Climate change and carbon dioxide storage

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1. Introduction

It is currently believed that the universe started approximately 13.7 billion years ago. The Big Bang, from an almost isolated singularity, spread material in a roughly symmetric fashion. Particulate matter, or planetesmials, came together in the turbulently flowing gases and, by gravitation, attracted more matter until the stars and planets were built. The Earth is approximately 4.5 billion years old, with some of the oldest rocks on Earth having been found in Australia.

Of course the Earth has changed dramatically over these four and half billion years, both in the interior and on the surface, with the alteration of the surface features due in part to continental drift. In addition the Earth was at least once totally covered in ice -- the Snowball Earth -- and hence uninhabitable by humans.

During the last 800,000 years the average global temperature has varied on many timescales ranging in magnitude from roughly 9 degrees colder than at present to 6 degrees warmer. Closely correlated to the temperature record, the concentration of carbon dioxide in the atmosphere has varied from its lowest at 170 ppm (parts per million) some 650,000 years ago to its maximum of something like 400 ppm now.

Why is the Earth as warm as it is – in contrast to some of the other planets which are either much hotter or much colder? The first person to consider this question seriously and quantitatively was John Tyndall (1820-93), one of the great physicists of the 19th century. He calculated what the steady state temperature of the Earth should be given the incoming solar radiation and the expected emitted radiation from the surface. This resulted in an anticipated surface temperature of approximately -30ºC. Tyndall knew this was incorrect. He wondered if the atmosphere might make a difference. The Victorians were skilful exploiters of the 'greenhouse effect', in particular in their spectacular tropical greenhouses at Kew. This occurs because the incoming visible solar radiation, to which the glass is transparent, is absorbed by whatever is inside the glasshouse, which then re-radiates some of the energy it has absorbed in the (much longer wavelength) infrared. Glass, however, is partly opaque at this wavelength, and some of the solar radiation is thus trapped inside the glasshouse.

Similarly, much solar radiation passes through the Earth's atmosphere, though some is partially reflected by it. Some of the transmitted radiation warms the surface and the remainder is reflected. As it passes back through the atmosphere a fraction again is reflected. In this way some part of the initial energy is trapped within the atmosphere of the Earth. This effect was first considered by the great French physicist Fourier in 1824 and quantitatively experimented upon by Tyndall in 1858.

In his first experiments Tyndall measured the greenhouse effects of the two major components of the atmosphere: nitrogen, which makes up 80%; and oxygen which contributes 20%. Much to his disappointment, neither of these gases showed any greenhouse effect. He was considering discarding his experimental investigations when it occurred to him, almost in the last minute, that he might look into the three more rare components: water vapour, which makes up between 1.5 and 2% by volume; carbon dioxide which makes up something like 0.04% (at least at the moment); and methane, which makes up 2 ppm (parts per million). Rather to his surprise he found that all three had comparatively large effects, with methane per unit weight, having the largest effect, though it deteriorates most rapidly within the atmosphere. (Methane is 70 times more effective per unit weight than carbon dioxide over the first twenty years, which decreases to 25 times over one hundred years.) Using the then value of about 300 ppm of carbon dioxide he calculated the average temperature to be roughly 10 ºC, in reasonable agreement with observations.

The next step was taken by Dave Keeling, who, in the late 1950s, came to the Scripps Oceanographic Institute in Southern California to a post-doctoral fellowship under the directionship of Roger Revelle. Neither Keeling nor Revelle really knew what they wanted to do together, but Keeling thought it would be fun and interesting to measure the carbon dioxide content in the atmosphere over Mauna Loa in Hawaii and Revelle could not think of a good reason to stop him. Thus started a famous series of measurements, which are nowadays continued by Keeling's son. The data indicates clearly, and has been reproduced elsewhere, that the annual average carbon dioxide content in the atmosphere has risen continuously from its value of 315 ppm in 1960 to 390 ppm in only 50 years, an increase of approximately a quarter over this time. Superimposed on the monotonic increase are small seasonal variations of about 3 ppm which are due to leaves taking in carbon dioxide as they grow and giving it back to the atmosphere as they die.

