Humans and carbon: a Faustian bargain?

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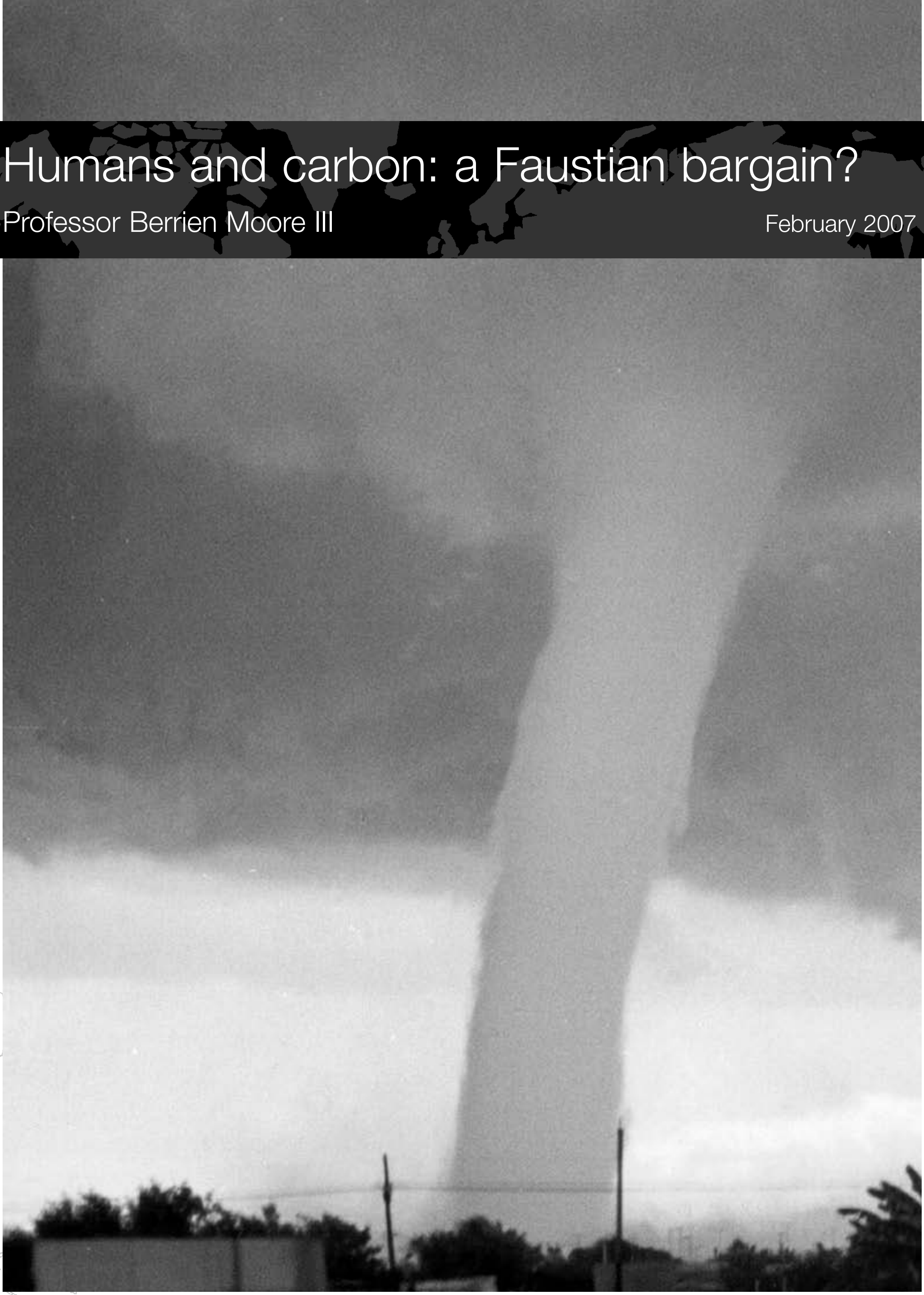


I am going to talk about the carbon cycle and the CO_2 problem. I have used in the title of my lecture the phrase 'a Faustian bargain', and hope that the rationale behind my choice of words will become clear as we go along. Carbon is the fundamental material in the cycle of life on our planet. The Bible refers to it as 'dust to dust' – the formation and decomposition of organic material. Some of that decomposition has left us with a lot of stored carbon in the form of fossil fuels, and we are taking it out of storage much faster than nature had in mind.

