. (2009), help to answer this question. Each report reviews the range of geoengineering methods that have been proposed for tackling global warming. The reports estimate the maximum potential CO_2 drawdown that could be achieved by 2100 for the following direct CO_2 capture methods,

- Reforestation, afforestation and land use management to protect or enhance land carbon sinks
- The use of biochar for carbon sequestration
- The use of biomass for energy when combined with the capture and storage of the CO_2 emissions (BECS)
- Enhancement of oceanic uptake of CO_2 by fertilization of the oceans with naturally scarce nutrients
- Engineered chemical capture of CO_2 from ambient air

The first four methods use biological processes to capture CO_2 directly from the atmosphere. The last method would involve building a man-made device to chemically capture CO_2 from the atmosphere. Two other proposals, enhancing the natural weathering process by adding minerals like olivine to soil and the modification of the deep ocean circulation, are not considered here because they are not likely to be effective [50, 51]. The reports assume that each method is deployed to its maximum, regardless of cost, potential conflicts or possible side effects. A summary of the findings of the two reports is shown in Table 4.1. The findings are in good agreement although they cannot be considered to be completely independent as they draw on a similar body of research [52, 53].

Direct CO_2 capture method	**Maximum reduction in CO_2 (ppm) by 2100**	
	Royal Society Estimate	Lenton et al. Estimate
Land use & reforestation	28	34
Energy from biomass with capture & storage (BECS)	50 to 150	186
Biochar	10 to 50	37
Ocean Fe fertilization	10 to 30	19
Ocean N & P fertilization	5 to 20	21
Chemical air capture & storage	Limited only by cost	Limited only by cost

Table 4.1: The maximum potential CO_2 drawdown that could be achieved by 2100 for each direct CO_2 capture method [52, 53].

Assuming the maximum potential for each method could be realized, they could all make a significant contribution to the reduction of the atmospheric CO_2 concentration. Energy from biomass with capture and storage (BECS) and chemical air capture and storage seem to have by far the greatest potential. In reality, the maximum potential for each method is unlikely to be achievable because of cost constraints and resource conflicts. These constraints need to be examined further to get a better idea of the realistic CO_2 drawdown potential of each method.

4.2 Biological direct capture and storage

Biological direct capture relies on plants or algae to capture CO_2 from the atmosphere by photosynthesis and then store it, usually as biomass. The major constraint for all forms of land-based biological direct capture is the large amount of fertile land that is required. This can bring these methods into conflict with food production.

Reforestation and land use management aims to stop deforestation and then capture and store CO_2 by replanting forests on previously deforested land. The potential for a program of reforestation is significant, for example, the beech forests in western Germany have been estimated to store on average the equivalent of around 400 tons of CO_2 per hectare [54]. Currently, croplands, pasture, and urban areas cover nearly 35% of the continental surfaces and Latin America, Africa and South and Southeast Asia have all seen an exponential increase in cropland expansion in the last 50 years [55]. Deforestation continues on a massive scale, with around 6 million hectares of primary forest being lost or modified each year [56]. Land use change still accounts for around 20% of global CO_2 emissions [5]. Pressure remains high on the forests that remain because the growing human population is increasing the demand for forest and agricultural products. The human population is projected to increase by a further 3 billion within the next 40 years and most of this growth is happening in the regions where deforestation is happening most quickly [57, 68]. There are signs that programs to protect and restore forests are beginning to work, the net rate of loss slowed from 8.9 million hectares per year in the period 1990-2000, to 7.3 million hectares per year between 2000 and 2005 [56]. The prospects for a program of reforestation and land use management to make a net reduction in the atmospheric CO_2 concentration over the coming century remain uncertain.

Growing biomass for use in energy production with CO_2 capture and storage (BECS) could also conflict with food production. It may be possible to grow suitable biomass on degraded land that is not suitable for food production, but BECS could then conflict with other CO_2 mitigation efforts, like the production of some second-generation biofuels [57]. While this method still has the potential to be one of the most significant contributors to the biological drawdown of CO_2 from the atmosphere, the increasing demand for land over the coming century means that BECS may fall far short of its maximum potential.

Biochar is a fine-grained, highly porous charcoal that can be used to restore soil fertility while storing carbon for centuries to millennia. Biochar can be made from the agricultural waste produced by crops, forestry and animals and therefore does not necessarily conflict with food production [58]. The International Biochar Initiative estimates that biochar, used to enrich soils for agriculture, could capture and store around 0.5Gt of carbon a year by 2050 [59]. That's a total CO_2 drawdown potential of between 10ppm and 20ppm by the end of the century.