The current anthropogenic carbon dioxide output into the atmosphere, known by its isotopic signature to be man-made, is approximately 31 billion tonnes per year, with the United States and China each emitting 6 billion, the United Kingdom 0.6 billion and Australia about 0.3 billion directly. This leads to a total average output per person of about 4 tonnes per year, with the United States and Australia heading the list at 20, the United Kingdom 10, China 5 and Nepal a mere 0.1. However, the figure for Australia has to be looked at carefully. It *only* represents the amount of carbon dioxide put into the atmosphere due to the burning of fossil fuels in Australia itself. If one includes the carbon dioxide put into the atmosphere due to the burning of coal which is mined in, and then exported from, Australia, generally to Asia, this adds another billion tonnes per year, thus increasing Australia's contribution by about a factor of four. There is some justification for this sort of accounting, It would mean that per person Australia heads the list by quite a way (because the United States exports only a little coal).

With greater difficulty, it is possible to evaluate the global temperature change and its effect on regional precipitation patterns and sea level. This is a much noisier record, but it indicates that, *on average* the mean global temperature over the last 150 years has increased by some 0.8 degrees, from roughly 14.6 to 15.4ºC. More recently, over the last 45 years or so, there have been definite marked increases in temperature. The average daily maximum change over Britain during that time ranges between 0.4 and 2.5ºC, with no decrease anywhere in the country. In Australia from 1 August 2006 to 31 July 2007 there was an area totalling roughly three times the size of Tasmania for which the rainfall was the lowest on record. A comparable area had severe deficiency in rainfall. In addition, the increased temperature, through thermal expansion, has raised the height of the sea, of average depth 4km, by an amount of 3.3mm per year, remarkably uniformly for at least the last 20 years.

Homo sapiens originated around 100,000 years ago, developed significant numbers around 10,000 years ago and, relatively, there has not been much evolutionary change since. However, there have been many changes during the past 100 years in how they live and occupy the Earth. Over this time the population has increased by factors of 4 for the world, 4 for the United States, and 4.6 for Australia. However, the world energy usage for that same period has increased by about 13 for the world, 9 for the US and 5 for Australia. It is virtually impossible (and rather meaningless as well), to evaluate figures for India and China over 100 years. However, what one can say is that over the last 45 years India's energy consumption has increased by a factor of 7, China's by 13 and Australia's by 3. To show how rapidly China in particular is growing, one may note that energy usage in China was half that of the United States only 10 years ago; now it is equal to that of the United States.

Much of this energy comes from the burning of fossil fuels; indeed approximately 85% of the energy used on Earth today comes from gas, oil or coal. Most of the remaining 15% comes from nuclear, hydro, waves, wind and the like, but these renewable sources contribute relatively little. One usage of oil is seen in the fact that at the moment there are something like 700 million cars in the world; 275 million in the US and 16 million in Australia. In 1900 there were 8,000 cars in the US and 144 miles of paved roads there, none of which were in California. In 1960 there were 2.5 million cars in Australia.

There can be absolutely no doubt about these past data. What is far more difficult and contentious is to forecast how temperature and carbon dioxide in the atmosphere might progress in the future. Whatever happens, the Earth itself is safe – it will live on for another 13 billion years or so at least – but the people on the Earth may not be safe. My friend and Cambridge colleague, (Lord) Martin Rees, has hypothesised that, by either error or terror, as he so imaginatively puts it, there is likely to be a major human catastrophe before the end of the century.

