Climate Change & Global Warming

In this section we shall take a long look at the evidence for climate change and some of the factors that produce climate change, including the influence of greenhouse gases. Climate change is undoubtedly a reality – what are some of the implications for the future of the current global warming phase? Climate change is discussed in chapter 16 of Ahrens' book, where you can read an account independent of these notes.

Looking back over these notes I see I've already used the word 'climate' on many occasions, assuming we all know what it means. In meteorology 'climate' is taken as the average weather over 30 years. 'Weather change' is not the same as 'climate change'. How often does one see in the media articles discussing whether such and such storm or flooding is due to climate change? Frequently, these days. It's a question that sounds reasonable but isn't, because the participants have forgotten the definition of climate. Climate is the average of tens of thousands of weather events. Among these events will be extreme ones, though in any particular 30 years not necessarily any one particular extreme event. For example, even an exceptionally hot and dry summer is not strong evidence of climate change, for it takes sustained changes over years to change a 30-year average significantly. Climate change is measured roughly on the timescale of human generations. It happens. The average weather our grandparents experienced when growing up may have been significantly different from our own experience in the same part of the country. That would show climate change over two generations. If the climate has changed since our grandparents' youth, then all the weather we experience is a result of climate change, even today's common and nondescript weather.

A topic of the times

If I'd asked the class a few years ago if global warming was a reality or simply a prediction for the future, then a good many would have opted for the prediction. Even a few years ago it was a reality. Today, it is the media topic of the decade. Al Gore's film on the subject "An Inconvenient Truth" won an Oscar in early 2007 and he won a share of the Nobel Peace Prize in late 2007 for this film and his campaigning. That would not have happened a few years previously. David Attenborough said in a much-watched TV program in 2008 that global warming was 'the greatest problem facing mankind', or words to that effect, and since there are plenty of problems challenging for that title, then that means it should be pretty high on everyone's agenda. That was a decade ago and since then global warming has indeed become much more prominent in the public consciousness.

Global warming isn't a new issue on the public agenda. My opening slide shows magazine covers from past years. The *Time* magazine cover looks as if it could be from this year but is in fact from 1987, a third of a century ago; the others are more recent but not very recent. In fact, climate change has a very much longer pedigree. Listen to a predecessor of mine at the University of Aberdeen, A. E. M Geddes who was a real meteorologist and wrote a well respected book on the subject. "*There appears to be a fairly persistent belief that our climate is changing,*" he wrote, "*and that winters are not what they were in our fathers' and grandfathers' times as regards severity, nor are the summers so bright and warm.*" When did he write that? A prescient voice in the 1990s perhaps? No: in 1935, opening a discussion on temperature trends since 1870. Other, broader studies at the same time came to similar conclusions. I'll quote another piece of even earlier local history. A letter from the Duke of Gordon [local proprietor of a large estate] to Professor Copland of Marischal College written on a cold January day in 1818 comments *"I lately received a letter from London which states, that Sir Joseph Banks* [President of the Royal Society]*, & some other Philosophers say, that we* *have reason to expect an amendment of our climate, in consequence of our breaking up, and final destruction of about 50,000 square miles of Ice, which had beset Old Greenland for the last 400 years. I hope these Philosophers are true prophets*". That was 200 years ago, though I haven't looked up the details that prompted this remark. In these quotes there lies a very important point, with several implications. The first one is that climate change is not a creation of modern times; a second one is that global warming as a phenomenon is not a creation of modern industry.

Cartoon

How many times have you heard the implication that global warming is all the fault of industrialisation? It's simply not true. Global temperature changes were taking place long before the first cars took to the roads accompanied by a man with a red warning flag, long before Wilbur Wright flew his first plane. Industrialisation is playing a significant part in the modern story but the situation is much more complicated than is often portrayed.

The cartoonists have been giving their one-picture summary of perceptions for equally as long. It's worth remembering that global warming isn't all about science. There's a lot of economics and politics involved in related decision making. I'll come to this point later. The science is trying to provide the facts but plenty of people in almost every camp are capable of ignoring facts that don't support their viewpoints.

Do we notice global warming?

Who says the planet's getting warmer in any case? I've plotted on this slide 7 years of Aberdeen's average daily temperatures, 2500 days, covering a span of years in which global warming became a public issue. The temperatures go up and down over the years by about 15 degrees Celsius. These fluctuations exclude temperature changes over the day and night. The average global warming over the whole of the 20th century was about 0.8 degrees Celsius. You just won't see that in the daily figures, or even the annual figures. We may have had a warmer winter than average this year or a warmer summer a couple of years ago but that on its own doesn't tell us about the planet as a whole. Climate is defined by the weather over decades, not years.

How do we find out the facts?

Detecting global warming is a matter of statistics. You have to collect a very large amount of accurate data, over the whole world and over a long time period. This is one area where science comes in. The temperature data needs to be accurate if you are looking for small changes in a long timescale. Accurate calibration is not easily achieved and it isn't an idea that people paid too much attention to many centuries ago.

For over 50 years there has been global coverage of the world's weather from satellite measurements, over and above all the traditional methods. The composite image on the top right contains a picture of the world, colour-coded according to the temperatures measured near midday on the date shown. Satellite imagery and remote sensing are immensely powerful techniques. Climate monitoring is a huge undertaking and doesn't just rely on satellites. As an illustration of how much effort now goes into this activity, the Global Climate Observing System (GCOS) was set up by the WMO (World Meteorological Organisation) and other UN bodies in 1992 to collect and process data from ground-based observing stations around the world with a proven record of standards and reliability. By 2008, 15,433 stations world-wide contributed their data, current and historical, to GCOS. See https://public.wmo.int/en/programmes/global-climate-observing-system for current data.

For a few centuries before the satellite age, there have been historic temperature records from selected areas of the world, with long-term data only from pretty select areas really. Remember that 2½ centuries ago, substantial parts of the world weren't known about in Europe. Even fewer parts of the world had any history of making temperature measurements. There is also the important scientific question of how accurate are the historic temperature records that we do have in any case? The humble thermometer, about 300 years old though it is, hasn't provided the long-term records we need to assess climate change. The graph shown is the best reconstruction of global temperatures derived from thermometer records over the past 150 years, as reported by the IPCC (more about them soon).

You can also look for indicators like the onset of frosts, the freezing of local ponds, lakes and rivers, the onset and persistence of snow as measures of cold weather; the dates of spring blossoming; droughts, famines and crop yields as evidence of summer weather. That's not a bad idea. Careful examination of historical records is known as *documentary climatology*. It's a respectable subject that provides very useful information over the past millennium. For example cherry blossom flowering records are available in Japan from the 11th century: a thousand years of records, thanks to the cultural significance of cherry blossom in Japan. This concept of looking at records of the effects of climate is in fact the main source of our information on climate past. It is embodied in the concept of a **proxy**. A proxy is something you measure instead of the factor you really want to know about. From the alternative measurements that are proxies for temperature, you deduce changes that have taken place in temperature. The best proxies are not written historical records, though, but natural processes, as we'll see.

Proxies

There are a number of proxies that effectively measure average regional temperature, such as tree ring sizes, coral band sizes, sea-floor sediment thickness and so on. These are being extensively investigated. Most of the proxies relate to the influence of temperature on the growth of something but their interpretation is never quite straightforward because growth is the result of a whole complex of interactions including nutrients, water and environmental temperature.

Trees have lifetimes of centuries and occasionally thousands of years. Tree-ring growth is closely tied to the average temperature in the growing season, though nutrient availability and rainfall are also factors. Tree-ring derived temperatures can be taken back over 5000 years.