Ocean fertilization encourages the growth of surface algae that capture CO_2 from the atmosphere by photosynthesis. This material eventually sinks and becomes a part of the deep ocean food web, potentially locking up some fraction of the captured CO_2 in the deep ocean for centuries. Whilst this method does not conflict with land use it still may affect the food supply, impacting fisheries directly or indirectly by changing the structure and function of biological communities. Supporters claim ocean fertilization could actually increase fishing yields, but more research is needed before the potential impacts of this method are understood and ocean fertilization can be considered a viable option [60].

Hansen et al (2008) have described a feasible scenario in which the use of waste-derived biochar in agriculture and a successful program of reforestation could be combined to reach a CO_2 drawdown of 50ppm by 2150 [8]. Making the optimistic assumption that BECS and ocean fertilization can be combined with this scenario and get close to the lower estimate of their maximum potential (Table 4.1), we can estimate that a realistic maximum CO_2 drawdown potential for all of the biological direct capture methods combined is between 50-100ppm by the end of the century. While this certainly makes these methods very worthwhile, it does mean that biological direct capture would not be able to return the atmospheric CO_2 concentration back to 350ppm by the end of the century unless the emissions cuts were deeper than in our benchmark scenario.

4.3 Chemical air capture and storage

If the atmospheric CO_2 concentration peaks above 500ppm it is unlikely that biological methods for directly capturing CO_2 from the atmosphere will be enough to return the CO_2 concentration to 350ppm by the end of the century. In this case, the only remaining option that could remove a significant amount of atmospheric CO_2 is chemical air capture and storage.

Technology that captures CO_2 directly from air already exists and is used on a small scale to reprocess the air in submarines and spacecraft. In principle this technology could be scaled up and the amount of CO_2 that could be removed from the atmosphere would be limited only by the cost of the process and the ability to store the captured CO_2. The current estimate for the available geological storage is at least 2000Gt CO_2, which would allow the capture and storage of around 250ppm from the atmosphere. Of course, a significant fraction of this storage capacity is likely to be used to store CO_2 captured from power plants, so storage capacity could be a limiting factor. CO_2 can also be stored through mineralization or in the deep oceans but this may be less effective or more expensive than geological storage [30].

Keith et al. (2006) have described how a prototype chemical air capture device could work using existing technologies and well understood processes. Air is blown through a large chamber, which contains a fine mist of chemicals that react with the CO_2. The chemicals they propose to use are cheap, abundant and relatively safe. The primary expense comes because heat energy must be used to regenerate the chemicals and recover the CO_2 for storage once it has been captured. They believe with research funding they could build a scalable system for chemical air capture within a decade. To estimate an upper bound for the cost of capturing the CO_2, they considered a complete system, built from components available today with a minimum of new design. They estimate the upper bound to be around \$140/ton CO_2, and expect this would be considerably reduced with optimization and the development of new technology [61, 62].

Lackner (2009) has described a more novel design for a prototype chemical air capture device that could capture a ton of CO_2 a day [63]. Klaus Lackner is the co-founder of Global Research Technologies (GRT), the company that is developing the air capture device [64]. The device uses a number of filters that contain a chemical resin to capture CO_2 directly from the air. The device requires a wind speed of around 1m/s to push the air through the filter. Once the resin is saturated with CO_2, the filter is removed from the air and placed in a humid environment. This causes the resin to release the CO_2, which can then be collected and stored. Compressing the CO_2 releases heat, which is used to keep the humid environment warm. Once the CO_2 has been removed from the resin, the filter is returned to the open air where the resin will once again begin capturing CO_2. At any one time each filter is at a different stage in this cycle, so CO_2 is continuously removed from the atmosphere. The device needs electricity to operate, but as it relies on natural airflow and does not have to heat the chemicals to release the CO_2, it is very energy efficient. If powered by the energy mix currently found in the U.S., the device would effectively lose 21% of the CO_2 it captured because of the emissions from the power plants. This loss rate will fall as the global electricity supply is decarbonised over the coming decades [63, 65].

The GRT air capture device is designed to fit into a standard shipping container, so it is very portable. A number of the devices could be deployed in a large cluster to make an air capture farm. As each device requires a very low wind speed to operate, it would not conflict with wind power and the devices could be packed much more closely together than wind turbines. The device can operate almost anywhere, which means an air capture farm could operate alongside a storage site, eliminating the need to transport the captured CO_2. In terms of land area, the air capture device compares favourably with biological direct capture. A large tree captures several tons of CO_2 over its lifetime of 30 to 50 years and forests can hold the equivalent of around 400 tons of CO_2 per hectare. The air capture device has a land area footprint of less than 1% of a hectare and can capture a ton of CO_2 a day [63, 54].