2. Predictions

Predictions of future carbon dioxide concentrations and temperature of the atmosphere depend on a large number of factors including: our reaction to consumption; our efficiency in insulating buildings; our handling of the output from power plants; and the predictive accuracy of large-scale numerical models (which are definitely not able to evaluate effects accurately on small grid-scale levels). Taking into account all these problems, the International Panel on Climate Change (IPCC) estimates that by the year 2100 the global average temperature, now 15.4ºC, could be anywhere between 16.2 and 20ºC. For this predicament to prove incorrect we must either change our habits enormously, or, as this article will try to outline, we make the sensible decision to store safely a large part of the carbon dioxide which we currently put into the atmosphere. A 20ºC average global temperature would be absolutely disastrous. There would be much more flooding than we are used to, in particular of cities like Tokyo, Shanghai, Rotterdam and London. It has been estimated that as many as 150 million people in Asia would be exposed to coastal flooding. The problems with drought in Australia would be very much exacerbated. Of course, some changes may be advantageous: for example, there are likely to be two growing seasons in Northern Canada, allowing farmers there to make far more money and use their land more efficiently.

Another numerical prediction is that by the year 2100 the UK summer temperatures would be some 6 degrees higher than they were at the end of the last century. To get some feeling for what 6 degrees means, it might be compared with the so far record mean summer temperature in 2003, which was an excess of about 2 degrees. This heatwave in Europe during 2003 is reported to have been responsible for 15,000 deaths in France and 2,000 in the United Kingdom, mainly of old people who could not take the heat. Turning to advantages again, many more people die of cold during the winter in the Northern hemisphere than heat during the summer; and so it is arguable that increasing the temperatures, over both the winter and summer, will result in a net increase in longevity.

3. Possible solutions

The solution to the global problem that faces us, almost the first global problem that mankind has ever faced, is either to change human psychology or the amount of consumption, something that I believe rather unlikely, especially taking into account the gigantic populations of rapidly developing countries like China and India, which, understandably, want to have the same sort of standard of living as the West has enjoyed for many decades.

Some solutions have been proposed which would use geoengineering to change the way the atmosphere of the Earth behaves. They are roughly divided into solar radiation management (SRM) and carbon dioxide removal (CDR). Under SRM are included such strategies as: launching mirrors into space, where they can reflect some of the incoming solar radiation; stratospheric aerosols, whose aim is to do the same; white roofs to increase the albedo and reflective amount of incident energy; white roads, which would do the same; enhancement of the cloud albedo; and putting sulphur dioxide into the atmosphere by sending it up a hose some 20km into the atmosphere with the top tethered by a balloon, whose current design features include a diameter of 285 metres!

In my opinion there are problems with each one of these, including the important idea that if they are found to overachieve their effect – and plunge the Earth into coldness – it may take a very long time to outride their influence. In addition there are particular problems with each of the above ideas. For example, I was once asked to consult about the idea of painting all roads white, to increase the amount of radiation they reflect back to space. I found it interesting, and rather surprising, that the total area of roads in the United States is comparable to the area of Texas, and that painting these roads white would involve considerably more titanium, a minor component in paint, than we have access to on the Earth at the moment. However, an immediate important advantage of SRM techniques is that they are generally fast.

The second form of geoengineering, CDR, includes ocean fertilisation, meaning seeding the surface of the ocean with iron so as to enhance biological productivity which attracts the carbon dioxide out of the atmosphere and then gently takes it down to the ocean. This has been tried over the last 5 to 10 years and generally the experiments have not been successful. Capturing carbon dioxide directly from the atmosphere has been considered. This has turned out to be both chemically difficult and expensive, mainly because there is rather little carbon dioxide in the air -- even though it has such a large influence.

Another possibility that has been suggested is mineralisation. The argument here is that the Earth itself is constantly forming calcium carbonate, or limestone, and that we humans could do the same. In my opinion the answer is that the Earth has had a very long time to do this and the rate of mineralisation is enormously slow by human standards. It also requires quite a lot of energy, and hence is likely to be costly.

The currently favoured solution is to capture the carbon dioxide from its main sources, such as power stations, cement factories and the like. Once captured, however this is done, it would be stored, with the current idea being that it should be stored, and safely, for at least 10,000 years. The idea of capturing and storing together leads to the idea of CCS: carbon capture and storage.