All the signs and the proxy measurements point in the same direction. The climate is changing. The climate is always changing. It is never steady. However, particularly over the last 30 years there has been a significant global warming signal and this trend is continuing.

Global mean surface temperatures have increased

Global warming isn't a myth generated by computer predictions. It is a reality here and now.

The top of the slide shows a collection of authoritative studies that recreate temperatures over the past 1000 years. There is clear range of values for times going back several centuries, a smaller range for more recent results, as you'd expect. There is a conspicuous signal in the decades leading up to today, less so before then. The zero for the scale is the 30 year average from 1961 to 1990. The two world maps show the location of proxies in the studies in the years 1000 and 1500. You might conclude from this that temperatures have been pretty steady for centuries and then begun to change.

On that time-scale they more or less have, though in the records of Western history at least there have been long cold and warm eras too, within that period, sufficiently well defined to be called the 'little ice age' and the 'mediaeval warm period'. How reliable are the figures on the graph? They are the presentations of the Intergovernmental Panel on Climate Change – the IPCC who feature a lot in the international debate on climate change. The figure of 0.8°C global temperature rise for the last century is quite consistent with the energy required to produce the observed change in the ice-coverage on the Earth in the 20th century

The IPCC

The **I**ntergovernmental **P**anel on **C**limate **C**hange is essentially a panel of 'expert witnesses' given the task under UN mandate of assessing the scientific evidence on global warming and providing an authoritative basis for governmental action. The Chair of the panel put it that one of their duties was to '*reach across national boundaries and political differences in pursuit of objectives defining the larger good of human society*'. Their remit is intended to be non-partisan but inevitably its judgements have political implications and therefore political content. The IPCC is advised by many hundreds of meteorologists, oceanographers, glaciologists, atmospheric and environmental scientists and others from around the world.

The IPCC has 3 main working groups: Working Group I (WG1) *assesses the physical scientific aspects of the climate system and climate change*; Working Group II (WG2) *assesses the vulnerability of socio-economic and natural systems to climate change, negative and positive consequences of climate change, and options for adapting to it*; Working Group III (WG3) *assesses options for mitigating climate change through limiting or preventing greenhouse gas emissions and enhancing activities that remove them from the atmosphere*. The 'working groups' complete set of individual reports published in 2007 are being updated in 2013/2014. You can find the web link to IPCC on our 'links' page.

The IPCC does a good job of laying out the facts of the situation. Its interpretations and predictions are only as good as the science of the day and what has changed in these past half dozen years is that the science is much less uncertain than it was before. Climate models are more sophisticated and contain fewer sweeping approximations. Serious attention has been given to some earlier criticisms and the predictions have a greater reliability than before. Substantially more data is available now on all fronts than was present when the 3rd report published in 2001 was being prepared. The single most important conclusion of the 2007 4th report was that the probability that the observed global warming over the past few decades has been driven by man's activities has gone up from about 60% (which is little more than 50:50) to over 90%. In essence the jury returned the verdict that accelerated global warming is due to mankind. The main 'drivers' have been land use changes and CO_2 emissions. This conclusion is reinforced in the WG1 5th report of 2013. By the way, this report is over 2200 closely argued pages long, so not a quick read.

If anything, the 4th IPCC assessment report (referred to as AR4 by the IPCC) was conservative, emphasising only conclusions that could be backed-up by quantitative work corroborated by different research groups. The 5th report, AR5, continues that conservatism, with all important statements accompanied by a confidence statement such as *likely*, *high confidence*, *very likely*, etc. or if the statements are amenable to direct probability predictions then with words like *high probability*, etc. The issue of global warming creates a wide range of viewpoints, from the sceptics who frequently have a vested in interest in the status quo, to end-of-the-world-as-we-know-it alarmists who preach with missionary zeal. The IPCC has focused on the well-established. Even that has huge implications that politics, economics, global business and society at large have not yet taken on board. Again, I'll pick up this point later. The 5th report (AR5) is appearing in stages from the working groups. As I'm updating these notes, WG1 have published in 2013 their contribution on the Physical Science Basis of Climate Change. WG2 have reported at end March 2014, WG3 in April 2014 and a synthesis report of the 5th assessment is due in October 2014.

Climate change over 400 millennia

A millennium is a short time in terms of some natural processes that affect the Earth, so what has happened on an even longer time scale? Is such a change that has been observed over the last century within the level of natural fluctuations? To answer this we either need a very good understanding of global climate changes, and we're not there yet, or reliable, very long term, temperature records. Science is finding it easier to improve our knowledge of temperature records than obtain confidence in global climate modelling, though a lot of work is being done in both areas.

One very successful example of efforts to get such long-term records by reading the book of nature is ice-core analysis. The amount of information that can be extracted from ice-cores is impressive. The slide gives some idea. It's been said that ice-cores are as good as having had a weather-station measuring conditions on the planet for the last half million years. We'll look at the temperature information available.

Borings have been made in Greenland, Antarctica and elsewhere to extract ice cores. Recent ice-core data from Antarctica takes us back three-quarters of a million years, on a year-by-year basis. Temperature is one variable that can be found, by proxy of course. Temperature affects the isotopic ratios of oxygen trapped in each level of the ice. The slide shows the % departure in Greenland ice-cores of the ratio of $^{18}O/^{16}O$ from a standard value. The method works like this. Remember that ice is compressed snow that has fallen from clouds caused by evaporation of ocean water. The $H_2{}^{18}O$ molecule is heavier than $H_2{}^{16}O$ molecule. If the water in the ocean that evaporates to form the clouds is cooler, then proportionately less $H_2{}^{18}O$ evaporates than when the water is warm. When you measure the snow that has fallen from this cloud and become ice, the $^{18}O/^{16}O$ ratio is smaller. In short, the figures plotted are equivalent to lower temperatures at the bottom of the graph and higher temperatures further up.

The same technique is used with deuterium (D), an isotope of hydrogen (H) that has almost twice the atomic mass of ordinary hydrogen. The change in the ratio of D/H is the proxy for temperature.

A Table of Climate Related Measurables from Ice Cores

This slide highlights that ice-cores are a superb historic record of both the variables that drive the climate and the climate response. They are a record that does require a good knowledge of the compaction process of snowfall turning into ice-fields. For example, years are quite spread out at the top of the cores but become very close together further down by an amount that will be influenced by motion of the ice. Greenland and Antarctica produce by far the longest ice-cores, and hence the longest time spans, but the technique can be used in other permanently frozen regions.

Longer ice-core temperature series

The slide shows two Antarctic ice core results, one from a Russian core taken above Lake Vostok and the second from a European multi-national project at Dome. Although the latter didn't have such a long core, the data went back almost three-quarter of a million years. Ice-ages and interglacial periods can be seen very clearly. There is a very strong correlation between the two trends over the 450,000 years of the Vostok core. The Vostok readings have been plotted as temperature changes, which nicely scales both graphs.

Observing how the Earth's climate has changed over the past million years is scary. Ice-ages have swept as far south as southern France, punctuated by interglacial periods a bit like the one we're in now but frequently less stable. There have been times, at the end or start of ice ages, where average temperatures have changed much faster than 1°C per century. For all the recent hype, mankind's influence on global climate has been small compared with past natural fluctuations. This is not to say that we can ignore recent changes but so far they haven't taken the climate to anywhere it hasn't been to before.

These and other ice-core records put quantitative figures on what the geologists have been telling us from rock and fossil evidence. Over the past few million years, which is a pretty small fraction of the Earth's history, there has been a series of glacial periods followed by interglacial interludes. We are in an interglacial interlude. From this and other evidence, the Earth's climate is never settled. It is always changing: sometimes quickly by large amounts, sometimes quickly by small amounts, sometimes more slowly. Barely 25,000 years ago Aberdeen was under more than 1 km of ice; Scotland didn't exist as a habitable place. Britain was not an island, but connected to Europe. None of the changes that created our modern Scotland were driven by mankind. One important message from the evidence is that global changes in climate, in geography, in eco-systems, in land use, in human spread around the world have been driven by nature for millennia. The jury has now returned the verdict that mankind's activities **are** influencing the situation, but they come on top of natural variability.