The cost of the first prototype is estimated to be around $200,000 and, assuming a 10-year lifetime for the device, it could break even at $200/ton CO_2. By considering the areas where further research could make improvements, Lackner estimates that the cost of a future device could drop to around $20,000 and that a plausible long-term price for air capture could be as low as $30/ton of CO_2 [63]. These cost estimates do not include the price of storage, which is likely to be less than $10/ton CO_2 [30].

At a capture capacity of 1 ton CO_2 per day, it would require 50 million air capture devices to drawdown 2ppm CO_2 per year. If this rate of capture could be achieved by 2050, it would give a total CO_2 drawdown of 100ppm by the end of the century. Manufacturing 50 million air capture devices would be a serious undertaking, but in a global context it is achievable, in 2008 the world manufactured over 50 million cars in just 1 year [66]. To calculate a ballpark figure for how much this is likely to cost we will assume the lowest cost estimates made by Lackner and an average lifetime of 10-years for each device. This means the cost for the hardware would be $5 trillion by 2100 at today's prices. Assuming a capture and storage cost of $40/ton CO_2 the cost of running the machines would add another $32 trillion. Allowing for other costs like the infrastructure that would be required for the devices to operate in large clusters, the land the clusters would occupy, redundancy, maintenance and servicing, a rough estimate of the cost for the capture and storage of 100ppm CO_2 by 2100 may be around $50 trillion. That is $1 trillion per year between 2050 and 2100. To put this into context, $1 trillion is about 1.7% of the global GDP in 2008 [67].

The cost of chemical air capture is prohibitively expensive today, but that may change within the next few decades as research makes the capture process cheaper and the financial penalties for emitting carbon become more severe. A study from the Massachusetts Institute of Technology predicted that to stabilize global emissions at their current level, the carbon price would have to reach $100/ton CO_2 by 2050 (Section 2.6) [31]. Using chemical air capture for large scale geoengineering projects will always be expensive, but with a high carbon price, chemical air capture could become financially viable as a carbon management tool because it can offset the emissions from any source. This would offer a means of tackling emissions that are otherwise hard to avoid, for example, the emissions from mobile sources like airplanes and vehicles.

In summary, if chemical air capture were deployed on a global scale it could possibly achieve a CO_2 drawdown of 100ppm by the end of the century. If it is combined with the biological direct capture methods discussed in Section 4.2, the potential drawdown could reach between 150-200ppm. This means that if we use every available means of direct CO_2 capture and each method works at close to its maximum potential, it may be possible to return the atmospheric CO_2 concentration to 350ppm by the end of the century in our benchmark scenario. However this is likely to be very expensive and would require an enormous effort on a global scale.

5. Discussion and conclusions

Reducing the atmospheric CO_2 concentration as soon as possible after it has peaked has the potential to quickly reverse a dangerous increase in the global temperature. If used proactively, a program of direct CO_2 capture could help to prevent warming and keep the global temperature below the 2°C target.

Biological direct capture has a significant potential for reducing the atmospheric CO_2 concentration and could have many other beneficial side effects. A program that stops deforestation and then restores deforested landed would help to protect and preserve the world's rich biodiversity. It has been estimated that tropical forests may contain 90% of the world's species, making these forests an asset of immeasurable importance [69]. Biochar can be used to sequester carbon for centuries and at the same time can enrich soils making them more fertile and more productive. Ocean fertilization needs further research, it is likely to change the structure and function of the oceans biological communities and it is unclear how this would impact the ocean ecosystem.

The major constraint on biological direct capture is land use. Because many of the methods require relatively fertile land, they conflict with food production. This is a conflict that will be increasingly difficult to resolve as the human population continues to grow over the coming decades. Still, biological direct capture has great potential and could help to both reduce and reverse global warming. It has been estimate that biological capture could drawdown between 50ppm and 100ppm by the end of the century. If these methods are used in conjunction with a very strict emissions reduction program they could return the atmospheric CO_2 concentration to 350ppm by the middle of the next century.

Chemical air capture is still in its infancy, but it could potentially drawdown an unlimited amount of CO_2 from the atmosphere. In reality there may be issues with CO_2 storage and the technology could be too expensive to use on the scale required for geoengineering. Still, chemical air capture could have an important role in carbon management, offering a means of offsetting the emissions that cannot be captured at source. Investing in the development of this technology can also be seen as an insurance policy. If climate sensitivity is higher than expected and global warming becomes extreme, this technology could be combined with biological direct capture to create the potential to reduce the atmospheric CO_2 concentration to 350ppm by the end of the century.

None of the direct CO_2 capture methods can be considered a substitute for deep emissions cuts. In fact, direct CO_2 capture will only be able to reduce the atmospheric CO_2 concentration to 350ppm within the next century or two if it is used in conjunction with a strict emissions reduction program.

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