One way to think of the carbon problem is in terms of economies or inflation. By burning fossil fuels we are in a sense printing carbon money; we are taking this carbon money from bank accounts where it has been out of circulation and reintroducing it into the system. The carbon that was sequestered, or removed from the system, is now reentering the cycle and effectively inflating it. This, in itself, would be important because it is a significant change in the fundamental chemical cycle of the planet, but as is well known, the change is magnified because increases in CO_2 lead to an increase in the trapping of heat in the Earth's atmosphere, which alters the net energy balance of the planet. Even a slight change in the balance between energy entering the atmosphere and energy leaving the planet potentially affects the climate.

Here are a few numbers. In the 1990s, through the burning of fossil fuels, we were adding about 5.5 gigatonnes – or billion tonnes – of carbon to the atmosphere as CO_2 annually. And in the mid-1990s there were about 5 billion people on the planet, so around a tonne of carbon per person per year was being produced as CO_2, primarily through fossil-fuel burning and cement production. Of course deforestation also produces CO_2, but the difference between burning a tree and burning oil is that the tree might recover or be replaced, allowing the carbon to flow back into vegetation.

Of course a great deal of carbon goes back and forth in gross fluxes. Around 90 gigatonnes annually flow between the ocean and the atmosphere, with slightly more (about 2 gigatonnes) entering the ocean than leaving it. This net inward migration occurs because as you put more CO_2 into the atmosphere, the partial pressure difference forces it into the ocean.

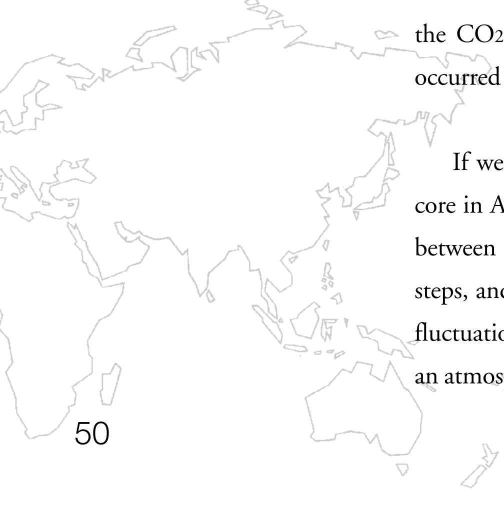
The carbon exchange with the biosphere is about 120 gigatonnes. Of the 120 gigatonnes that are fixed by vegetation through photosynthesis, 60 gigatonnes integrated over the year are respired back from vegetation during the nighttime, and the remaining 60 gigatonnes go back over a longer period of

time from the litter and soils. Overall, there is very little net change to the stored carbon in living vegetation of around 610 gigatonnes. The atmosphere holds around 750 gigatonnes of carbon, more than living vegetation, but so dispersed that it is measured as a trace gas in parts per million (ppm).

Some remarkable data was gathered by Charles David Keeling, who started measuring atmospheric CO_2 in 1957 at Mauna Loa, the second highest mountain in Hawaii. He took his measurements daily at about 3,350 metres in very clean air away from the active summit.

Initially, it looked as if CO_2 was rising absurdly fast, but of course what was happening was the annual cycle. Measurements began in the fall of the year when respiration dominates photosynthesis; this was what was being observed. By spring the growth slows and turns down as organic matter is being formed; in fact CO_2 is drawn down throughout the growing season, and then released back into the atmosphere when the material is oxidized in the autumn. An enormous planetary metabolic cycle takes place, with atmospheric concentrations rising and then falling again by around 5 ppm annually. But on top of this natural annual flux, Keeling's measurements recorded a near continuous rise of atmospheric CO_2 of about 60 ppm over the second half of the 20th century and into the 21st, reflecting our industrial activity.

If we look back over the last 1,000 years by examining the Law Dome ice core records, here too we can see evidence of the Industrial Revolution taking place. Of course there were modest fluctuations in CO_2 concentrations prior to the 1800s, of the order of 10 ppm, but since the middle of the 19th century the trend has only been up. And as we have moved into the modern era and taken atmospheric rather than ice core measurements, the curve has only steepened. An interesting point is that about half the CO_2 released during the industrial era – through fossil-fuel burning and cement production – occurred prior to 1974, and about half since that time.