Why has it taken so long for this conclusion to be reached? Has someone been asleep on the job? Certainly not the meteorologists, who have been observing climate change for a century or so and shouting about it in recent decades. It's probably not even fair to suggest that governments have been asleep. The issue has been that the required responses are so enormous, radical and imply such a change in direction for societies that the evidence has had to be all but certain before being accepted. Having waited so long, the changes required now have to be implemented in a shorter space of time and it's not clear that the magnitude of the response has yet been appreciated by many government bodies or industry magnates. I'll take up this theme after saying more on the relevant science.

Conclusions on climate change evidence

- There have been large fluctuations in global temperatures over very long timescales from natural causes
  - are there hidden patterns? Patterns point to causes. There are some patterns.
- Some possible causes:
  - variation in the parameters of the Earth's orbit around the Sun (this variation does contribute definite climate patterns and is the strongest single effect changing climate)
  - the effect of plate tectonics and volcanoes on the climate

– variation in the Sun's total output (this aspect is more subtle than you might think. Light output of the Sun is astonishingly stable)

An overview of the climate system

This slide comes from the IPCC. It shows a schematic view of the components of the climate system, their processes and interactions. It's a slide to look back to after I have talked about some of the issues involved in climate change. There is lots of talk these days about CO_2 and I'll talk about it too but this slide is a reminder that the climate is controlled by many factors over and above the CO_2 concentration in the atmosphere.

Human activities have changed the composition of the atmosphere since the pre-industrial era

Why, then, is global warming the issue of the decade, if not the century? The question of the moment is not whether the greenhouse effect is good for us – it's vital in fact – but whether our activities are changing the size of the greenhouse effect enough to alter global temperatures.

Firstly, are we making measurable alterations to the composition of the atmosphere? The answer is clearly 'yes', though on a scale that is a small fraction of 1%. To put the numbers in perspective, 2 ppm, the annual average CO_2 change, would be equivalent to an alteration by 2p in a sum of money of £10,000. So, yes, mankind is changing the atmosphere but not by much. This slide showing changes in 3 greenhouse gases over the past millennium is from the 2001 IPCC scientific report. It also shows the variation of sulphate aerosols.

Long-term greenhouse gas changes

The second slide, from the 2007 IPCC report, shows long-term changes of 3 greenhouse gases, CO_2 (carbon dioxide), CH_4 (methane), and NO (nitrous oxide). The slide illustrates that these gases all occur naturally in the atmosphere but their concentrations have increased in the past two centuries well above the naturally occurring fluctuations over the past 10,000 years. There are many more greenhouse gases whose contributions have increased too but their overall concentrations are still very small.

Focus on CO_2 trends

The important question has been 'the atmospheric changes may be small but are mankind's activities influencing global warming significantly'? That is implicitly a quantitative question and another one for modern science. The answer, with contributing evidence from literally thousands of meteorologist, oceanographers, environmental scientists and many more, is 'yes'. This answer was announced in the 4th report of the UN's IPCC, in 2007.

Two mechanisms are driving mankind's input. One is land use change, the other is the release of CO_2 from the use of fossil fuels coal, oil and to a lesser extent natural gas. These put carbon dioxide into the atmosphere that was previously sequestered in the ground, or at least the carbon was sequestered in the ground. As you know, carbon dioxide absorbs heat energy that would have been radiated away into space. The extra energy absorbed heats the atmosphere and increases the radiation sent back towards the ground, heating us up.

First, by how much have CO_2 levels been changing in recent times? One of the longest series of reliable data is that collected by the Climate Modelling and Diagnostics Laboratory on Mauna Loa in Hawaii. You can see yearly fluctuations related to CO_2 update changes in the world's forests and, on a longer time-scale, how in almost 60 years CO_2 concentrations have increased from about 310 ppm to about 400 ppm, which is 0.04%. The current rate of increase is just under 2 ppm per year.

The fact that land use would change on a global scale and mankind would create more CO_2 in the atmosphere were extremely predictable circumstances. With a human population of over 7 billion and rising, using the most readily available high-density energy sources, the rise in CO_2 levels in the atmosphere was a certainty. No-one should be surprised that it's happening and it's no-one's 'fault'. Talking about 'blame' is a complete red herring and diverts attention from what needs to be done now. The question that we didn't know the answer to before and whose answer has just become clearer this century is 'what effect will increased CO_2 levels have on climate change?' Mankind went with the flow in the 20th century and did little to influence either land use change or CO_2 levels. Should we do something now?

Before answering that we need some more information about the overall scene. Although the direct influence of CO_2 is not particularly big, changes in CO_2 can enlarge other effects. This is known as "positive feedback" and the combination of CO_2 and positive feedback is now considered to be responsible for the sharp changes observed in recent decades.

What other natural processes may have had a significant impact on last century's global temperatures?

IR absorption spectra

The most important greenhouse gas is water-vapour. It is present in the atmosphere in very variable amounts but in our part of the world can be 100 times more plentiful than CO_2. The biggest contributor to the world's greenhouse effect is water-vapour. That needs to be said in view of all the emphasis on CO_2. As the world warms, more water-vapour enters the atmosphere, providing a positive feedback effect. You can see on the slide where in the IR water-vapour absorbs. There is immediately a complicating factor here in that more water vapour in the atmosphere also means more clouds and clouds reflect away sunlight before it has a chance to heat the surface, so clouds have a negative effect on global warming, i.e. they contribute to global cooling. Which effect wins? One needs to model the atmosphere numerically accurately to find out.

CO_2 is a greenhouse gas. More CO_2 is being produced by mankind now than before because there are more people on the planet who are using an increasing amount of energy produced by burning processes. Everyone is agreed so far. Everyone is also agreed that global warming is greater than is simply produced by the increase in CO_2 concentrations alone. Other things are going on. In the region of the IR where CO_2 absorption is most prominent (at 12 - 18 μm) is not quite where the Earth is radiating the most IR, which is around 10 μm. I've superimposed the blackbody radiation curve for the average temperature of the Earth as a red line on the absorption graph in the slide.

For a trace component in the atmosphere, the amount of CO_2 in the atmosphere is already quite substantial and its absorption in its own part of the IR is already high, though not saturated. Adding more CO_2 doesn't affect the atmospheric absorption that much. The direct effect of increased CO_2 concentration varies logarithmically with the concentration, which is quite a slow change with concentration. This certainly works in our favour. CO_2 levels are likely to double from the pre-industrial baseline but the global warming created by CO_2 will not nearly double. I'll say why in a bit more detail later. There are other gases that absorb in a more effective part of the IR and whose concentrations are small at the moment but to which the greenhouse effect is more sensitive.

The carbon cycle and CO_2

CO_2 can't be ignored because CO_2 is part of a natural exchange cycle that makes our world tick, called the *carbon cycle*.