Where would suitable storage sites be? There are numerous suggestions that have been put forward and my friend and colleague Dan Schrag at Harvard says that this is such an important problem that we should use our imagination to its utmost extent. Thus it has been suggested that we store carbon dioxide in ecosystems – trees, shrubs and plants. Unfortunately quite a large area is needed to satisfy such a criterion. For example, it is estimated that a third of England would need to be covered by forest just to capture the carbon dioxide put out by power plants in Great Britain.

Another possibility is to store the carbon dioxide at the bottom of the oceans, as is favoured by Schrag, where, so it is envisaged, the carbon dioxide would be stored stably. However, it is not clear that it could be safely stored there and any introduction to the oceans of carbon dioxide can lead to extra acidification, which we know has already caused great difficulty to corals, plant life and fish. Another possibility is to use depleted oil reservoirs, which have the advantage that we know that they have managed to hold oil for a considerable time. We might also use brown coal seams, where the coal is sufficiently porous to represent a good storage site but is not of sufficiently high quality to financially justify mining it.

All these considered, the generally agreed best storage sites are saline aquifers: large porous reservoirs of storage where at the moment the interstitial fluid is brine, or salty water. The density of (gaseous) carbon dioxide increases dramatically with pressure, or depth, beneath the surface of the Earth. At a depth of about 800m, at which point its specific volume is less than 1% of what it was at the surface, the carbon dioxide becomes what is known as a supercritical liquid and no material remains in the gaseous state. Further depth, and pressure, increases change the density relatively little. Thus it is best to store the carbon dioxide below a depth of approximately 800m where it is more compact and free of the problematic gas phase.

4. Further processes

There are a number of questions concerning the stability of the carbon dioxide sequestered at a depth greater than 1km beneath the Earth's surface and the possibility of accidental release back into the atmosphere. Accidents can always happen: whether one is driving a car slowly, and with due diligence, an automobile; playing sport; or at work. The aim is to try to minimise these accidents. One can make processes safer and hence more likely to be successful. This can be done in a number of ways for carbon dioxide storage, which we briefly outline.

a) Surface tension effects

Surface tension, which holds a drop of water on a tap, rather than allowing it to fall through the air, plays an important role when a two-phase liquid, in this case carbon dioxide and brine, make up the interstitial fluid of a porous medium. This is well-known in the oil industry, where roughly 40% of the oil clings to the rock and cannot be swept out by water. For the current problem surface tension leads to what is known as capillary trapping, where surface tension holds carbon dioxide within the pore spaces of the rock, much as water is held within a kitchen sponge. There are some who think that this by itself will be completely effective and mean that there is no chance of leakage.

b) Dissolution

It is a physico-chemical fact that when supercritical carbon dioxide, which is less dense than the surrounding interstitial brine, dissolves into water it forms a mixture that is more dense than either of the two inputs. While this is at first counter-intuitive, such an effect has been well-known for a long time to operate in the oceans, where fluid of one salinity and temperature mixes with fluid of a different salinity and temperature and forms more dense water – this is known as caballing or nonlinear mixing – and the resultant water descends in plumes. Here this dissolution will also lead to downward propagation of the supercritical carbon dioxide, which will then be stored permanently (because it is more dense than the surrounding brine). I and my group have conducted numerous experiments and theoretical analyses of this situation, and we are quite confident that it will occur. The only problem is the timescale, which can be at least decades. For example, at Sleipner in the North Sea, where carbon dioxide has been injected into a saline aquifer, with a known input rate of 1 million tonnes per year since 1996, it has been calculated that approximately 0.1 million tonnes per year are dissolved this way. This means that if the input was shut off after one year, in 10 years (very roughly, using linear extrapolation) all the supercritical carbon dioxide would be stored stably. If the input continues for 10 years then the dissolution process takes approximately 100 years for completion. And so on.