If we go back further in time, temperature records for the last 400,000 years from the Vostok ice core in Antarctica show us the patterns of the last four glaciations, with temperatures varying by 10°C between the glacial and interglacial periods. It is an extremely rhythmical pattern: temperatures fall in steps, and then rise in one comparatively gigantic leap, only to repeat the pattern. If we compare these fluctuations with CO_2 concentrations, we find them in lockstep. Each glaciation consistently gives us an atmospheric CO_2 concentration of around 190 ppm at peak glaciation, while each interglacial period has an atmospheric CO_2 concentration of around 285 ppm. It's a perfectly coordinated dance routine with CO_2 reinforcing the orbitally induced climate changes.

But let's look again at current concentrations. At 380 ppm these are far above anything that has occurred over the last 400,000 years, so even if we weren't concerned with greenhouse gases and our climate, we would know that something unusual is happening to the global carbon cycle. And, according to the Intergovernmental Panel on Climate Change (IPCC), we are heading towards concentrations of more than 650 ppm by the end of the century, far more than double the historical interglacial levels.

As I mentioned earlier, in the 1990s we were producing around a tonne – perhaps a little more – of carbon per person per year on average. Of course not all people emit the same amount. The average US citizen accounts for nearly 6 tonnes per year (up from around 4.5 in 1950), while the average Chinese citizen accounts for around 0.75 tonnes (up from about 0.04 in 1950). On a per capita basis, China is still below the world average, though as a country it is on the brink of overtaking the United States as the world's greatest emitter.

Let us go back to the climate system for a moment, because that is of course the central issue with CO_2. The energy that reaches our planet is partitioned in many different ways. Some of it bounces right back out again because it is reflected by clouds or ice. Some is turned into thermal energy and escapes back to space. Some is absorbed and stored. But by adding CO_2 to the atmosphere we are changing ever so slightly the net energy balance and this is now beginning to change the climate.

Let us reflect upon the last two IPCC Assessments. From the Third Assessment Report of the IPCC: 'There is an increasing body of knowledge of climatic and other changes in physical and ecological systems that points to a warming world. Global surface temperatures have increased by more than half a degree since the beginning of the 20th century, and there is ever stronger evidence that most of the warming observed over the last 50 years can be attributed to human activities.'

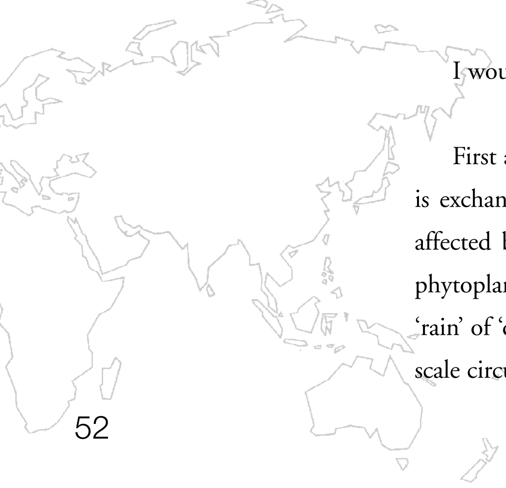
By 2007, the picture was more certain. The IPCC's Fourth Assessment Report states that the warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea

level. It is warmer now than during the last 1,300 years, and the last time the polar regions were significantly warmer than at present for an extended period (about 125,000 years ago), reductions in the volume of polar ice led to a sea-level rise of 4 to 6 metres.

For the next two decades, an increase in the average global temperature of about 0.2°C per decade is predicted. And even if we levelled off the atmospheric increase of CO_2, temperatures would still continue to go up by about 0.1°C per decade as the planet comes into a new equilibrium. Climate response will lag behind the CO_2 force, and this is what needs to be thought about right now. This is the key statement: anthropogenic warming and sea-level rise will continue for centuries even if atmospheric greenhouse gas concentrations were to be stabilized immediately.

In the Third Assessment, using various IPCC scenarios and models, we see that global temperatures are expected to rise by between 1.4 and 5.8°C over the next century. There is a great deal of uncertainty, hence the wide range of outcomes. About half of this is due to the variety of energy policies we could pursue. The other half reflects scientific uncertainty about climate change *per se* because of various feedback loops and the difficulty in predicting their effects.

In the Fourth Assessment, the range of models now available suggests a strong climate-carbon cycle feedback – as the climate system warms, higher levels of CO_2 will be released into the atmosphere. This tends to shift the expected temperature range to the high end of the Third Assessment. But the magnitude of this feedback is uncertain, increasing the uncertainty in the trajectory of CO_2 emissions required to achieve a particular stabilization level of atmospheric CO_2 concentration.