The carbon cycle is the huge exchange of CO_2 between the atmosphere and the biosphere that occurs naturally, mainly without any industrial input from us. Mankind produces about 8 Gtonnes (carbon mass) of CO_2 annually. The carbon cycle sees over 100 Gtonnes (carbon mass) of CO_2 exchanged annually between biosphere and atmosphere. The slide shows the carbon masses, not the CO_2 masses, in the carbon cycle. Plants on land and life in the sea take up carbon. Plants and sea-life decay, giving up carbon. In addition, water dissolves CO_2 and also gives some back to the atmosphere. Our emissions merge into this natural carbon cycle. About 5 Gtonnes (carbon mass) per year of our production is taken out by growth on land and absorption in the seas. This is a lot and mankind will be hard pushed to add much to this by policies of carbon sequestration and CO_2 usage. [Large scale 'sequestration' involves injecting CO_2 into used oil or gas reservoirs or deep aquifers, a technique that does work, or potentially injecting water with CO_2 dissolved in it into rocks like basalt and allowing nature to form carbonates, the underlying process used to create limestone. At the scale required, rock formation is still at the stage of 'future technology']. One of the 'new ideas' we read about is CO_2 being used as an industrial feedstock to make things. Using CO_2 as a feedstock is of course just what nature has been doing on Earth for a few billion years. All the carbon in the trees, in grasses and in every plant you can see comes from CO_2 in the atmosphere. All the carbon in our bodies and those of every other animal was at one time atmospheric CO_2. Where did you think it came from? Using a Gtonne (carbon mass) of CO_2 as industrial feedstock to make carbon-based products, the amount needed to make a significant difference, is far beyond current capabilities. And what we make has to be non-biodegradable so it can be buried when we're finished with it and the carbon kept out of the atmosphere. Using CO_2 as an industrial feedstock will happen, but it won't solve the global warming issue.

The current 'buzz word' to cover the technologies mentioned in the previous paragraph is NET, which stands for 'negative emissions technology' – technologies that remove carbon from the carbon cycle. Increasingly one sees statements that atmospheric CO_2 targets will not be met without the deployment of negative emissions technology. I've a lot more to say about influences on climate change but in my opinion the idea that one can keep using fossil fuels and mitigate their effects using NET is unrealistic for the simple reason that the amounts involved are gigatonnes, that's a thousand million tonnes. The cost of creating the necessary technology to handle that amount of 'stuff' means it just won't happen. It's not beyond the laws of physics but it's surely beyond the willingness of mankind to spend the kind of effort needed. We will get negative emissions technology on a smaller scale to address local problems – indeed pilot plants exist - but NET is not going to 'save the world' from warming.

The natural cycle has its own variations that can influence climate. Let me cite just one. The permafrost in what are often called the northern wastes have frozen huge amounts of decaying vegetable matter. Global warming will unfreeze permafrost, releasing through the completion of the decay process very substantial amount of CO_2 and methane (CH_4, another greenhouse gas) into the atmosphere. The reserve locked up is said to be around 200 Gtonnes (carbon mass) of CO_2. To model climate change, you need to model the entire biosphere, not simply the alteration in mankind's annual CO_2 production. To do this modelling effectively you need to understand the carbon cycle and all its ingredients.

One warning fact that other influences are at play is that in both historical and pre-historical times there have been major changes in world climate lasting centuries when the CO_2 remained pretty constant.

Returning to the topic of the atmospheric CO_2 level, which is one of the drivers for current global warming, *the* key question is "how much CO_2 increase should we target as being acceptable for the future?"

Constant emissions of CO_2 do not lead to stabilization of atmospheric concentrations

The slide shows the projected CO_2 increases from two models considered by the IPCC. Because there is a surplus of CO_2 from mankind's emissions that remains in the atmosphere each year and isn't absorbed by oceans and vegetation, then even if emissions are curtailed to current levels, the CO_2 concentrations will increase steadily. To stabilise CO_2 levels, emissions have to be cut. What stabilisation target should we be aiming at? The smallest realistically achievable target is a doubling to pre-industrial levels, i.e. about 550 ppm.

Projected concentrations of CO_2 during the 21st century are two to four times the pre-industrial level

The 4th Report of the IPCC was based on 6 possible future scenarios (called SRES by the IPCC, which stands for *Special Report on Emission Scenarios* and referred to their report issued in 2000 that detailed these scenarios. Scenarios include population growth projections, rate of adoption of new technologies, whether countries around the globe adopt convergent technologies and lifestyles or remain quite nationalistic, and so on. Each scenario had a different rate of mitigation of CO_2 production. Climate modellers and economic modellers were encouraged to use these 6 models as the basis of their future predictions. In terms of CO_2 they correspond to final levels (in well over a century's time) of about 600, 700, 800, 850, 1250 and 1550 ppm). Four times the pre-industrial level seems unlikely, for people have pointed out that we haven't found enough coal and oil reserves to burn to create that much CO_2 in the atmosphere. See 'the numbers game' in the blue panel on the course web page.

The 5th Report has changed the jargon, using the term *Representative Concentration Pathways* (RCPs). The name doesn't say much to me either but they are fully described in AR5. The differences from the previous scenarios are the implicit inclusion of the effects of existing United Nations agreements and a foundation resting on the concept of the *radiative forcing* (which is described later in this chapter of the notes) that could exist in 2100. Radiative forcing is a measure of the additional energy input to the Earth's surface from all effects, measured in W m^{-2}. RCP2.6 assumes 2.6 W m^{-2} global forcing by 2100; similarly for the selected values 4.5, 6.0 and 8.5 W m^{-2}. The various scenarios are considered plausible and illustrative at this stage. Climate modellers convert each selected value into a time series for greenhouse gas concentrations and then run their climate models. The net result is considered by the IPCC to be more realistic than the earlier SRES based method but the differences are more noticeable in the long term than in the short term. Some of the slides in the accompanying lecture are based on SRES numbers and a few on RCPs.

What is now clear is that CO_2 concentrations are part of a complex interacting system of influences on the Earth's temperature. Most of these influences we have little control over. It's my personal view that we may think we have control over CO_2 levels but in reality mankind is going to have to work very hard and co-operatively to exert that control. An increase in CO_2 was historically inevitable. I believe we won't stop levels doubling from pre-industrial levels. Setting an achievable target is good policy and that is what the Kyoto agreement that was ratified on 16th Feb 2005 was about. A series of summits since then that have done little to move policies on suggest that the international agreement necessary for effective cooperation is still a long way off. There is an update on international agreements in several pages' time.

Estimate of global warming for this century

The IPCC estimates on the slide come from computerised atmosphere-ocean global models.

There is a broad band of predictions, depending on the scenario imagined and, in detail not shown on this slide, even on the range of results produced by each computational model. Average values come out to be in the region 3°C over the next century. All of you will hopefully live most of your lives in the 21st century, so this is very relevant.

Temperature changes in 20 and 90 years

AOGCM stands for *Atmosphere-Ocean General Circulation Models*. I'll speak a bit more about these later in the course. The three lines of pictures refer to 3 different IPCC scenarios, the first one being the doubling of CO_2 levels. The orange curves show a range of predictions for global temperature changes in the decade 2020 – 2030. Each bell-shaped curve represents temperature change versus the probability of a given figure happening. These probabilities are obtained by running the computer models many times with a wide range of reasonable parameters. Each model therefore produces a probability curve. AOGCM models are the most sophisticated climate models in that they incorporate atmosphere-ocean interactions in some detail.

The red curves are for end-of-century predictions, more relevant to your grand-children in their middle age. Buy some shares for them now in bottled water companies.

Best estimate of warming variation with an average rise of 4ºC since 1890

This slide, produced by the Met Office's Hadley Centre, their specialist centre for studying climate change issues, shows very well that a single figure characterising global temperature increases is a poor summary of how global temperatures may change. The parts of the world that will warm most, and that includes quite a lot of land, may change their average temperature by at least 10º C. Even that figure doesn't tell the whole story. A 10º C rise in temperature in the winter in the steppes of Russia or the plains of Canada would be pretty welcome. A 10º C rise in the heat of summer would create significant changes in the environment, damage crops and take its toll on society. How will temperature increases be distributed over a year?