c) Leakage

This is without doubt something that needs consideration. A pool of supercritical carbon dioxide can propagate roughly horizontally, underneath a caprock, for maybe even decades, before it may find its way to a fault in the containing rock and rises. This fault may be a previously drilled oil well, a fracture in the Earth, or many of a series of geometries. How rapidly the leakage takes place will depend critically on the parameters of the reservoir, the size of the leakage point and its geometry. What happens to the leaked carbon dioxide depends on the geology above the leakage point. It may be that the leakage takes place for a few tens of meters, say, before it is trapped by another caprock and spreads horizontally. In some sense this happens currently in the nine or so horizons at Sleipner. On the other hand, the supercritical, liquid-like carbon dioxide might rise sufficiently to no longer be supercritical, and explosively exsolve gas bubbles. This would be a problem. It is well known that even relatively small amounts of gas, because of its large compressibility, can lead to explosive eruptions in volcanoes; and there is no doubt that expansion effects due to the presence of vapour could also happen here. Even worse would be a leakage that goes all the way to the surface and spreads along the ground as a heavy, poisonous cloud. Eruption at the surface could be either slow, and hence just waste all the energy that has been used up to initially store the carbon dioxide, or fairly rapid, so that the carbon dioxide spreads as a heavy gas, resulting in many deaths due to suffocation. There was a famous incident when Lake Nyos in Cameroon overturned in 1986, allowing carbon dioxide to spread above the surrounding countryside and kill 1700 people. There is also a very remote possibility of a big, violent eruption due to the exsolved gas.

It would seem to me that any of these scenarios is possible, dependent on the circumstances. Again, this is an area that I and my group have worked on extensively and have written a number of scientific papers outlining clearly what the expected response should be, with the amount of leakage very dependent on the particular parameters of the system. Being forewarned is forearmed; and I am quite confident that, with sufficient knowledge of the geological surroundings of the storage reservoir, the process can be developed to be safe. It is envisaged that only those reservoirs whose integrity has been tested will be used.

5. Conclusions

In summary, the world is at the moment putting out 31 billion tonnes of carbon dioxide, obtaining energy from the burning of fossil fuels. There has been a dramatic increase in the carbon dioxide content of the atmosphere over at least the last 50 years. There has been a corresponding dramatic increase in the average global temperature of the atmosphere. We have understood for almost 150 years how carbon dioxide acts as a greenhouse gas, increasing the temperature. Hence we should not be surprised that its increased concentration in the atmosphere leads to an increasing temperature. Exactly what will happen in the future is difficult to predict. But it is possible that it will be highly detrimental: more storms; more flooding; more droughts; higher temperatures resulting in deaths; …..

The expense of insuring ourselves against this process is relatively small. It has been estimated that the cost might be something like 2% of GDP, which is equivalent to about one year's growth. On the other hand, the potential cost of doing nothing could be very, very much larger. Part of the problem is that the situation is global:

for the first time ever it is necessary for all, or at least many, countries to act in order to mitigate the consequences, not just for themselves but for other countries. In addition the timescale of change is quite large – the inertia of the atmosphere is measured in many decades – and so to influence the result in 10, 20, … years' time we need to act now. Is it worth it?

Let me end with two different views, both of which I think are interesting. Sir David King, the previous Chief Scientific Adviser to the British government, who is a very keen proposer of climate change mitigation, said that the United Kingdom had to do something in order to show China, India and the other developing countries that it was concerned and serious.

On the other hand, Senator Kerry, the unsuccessful US presidential candidate (against George W. Bush), said that it would be very difficult to get any sort of bill on carbon dioxide mitigation through the Senate until the countries like China, India and others totally change their practice and show that they are serious. Which of these two lines is more persuasive; which is more moral?

Finally an Archbishop has said that how we are currently reacting to climate change – doing rather little – is tantamount to theft. We are stealing future happiness and chance of prosperity from our grandchildren.

Which line do you take? How do you react?