I would now like to return to the carbon cycle.

First and foremost, if you put more CO_2 into the atmosphere, more goes into the ocean because it is exchanging differences in partial pressure. Beyond this, the amount of CO_2 in the sea surface is affected by many things, two of which are particularly significant: first is biological activity, where phytoplankton in the surface waters take up CO_2 and move it down through the water column in a ‘rain’ of ‘dead’ organic matter, providing a storage route to deep ocean abysses; and second is the large-scale circulation of the ocean.

The reason you have springtime in England well before we have it in New England – even though England is on a much higher latitude – is because of the western boundary current of the North Atlantic. The American continent (and the rotation of the planet) effectively induces a circulation northwards – the Gulf Stream – that delivers heat to Europe.

As this water moves to high latitudes, it gets both colder and saltier, because as ice forms it leaves salt behind. In addition, evaporation exceeds precipitation in the North Atlantic, making it even saltier, eventually producing dense surface water that leads to convective overturning, and the water goes down. The solubility of CO_2 also increases as the temperature drops, so as the water gets cold it takes up more CO_2, and then that CO_2-rich water sinks down to deep areas. The macrocirculation of the ocean, along with phytoplankton, is what allows the ocean to take up a significant amount of CO_2.

In a warming world of course the surface ocean will get warmer and so solubility will decrease. The ocean may also stratify, with reduced nutrient upwelling, turning down the rate at which biota is formed. So many of the feedback loops suggested by a climate-warming scenario lead to oceans taking up less CO_2.

Let me move back onto dry land. Of the 120 gigatonnes of carbon that are taken up by vegetation annually, remember that about 60 gigatonnes go right back to the atmosphere during nighttime respiration and about 60 come out slowly later. Some of the carbon is disturbed through forest fires and so forth and immediately released, and maybe a small amount of 1 or 2 gigatonnes might end up in long-term storage.

Now all these numbers were put together in the 1980s, when we needed measurements of the carbon cycle in order to get to grips with the influence that fossil-fuel burning might be having. But it is a very tough set of numbers to get. What do you measure? How do you scale this up? How much is going into the ocean? How much is being released by deforestation? Only about half of the CO_2 produced through fossil-fuel burning was showing up in the atmosphere, so what was happening to the rest?

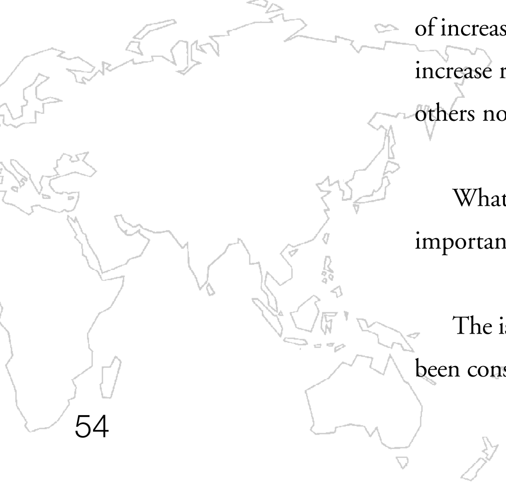
We needed to add up these numbers and work out how much carbon was coming in and how much was going out. But by the 1990s we simply said 'we don't know, we are not even going to write a number down because we don't know how to get at that number'. Clearly it was important.

The rising curve made by Keeling's measurements had become as familiar to us as the face of the Mona Lisa; you didn't even need an axis to know what you were looking at. But we still couldn't do the sums.

Keeling's son, Ralph, a scientist at Scripps Institution of Oceanography, continued with his father's CO_2 records, but added a new dimension to the equation. He began to measure changes in the oxygen concentration in the atmosphere. This is no trivial measurement: oxygen makes up 20 per cent of the atmosphere, and changes are very, very small – insignificant as far as we are concerned. But they reveal much about carbon sinks.

As carbon burns it uses oxygen, and with knowledge of the carbon-oxygen ratio of burning fossil fuels, you would expect a certain increase in CO_2 alongside a certain (very small) decline in oxygen. At the same time, it was known that there is no oxygen involved in the process by which the ocean absorbs CO_2 (simple acidic dissolution in the water), but that oxygen is produced in the process by which vegetation takes up CO_2. So by measuring the actual decline in oxygen and comparing it to the decline you would expect from our rate of fossil-fuel burning, Ralph was able to work out where the 'missing' CO_2 was going. He was able to differentiate how much CO_2 was going into the ocean, and how much into the land. A brilliant piece of data; absolutely remarkable.