It is very clear that the climatologists' best predictions of the details that will come with global warming are crucial in making decisions about how we as a society need to respond. Another issue that comes from such analyses is that predicting what might happen in various parts of the world can be done with more certainty than predicting when it might happen. The 'when' issue is very closely tied to the uncertainties of mitigation policies that are implemented world-wide, and how effective they are. The 'what' issues, though not completely time independent, are more closely tied to the science of the climate system.

Anthropogenic forcing

This slide comes from the IPCC 5th assessment of 2013/14. It illustrates the reality of anthropogenic forcing on the climate. The black lines show the measured surface temperature changes over time. The blue band is the range of predictions made by climate models including just natural fluctuations. The pink band shows the predictions of models that include the effects of mankind's 'anthropogenic force', including the effects of our CO_2 emissions. It is now clear to almost everyone that mankind is influencing the climate.

Radiative forcing

Looking at broader issues than CO_2 levels, the IPCC use the concept of **radiative forcing** to estimate how much individual effects contribute to global warming. Because of the close interactions between different effects it's hard to separate out the various contributions. Radiative forcing is measured in W m^{-2} and from the discussion in the previous section of this course you can appreciate that it is a measure of how much more energy is radiated towards the Earth on a sustained basis because of a given effect. Negative radiative forcing implies a cooling effect. One aspect that has changed in some of the assessments is the level of scientific understanding (the column headed LOSU), which has improved over the past decade.

The slide is worth studying in some detail. The largest single effect is that of changes in CO_2 levels, which is why CO_2 is the prime topic of discussion.

[Climate change opinion isn't all about accepting other people's viewpoints. There are background numbers that can be checked against basic science and plenty of people put forward arguments that don't stand up to this scrutiny. Here's a typical back-of-the-envelope calculation you can do to check if an argument makes scientific sense. The question is: *how much ice can extra energy input to the surface of the Earth melt, for example in the Greenland ice-sheet?* We'll use round figures to get an idea of what basic science says. Consider that, due to global warming, there is an **extra** 1 W m^{-2} of IR energy incident on the surface of the ice day and night, "24//7". That's probably a bit more than today's accurate figure. Suppose all of this is absorbed by the ice (again an upper limit). That gives an extra energy input of about 30 MJ y^{-1} m^{-2}, remembering that 1 W is a J s^{-1}. This is over and above the normally daily, weekly and monthly give and take of energy from the surface. What thickness of ice covering 1 m^2 can this extra energy melt? The latent heat of melting ice is about 330 KJ kg^{-1} and hence the energy input can melt at most about 100 kg of ice (per square metre year per). The density of solid ice with no air bubbles in it is just over 900 kg m^{-3} so in round figures the extra energy input isn't going to melt more than about 10 cm thickness of solid ice per year. Somewhat to my surprise, the results of 10 years of the GRACE orbiting satellite measurements agree with this. The average loss of ice over the Greenland ice sheet for the decade 2003-2012 is about one metre. The area of the Greenland ice sheet is about 1.7 million sq km and the area of the world's oceans 335 million sq km so melting equivalent to 0.9 m of water will raise the world's sea levels by about 4.5 mm (if the melt water spread evenly over the world, which it doesn't). The IPCC's AR5 report of 2013 estimates the Greenland contribution to see level rise as 3.3 mm in the preceding decade.

The first conclusion to draw from this is that in no way are the Greenland or Antarctic ice sheets, average thickness not far from 2 km, going to melt in even a few centuries from this extra heat input. [Antarctica is about 6 times the area of Greenland. Greenland is a little smaller than the Mediterranean sea, though it doesn't seem so on standard Mercator projection world maps]. Global warming implies greater evaporation from the seas and broadly speaking greater rainfall and snowfall. Will this be enough to sustain a greater rate of melting and keep the ice sheets at roughly the same depth? Maybe so, maybe not. Current precipitation over Greenland varies from around 20 cm per year to 80 cm per year (water equivalent depths, much of it is snow). Documentaries like to show apparently huge chunks of glacier dramatically calving into the Labrador Sea, the implication being that Greenland's ice sheet is collapsing. They fail to mention – it's not high visual drama - that more than 500 Gt (that's five hundred thousand million tonnes) of snow falls per year on the ice sheet. So what's winning, the calving or the snowfall? At the moment the melting and the calving is very slightly winning, with the ice-sheet decreasing in thickness by about 10 cm per year, but it's not much and with warmer oceans snowfall in future will increase. The back-of-the-envelope calculation certain rules out a good few scaremongering scenarios by people whose rhetoric is stronger than their science. Even without any detailed physics, the knowledge that the Greenland ice sheet has existed for some 3 million years and the East and West Antarctic ice sheets for 30 million years through warm and cold periods of the Earth's history, suggests that neither sheet is going to collapse even in millennia. Glaciologists will tell you that calving is sustained by ice creep, not by melting, and creep is a product of pressure and time.

Year on year melting is visible in Greenland, particularly where an area is dusted with cryoconite, dark debris from afar that accumulates in places on the surface. The coastal regions may be returning slowly to the greener land that the Vikings found but it's not worth your grandchildren investing in land in the plateau region, which was a huge country of rivers, valleys and mountains in Miocene times (5 million and more years ago). It will still be covered in ice long after they are in their graves. Notice that the case of the melting Arctic Sea ice is quite different from the Greenland ice sheet. Sea ice is only a few metres thick and it can melt due to being lapped by surrounding water as well as by absorption of IR from the atmosphere. A comparatively rapid melting of arctic sea ice in a few decades is quite a believable scenario.

This is a suitable place to mention that I've included the calculation above in a supplementary note called '*the numbers game*' that those interested can find in the blue panel on our meteorology course web page. Using science that everyone on the course should be able to follow, I've shown how you can put numbers to some interesting answers to important questions in the global warming debate. For example, you'll find that if the entire known reserves of coal and oil are burnt then they would not double atmospheric CO_2 concentrations from present levels. You can calculate that re-growing the world's forests is not going to provide carbon sequestration that will prevent CO_2 levels from rising substantially, and so on. You can look at the details in your own time. Comments are welcome. I'll return to the thread of the lecture.]

Related to the concept of climate forcing is the actual sensitivity of the climate system to change. The IPCC describe the equilibrium **climate sensitivity** as a measure of the climate system response to sustained radiative forcing. It is defined as the global average surface warming following a doubling of carbon dioxide concentrations. It is *likely* to be in the range 2 to 4.5°C with a best estimate at the moment of about 3°C. *Climate sensitivity* is a measure of the response of global climate considered as a physical system to the specified change in CO_2 in the atmosphere. Sensitivity includes the accompanying feedback influences of all the other consequential changes. Sensitivity is not a prediction of what's definitely going to happen; that will depend on the actual CO_2 change.

Effects of global warming

The slide shows baldly some of the effects of global warming. The implications are enormous.

- Climate change
    - variable around world; generally wetter; some dry areas will get drier, some areas colder
- Variation of ecosystems
    - population shifts and national economic changes
- Raising of world sea level
    - melting of some of the Antarctic ice sheet that is currently on land
    - thermal expansion of sea
- Ocean current changes

Environmental effects of climate warming

This slide is the IPCC's visual summary in AR5 of some effects of global warming on the environment.

Implications

Doubling the CO_2 from its pre-industrial level is about the minimum we will get away with. The resulting global warming will be about 3 – 4 degrees Celsius, having factored in many other changes that are likely to accompany this and that were happening to some extent in any case, such as melting glaciers. Modest rises in sea-level will result, probably no more than 40 cm, which doesn't sound much in this part of the world where we have a tidal range of about 4 m at springs but is significant in many other parts of the world. Global warming won't be the same the world over. Also it won't just be temperatures that are affected because more heat induces more vigorous atmospheric circulation that brings at times more wind and torrential rain, at least in northern latitudes.