The other remarkable record is Roger Francey's data from Australia. He looked more closely at the Keeling CO_2 record and observed that, while CO_2 concentrations are on the rise overall, the annual rate of change – and I'm not talking about the annual biological cycle here – varies significantly. Yet the rate of increase in burning fossil fuels is fairly constant, too constant to account for the variability in the CO_2 increase rates. In fact in some years it looks as if all of the excess CO_2 stays in the atmosphere, while in others none of it does. There are obviously other important processes going on.



What are these sources of CO_2 other than fossil fuels, and what are the sinks? This is a really important question.

The issue of unresolved sinks is particularly worrisome. For instance, many mathematical models have been constructed to establish long-term scenarios of anthropogenic CO_2 emissions and the measures that need to be taken to stabilize CO_2 at given levels over a given time frame. But it is easy to draw the wrong conclusions. High levels of CO_2 have a fertilization effect (actually making plants more water efficient), increasing the land's biomass. So the idea emerged that more CO_2 meant more land biomass, which meant more carbon storage, so that as long as you eliminated deforestation, the expanding biomass would balance out CO_2 emissions. The mistake was in concluding that this could go on *ad infinitum*. It appeared to suggest that as long as we kept expanding land biomass, we could just keep on increasing our emissions of greenhouse gases. An absolutely crazy idea the more you look at it. But the source-sink balance remains critically important with regard to what will happen in the future.

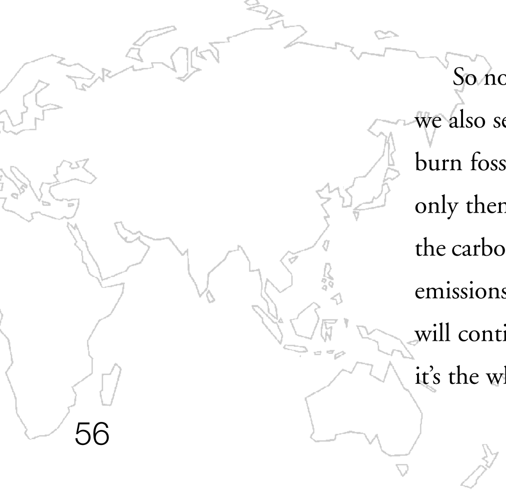
How can we get at that question? Well, one way is to go around and measure everything from the grassroots level, from the bottom up, starting with terrestrial systems. We put up tall towers to measure over the tops of forest canopies. We fly around in aeroplanes to monitor what is happening over landscapes. We make biomass inventories and study ecosystems. Or we go to sea in oceanographic vessels, we study VOS (volunteer observing ship) lines, mooring time series and ocean processes, and we use satellite data to study ocean physics. And then we can create mathematical models. But this is a very 'bottom-up' way to try to constrain the problem, and there is a lot of noise and uncertainty. I don't think this is the way to do it.

I think we are going to need to monitor CO_2 from space. CO_2 is chemically uninteresting in the atmosphere – it does not actually do anything; it is conserved. So if you measure minute changes in the concentration of CO_2 at many points around the planet, you could begin to plot exactly where it is coming from and where it is ending up. NASA's Orbiting Carbon Observatory (OCO), to be launched in 2009, will do just that.

However, the OCO is probably not going to deliver as much as we would like because it cannot gather data on atmospheric CO_2 at all times. It needs to measure the wavelengths of sunlight reflected back from the planet in order to detect CO_2, so can only measure CO_2 while photosynthesis is occurring, not during nighttime respiration. We cannot measure CO_2 in high latitudes during the winter. Perhaps the answer is to provide our own 'sunlight' by using a laser, firing it down to Earth from the Observatory and then measuring what comes back. Of course we would still need all the more grassroots methods of data gathering too, but by getting a global picture we might begin to constrain the problem.