Global warming will bring significant climate changes that have a big influence on agriculture. The demographic changes that will result from global warming will be huge, with hundreds of millions of people being unable to live where they now do, because of crop failures, flooding and other secondary factors of climate change. If we don't aim for the doubling of CO_2 levels but carry on as at present, CO_2 levels will inevitable rise even higher, with greater knock-on effects.

Some conclusions about the climate system

1) There is no 'stop button' for global climate change.

2) The world climate at any one time is not a steady balance between a few factors but the result of the intimate interactions of many influences, none of which are intrinsically steady. When one factor changes it doesn't just have an influence by itself but has a strong link to other influences. For example, a 1 K increase in temperature affects ice cover wherever the ice is thin and this in turn influences ground energy absorption, water evaporation, cloud and

precipitation, land use and perhaps even ocean currents, and so on. Changes in these in turn all influence global temperature. The system is sensitive to all these influences, not insensitive to them. As a result, there is no such thing as a steady global climate. The world's climate has always changed. Historical evidence in abundance has shown this.

I'll say the same in a less technical way. There's phrase we're all guilty of using that in almost every context is misleading: '*the balance of nature*'. The natural world isn't a balanced system. Mountains erode, rivers meander, estuaries silt up, coastal cliffs crumble, glaciers extend and recede. Climate is part of the flux of nature. Nothing in our surroundings is balanced. The landscape isn't in balance, the flora aren't in balance, the fauna aren't in balance. Our world is the product of evolution and an evolutionary system isn't balanced. 'The balance of nature' is a mythical concept coined by someone who didn't really know how nature works. There is certainly no balance of nature as far as climate is concerned. Humanity needs to acknowledge the real situation. Climate is just a part of the unity of nature and nature is a process not a steady state. It has taken modern science to put substance to this old idea. One way or another climate change is here to stay. Rhetoric from the green brigade about 'returning to a balanced climate' is mere fiction, as valid as a call to search for the golden fleece or quest for the holy grail.

3) Even if you could magically change CO_2 levels back to their pre-industrial value, you wouldn't change the climate system back again. Glaciers have receded, permafrost has thawed, land-use has changed, oceans have warmed and so on, much as they would have done whether mankind had invented cars, coal and oil-fired power-stations and the like, but more quickly recently. Every year we start from a different place and climate change policy, international politics and economics, have to adapt to change.

4) Mankind has to plan for global climate change. It's not really surprising that the activities of some 7 billion people on Earth will have an input into climate change through industrialisation, through farming, through deforestation, urbanisation and so on. I haven't said much about changing land use but it is a significant driver of climate change. To think that we will have no influence in an ideal world is naïve. Our influence will be added to the factors in a naturally fluctuating scenario. Understanding what that influence is is vitally important. Planning for change is vitally important. Stopping change is impossible.

The global warming sceptic

In politics there is often no right or wrong, just matters of opinion. Groups of differently minded people sit together in parliament and debate the issues of the day hotly. Though each may accuse the other of being in error, many debates boil down to opinion. It is the same in other fields too. There is no right answer as to whether pears are better than apples, or not. Politically motivated global warming sceptics seem to take the same line that whether global warming exists is just a matter of opinion, and my opinion is at least as good as yours. There are of course many political issues associated with global warming but the science behind what is happening is not a matter of opinion, it is a matter of painstaking deduction from observations and understanding. The issue of opinions is an important distinction between the sceptics and science as a whole. Global warming sceptics take a view they wish to defend, whatever it takes. Science actually has no view: its opinions are based on the deductions from observations and the principles underlying the behaviour of the natural world. If the conclusions of science were to come down against global warming as being a real phenomenon, then that would be the opinion of most scientists. The opinions of science are a reflection of the global understanding of the situation, not a particular position that has to be defended at all costs. That said, what arguments do the global warming sceptics bring to the table?

Global warming sceptics have few arguments that cut any ice. They will quote a few famous people who don't believe in global warming, even some meteorologists and environmental scientists. The battle of quotations is one they won't win because for every sceptic quoted one could find a large number of informed scientists who have studied the issues and can make a balanced judgement on the facts, supporting the reality of global warming. The sceptic's implication, or often quite explicit announcement, that there is no scientific consensus about the mechanisms of global warming is just not true. There is. Where there is uncertainty is what the implications are and what should be done. Another tack is to criticise Al Gore's film as summoning weak arguments in favour of global warming and hence conclude that global warming is a myth. The flaw in this line should be obvious. Another line is that it is all a conspiracy by the scientific community to ensure a plentiful supply of research money and to keep themselves in jobs. Would that it was. Another argument asserts that "the majority of the CO_2 in the atmosphere is produced by nature" (which is true) and hence atmospheric CO_2 is not an issue to worry about (false). Yet another CO_2 related argument is that CO_2 changes during past ice-ages when there were big temperature fluctuations followed the temperature changes and didn't drive them. This is true in some instances, the CO_2 changes in these cases arising from the absorption and out-gassing of the cooling and warming oceans. "CO_2 has never driven the climate" concludes the sceptic. Even if it were true, the evidence does not mean that CO_2 concentrations only respond to temperature changes and don't cause them. However, it's not true and in times of intense volcanic activity on Earth in the past, CO_2 levels have driven the climate.

Other sceptical arguments are to make a big issue of the uncertainties in climate model predictions, implying that if the outputs of climate models contain uncertainties, which they do, then they shouldn't be believed. Underlying this approach is a failure to understand the meaning of probability and its implications. Another argument is that if we cannot foretell the future in 50 year's time in respect of world politics, economics and technology, how can we possibly predict world climate in this time let alone in a century or more? Hopefully, by the time you have absorbed the science in this course, you can make a decent repost to this one. There is one argument implied by sceptics, not always explicitly stated by them, which deserves more attention than the arguments above. CO_2 levels over the past two hundred years follow a clearly rising line. If CO_2 really influences global climate significantly, then shouldn't there be a corresponding clear temperature rise over this period? Well there has been a temperature rise but it hasn't followed the simple rising curve of CO_2 concentrations. The reasons why highlight the complexity of the climate issue and why it has taken scientific analysis decades to unravel what is going on.

First, CO_2 levels are only one of many factors influencing global climate, as we've seen. The influence of changing CO_2 levels has not been large enough to stand out clearly over the 19th and 20th centuries. It will be in future. The whole gamut of other causes including changing land use, snow cover, cloud cover, atmospheric aerosols, etc. have all had their influence. These influences weren't even naturally steady on their own before CO_2 levels began to change and their own changes embody their intrinsic changes plus their responsive changes to the CO_2 rise. This complexity is the very reason that we need good computer modelling to work out what is happening and what will happen. Today's computer models agree to high probability that the CO_2 influence in the 21st century will be clear by 2030 at the latest and they also agree that the CO_2 signal would not have been clear in the 20th century. One of the entangled issues is the time it takes for the global system to respond to changing influences. While the forcing effect of CO_2 change is almost immediate the response of the whole climate system is not. Glaciers and snowfields take decades to melt significantly; oceans take decades to warm so that the resulting changes in evaporation, cloud cover and precipitation influence climate and average temperatures. Anyone who expects a clear CO_2 signal from past changes hasn't understood the complexity of the atmospheric/ocean/land system in determining climate. This applies to the future as well. If global temperatures cool in a few years' time that doesn't mean we've cracked the problem or even that we're winning. Don't forget about 'natural variations' that on a short timescale may be larger than trend changes.

Even the *New Scientist* can write stuff like "Temperature rises caused by greenhouse gas emissions are expected to trigger dangerous feedback loops". It's necessary to say that there are no special temperatures in climate models where effects spring into action. All the feedback mechanisms such as the influence of snow, cloud, aerosols, etc. mentioned above are present all the time. Indeed, it's even hardly fair to label them simply as 'feedback mechanisms', implying that they just influence climate in response to CO_2 changes, because these factors influence climate on their own, quite independently of whether CO_2 levels are changing or not. One can think of future possible catastrophes, like huge fires in sub-tropical forests that are suffering drought induced by climate change but these aren't a necessary consequence of climate change. Alternatively, the phrase "tipping point" is used with gay abandon. The *New Scientist* seems particularly wedded to it. It's journalese, a phrase used to imply alarm. The analogy is supposed to be with a balance that moves uncontrollably out of equilibrium with no counteracting effect when the weight on one side is increased. The climate system wasn't in balance yesterday or today and won't be tomorrow. There is, in effect, no balance to tip. The world's climate will be influenced tomorrow by exactly the same effects that influenced it yesterday and are influencing it today. They may have different relative values, but that's a matter of detail. You can re-zero a balance by taking the excess weight from one side but you won't reset the world's climate by restoring CO_2 levels to their pre-industrial values, for example, even if that were possible. Climate change is a one-way process in which local changes can take place rapidly, which is not the same as 'tipping'. I see the phrase 'tipping point' as an attempt to add emotional weight to an argument, which immediately makes me suspicious.

Levels of CO_2 have risen from around 300 ppm to around 400 ppm in round figures. You might have expected the raw influence of CO_2 to have increased by one third but even the raw influence has increased by less. Let me explain why by analogy. Suppose you have two grey filters that each cut down the light getting through them by a half. Now put one behind the other. Does each absorb half the light so you get nothing through? No. The second absorbs only half the light that reaches it, namely a half of a half, which is a quarter. So three-quarters of the light is absorbed by the two filters and one quarter gets through. The second filter is therefore less effective even though it is the same thickness as the first. The same happens with CO_2, which is back-scattering IR to the ground. If CO_2 levels double, then the greenhouse effect of CO_2 less than doubles. Actually, the working of the greenhouse effect isn't in detail the same as filtering. With more CO_2 the amount of IR escaping into space doesn't change but the surface temperature does increase, as discussed in the supplementary piece *New light on global warming*. Overall, though, the radiative forcing of CO_2, which determines the surface temperature, does change logarithmically with the CO_2 concentration. This reduced sensitivity works in mankind's favour but it doesn't give much comfort to the sceptics because a doubling of concentration still has a marked effect. How much? That's what climate modelling is all about, with due allowance being made for all the necessary accompanying changes. The answer is about 3° C. It does help to explain why the CO_2 signal in global warming is hidden by other effects when the CO_2 changes are not large.

One place where the sceptics are on stronger ground is to challenge the received wisdom of the impact that global warming will have. It's very difficult to separate out the possible effects of global warming from other de-stabilising effects on societies that are endemic in some parts of the world, such as exponential population expansion, food shortages, water shortages, persistent conflict and prolonged drought, much of which is a consequence of current climate. I'm not knocking the principle of scepticism. It's right that people should ask for good evidence and not accept the first thing that anyone says, whatever the reputation of the orator. However, when the facts become clear, as I believe they have become in recent years, then contrary opinions should change, and simply repeating the 'I don't believe it' mantra while the ice you're standing on is melting isn't convincing. Mankind can't afford to wait until global warming of a few degrees Celsius is history before starting to do anything but we have to act on the balance of probabilities well before then. The balance of probabilities is now with the camp that says global warming is being significantly affected by mankind's CO_2 output. It will take decades to put in place the necessary changes to mitigate global warming and its effects. I'll say a bit about this in the next sections and also in a supplementary note that you can access from the blue panel on the left of our meteorology web page.

Perhaps this is the right place to re-iterate a much earlier point, namely that global warming was taking place long before the modern era began. Those who deny the link between mankind's CO_2 output and global warming seem to think that the denial is sufficient reason not to implement responsive social policies to global warming. Even if their conclusions about CO_2 were right, their proposed inaction is completely wrong.

I don't know whether living in big cities de-sensitises one to natural changes but more and more people do live there and in big cities life tends to go on much the same in spite of all but the most dramatic natural changes. Such change in city life as does occur is planned. Unplanned becomes synonymous with 'unacceptable' or 'unthinkable'. I'm almost waiting for the tabloid headline 'Fury as leaves fall from trees in autumn'. It's not in the city ordinances. The concept that climate in every part of the world is changeable due to natural causes over a timescale of centuries and even decades can become unthinkable. The historical record says otherwise. The insularity of city life is an illusion. Climate is controlled by global forces and global phenomena and climate change is not a disaster due to human blundering but an intrinsic part of the package. The only blundering involved is the failure to recognise what is going on and respond adequately and sensibly. I've added this paragraph as another point worth debating.

I maybe shouldn't say in a course about science that the global warming sceptic may attempt to argue his or her case but I suspect that many are not really interested in the arguments, in weighing the evidence. They believe because their friends and others they respect believe and they don't want to argue with either group or upset them. Perhaps their personal interests or even their job depends on maintaining the status quo. They don't really want to study the science. You probably stand a better chance of persuading them to change the newspaper they buy than getting them to change their stance. If it were just a matter of private belief it wouldn't be so bad but when those with political and industrial clout ignore the science it doesn't help any of us. Unfortunately for them, and us, the gist of the science is right and that's not a judgement about two equally valid points of view. I rather like the sentence used recently by a *National Geographic* journalist: "young people have got the message – should they tell their parents?".

[*Very long-term CO_2 and temperature changes*

I'll add another section here that isn't likely to be touched on in the lectures, for those who might wish to pursue the global warming issue beyond this course. The current set of ice ages (the Quaternary ice-ages) began about 2.5 million years ago, though there was some glaciation during the preceding 30 million years. For well over 200 million years prior to that, since the end of the Permian era, the world had no permanent ice sheets, it was a lot warmer than it now is and CO_2 levels generally exceeded 1000 ppm. During this time life flourished in the sea, on land and in the air, as the fossil record fully testifies. Prior to this there was an extensive period of glaciation during the Carboniferous and Permian eras, when CO_2 levels were lower. Even earlier there were two other extensive periods of glaciation. If you want to see how bad it got then look into the Sturtian glaciation in the Cryogenian period about 716 million years ago. Geologists generally accept that ice over a km thick covered even equatorial seas, with temperatures of -50° C commonplace. Snowball Earth. This glacial period lasted over 50 million years. It sounds bad. It was bad but no multi-celled life existed at that time. In spite of such interludes, glaciation has been a feature of the Earth's history for less than 15% of its existence.

How do we know this? First, glaciation leaves its marks on rocks in many ways. Secondly, there are a variety of geological methods that can be used to take the CO_2 record back for hundreds of millions of years, at least in fairly broad brush. They involve examining fossil soils, fossil shells, fossil leaves and modelling long term geological processes of volcanism (which increases CO_2 levels) and weathering (that decreases CO_2 levels) and continental plate subduction that feeds carboniferous rocks into the volcanic system. At the other end of the scale there was the Palaeocene-Eocene thermal maximum some 56 million years ago. The Arctic Ocean was over 20° C; animals like hippos and crocodiles wallowed in the lush rivers of Greenland and Antarctica. Some of these parts of the world were 40° - 50° C warmer than they are now, though that wasn't typical of the world as a whole. The Palaeocene-Eocene thermal maximum was geologically short-lived but the broad take-home message from geology is that we are living on a planet that for much of the time it has supported life as we know it has been warmer than it now is, with higher CO_2 levels. People now lose sleep over the prospect of a 3° C temperature rise from pre-industrial levels but the Earth has experienced very much worse in the past. Of course mankind wasn't around for almost all of this time but we should know the kind of place that we've sprung to life on. The sheer scale and energy involved in natural processes suggests (to me at least) that in the long-term mankind will have to adapt to the Earth, rather than the other way around.]