Let me just change the topic a little and go back to the climate system. Now I want to begin to build the case for the 'Faustian bargain'. I am going to take just one piece of the climate system: Arctic sea ice. There is increasing evidence that there is a decline in the extent and thickness of Arctic ice, particularly in the summer. Satellite data since 1978 show that we are losing sea ice at about 3 per cent per decade, with larger decreases in the summer of maybe 7.5 per cent per decade. Why is that important? Arctic sea ice is white, highly reflective: turn the sea dark and you change the reflectivity – the albedo – of the planet. That changes the energy balance in exactly the wrong way: an increase in surface temperatures leads to a decrease in sea ice, which leads to a decrease in albedo, which in turn leads to an increase in temperatures.

It may be that there is some other feedback mechanism out there that could have the opposite effect – perhaps increased evaporation from an ice-free Arctic Sea would replace the albedo of ice with the albedo of clouds. There are lots of different feedbacks, but this one is right at the core of the problem and we simply don't know enough about it. And there is something else going on in the Arctic that worries me. If you start to decrease Arctic sea ice you will freshen the Northern Atlantic, which may affect the turnover current that warms northern Europe. If the ice is 'unforming', the water will become less salty and less dense, changing this major circulation of the ocean. According to the IPCC's Fourth Assessment Report, 'it is very likely that the meridional overturning circulation (MOC) of the Atlantic Ocean will slow down during the 21st century'. And it goes on to mention a reduction of anything from 0 to 50 per cent. However, it also says: 'It is very unlikely that the MOC will undergo a large abrupt transition during the 21st century.' But a 50 per cent reduction seems a pretty large one – I'm not sure exactly what's going on here, but this really needs to be thought about further.

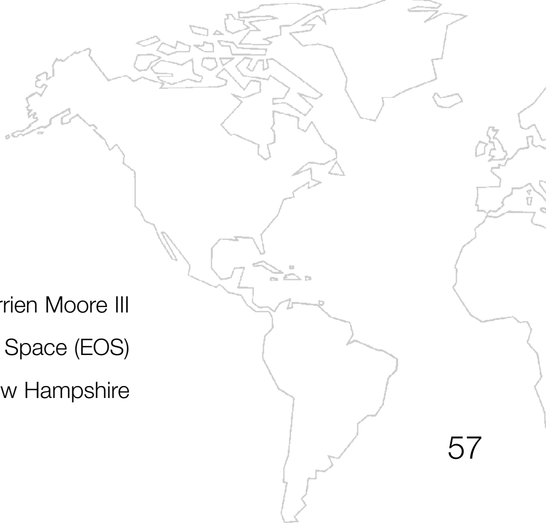


So now we come to the bargain. We seem to have made an agreement with our industrial selves, yet we also seem to think that we can get out of this agreement whenever we want to. So we'll continue to burn fossil fuels until we see something bad happening – for ourselves, our society or the world – and only then will we try to back out. But we can't. The climate is a dynamic system, and we have inflated the carbon dimension of that system by adding carbon that simply wasn't there. If we manage to stabilize emissions at 2000 levels, atmospheric CO_2 concentrations will continue to increase and temperatures will continue to rise at 0.1°C per decade. So it's not just our CO_2 emissions that need to be stabilized, it's the whole atmosphere, and this would require drastic reductions in emissions.

But this is where the real Faustian bargain comes in. The climate system is a dynamic system and changes in the composition of the atmosphere are an initial forcing mechanism for a set of ongoing climatic changes. We have kicked a ball off a hill, and now it is just rolling on down. Changes in Arctic sea ice and therefore the reflectivity of the planet no longer have anything to do with CO_2; the system was set in motion by changes in atmospheric CO_2 concentrations, but now other changes (e.g., Artic sea ice) begin to exert their influence. Even if we managed to stabilize not just our emissions, but the whole of the atmosphere, these changes will continue to take place. There is a precommitted climate change.

And if we carry on increasing our emissions, then reductions in CO_2 will have to be even more drastic – maybe to just a quarter of what they were in 2000. Even then, we can expect atmospheric and temperature stabilization to take several hundred years, sea-level rise through thermal expansion to continue for many centuries, and sea-level rise from melting ice to go on for several millennia.

Our part of the bargain is far more than we bargained for. This would not be so difficult if we were concerned with something like the ozone hole. There too, we kicked something off with our CFCs and our fluorocarbons, and sorting it out was difficult enough. But there is a huge difference. Fluorocarbons are on the edge of the economy and the environmental impact was limited to the high elevation of the atmosphere in the springtime in Antarctica. This was very important, but CO_2 is right at the core of the global economy, and climate change is not just over Antarctica; it's right over the planet.



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