Is a three degree change really relevant?

So what difference does three degrees Celsius make in any case? The average temperature in the South of England is about three degrees warmer than it is here in Aberdeen. The flowers and shrubs in South of England gardens are a bit more diverse and luxuriant on average than they are here, the summer season a bit longer but by and large life goes on much the same here as it does 800 km to the south. Should we be concerned about a three degree temperature rise?

Well, here are some points to consider. There is much more to climate than average temperature: rainfall, wind patterns, sunshine and temperature extremes are among the other factors. Three degree warming isn't just the same climate but three degrees warmer, it's a different climate regime. Many plant and some animal species thrive in quite a narrow range of climate conditions and hence, it is argued, changing climate in one place reduces bio-diversity. Personally I don't weigh this particular argument very strongly. Most of the garden plants, crops and forests in the South of England have been planted by mankind as suitable for the climate of the last half century. A change in climate will bring in some change of flora and fauna but species will move, either naturally or by deliberate relocation. All plants and most animals produce far more offspring with variant characteristics than *homo sapiens* and hence are potentially more adaptable in this respect than we are. The underlying issue is one of time.

The present background ecosystem has adapted to changing conditions in the past, such as the changes that came with the 'little ice age', but are the changes in the 21st century going to be faster than many species can adapt to? In a changing situation there are always winners and losers; it's part of the grand scenario of evolution. What is now different is that mankind has its hand on the tiller.

In Britain we have already modified most of the landscape to create today's society. Perhaps we haven't been over conscious that today's housing stock, communications, transport links and other infra-structure has been influenced by climate but it certainly has. A steady rise in temperature of a few degrees on its own may change the local balance of vegetation here and anywhere in the world but this isn't the main issue for most societies and it's not what's 'on offer'. The concern is largely with the events that make life difficult, the extreme events associated with the accompanying climate change. We may have to plan for more swollen rivers in winter or more extended hot, dry summers but in truth, global warming isn't going to make Britain uninhabitable. Extreme events will have a big local impact where societies are living in conditions that are hardly sustainable should the wrong kind of climate change come about. Unfortunately, the wrong kind of change is predicted for many inhabited places.

What are the wrong kinds of change? Think of droughts where there is now only marginal rainfall; a change in rainfall pattern that is unsuitable for staple crops; excessive rainfall where existing flooding is already stretching containment to the limit; stronger and more frequent hurricanes where the housing stock and infra-structure can barely cope with the existing hurricane season; sea-surges of several metres where coastal habitation is near or below sea-level. History is littered with case studies that illustrate the stark reality of the three options available in such circumstances: move, adapt or perish. The responsibility of the meteorologist is to point out that although weather has a degree of randomness, climate change has a degree of predictability if adequate resources are invested in the issue. The best estimates of what will happen to future climates are steadily improving. The response that we've survived being unable to predict future climate in times past and we don't believe the predictions now is no longer adequate. It's also not true. We have survived, for we're still here, but many past civilisations have not survived the impacts of past climate changes.

Appendix on future change

Most of this section is personal comment on the situation and not 'meteorology' as such. I have expanded this comment into a summary of '*mitigation of climate change*' on the course web page.

To achieve a mere doubling of CO_2 from pre-industrial levels means a huge cut in CO_2 emissions because present practices are adding CO_2 every year. We need to stop adding too much more. We burn fossil fuel to create energy for transport, for heat, for electricity. The only way forward is to invest heavily in **alternative energy**.

A reduction of our dependence on burning fossils fuels will require a huge investment in alternative energy sources. Investment in new infra-structure in society needs to be made in such developments as hydrogen distribution and supply for fuel-cell powered transport, electrical generation from wind, wave, tidal and nuclear options, much higher building standards for housing stock so we don't need to use so much energy in the first place, solar power sources developed at economic prices and so on. Nuclear power is the only high-density alternative energy. Cracking the problem of the disposal of nuclear waste should not be beyond mankind. Only the very largest bodies can provide the development resources necessary in most of these areas and drive the legislation required. The largest bodies are simply governments and multi-nationals. We as individuals need to be prepared to support the changes and pay for them. It won't be cheap. We need to get rid of the ethos that the best government is the one that will tax us the least, the best product is the cheapest product that does the job just now.

We as individuals need to be prepared to invest for the future. Our predecessors have invested in the infrastructure necessary to bring sewerage to every house, running water to every house, electricity to every house, tarmac roads, street lighting in towns, rubbish collection, telephones, communications and a raft of infra-structure we now take for granted. It has taken decades, over a century in many cases, and cost billions but our predecessors in paying were investing in their future, our present. If we want to curtail CO_2 in the atmosphere, and we do, we have to expand that investment into carbon free energy sources, not think we are making progress by tinkering at the edges of the problem by sharing cars and turning down thermostats. Global problems need global solutions. Of course I'm not against sharing transport as a buy-in to commitment to do something but it isn't going to make a significant impact on future global warming.

Proponents for action do some harm to the cause by citing worst case scenarios to raise media headlines or scare people. 'Message enhancement' seems to be the phrase that describes this approach but, like quite a lot of propaganda, the technique is counter-productive. Yes, if the entire Greenland ice-sheet melts, sea levels may rise by 7 m or so. That's scary but it's unrealistic to plan at the beginning of the 21st century for such an eventuality. Message enhancement is unnecessary. We should point ourselves in a sensible direction and plan on a timescale of several decades, which is probably ten times longer than most current planning, and leave responding to more distant and uncertain threats to future circumstances. In other words, tell the story like it is, aim for the achievable, put our energies into tackling issues we have some hope of doing something about and don't expect that this generation of politicians, industrial leaders and ordinary people like us are going to solve all the issues. We won't.

I'm tempted to add a comment here that follows from my remarks on the difference between climate and weather mentioned at the very beginning of this chapter. I pointed out that even in principle one can't attribute individual storms, flooding events or droughts to climate change. Climate change needs a sustained sequence of such events to become evident. Spurious attribution doesn't help people either. For example, minimising flooding of towns and cities from heavy and sustained rainfall needs relatively local action such as clearing drainage channels, reinforcing barriers or managing flood plains so they spread water predictably. Mitigating climate change is a matter of quite different long-term, global responses. There's also a public misunderstanding about the occurrence of random events. If a once-in-a-century event happens this year, it doesn't mean it won't happen again for another century. It's just as likely to happen next year as it was this year, without climate change. See the blue panel piece 'On randomness' on the course web page. At best it's fair to say that with global warming severe storms, exceptional flooding and at times unusually long hot spells are more likely than they were in the past. This should be a take-home message to politicians.

Hopefully, this chapter has convinced you that genuine evidence shows the climate is changing. There will be a great many research and development jobs in the next few decades both in global warming science and, in particular, the impact of global warming consequences, from the development of alternative energies and new infra-structure to coping with the consequences of climate change. It seems to me that from a parochial viewpoint it's a 'no brainer' that the UK should put much more effort than it's now doing into alternative energy technologies, both for our own future and in order to sell the expertise and products developed on the world market. What is also certain is that global warming isn't all about science. It's even more about politics, legislation, economics, changes in the way we do things and our expectations in society. We're at the dawn of a challenging era.

Finally, what response should we make as individuals? It's not for me to tell you what to do but I'll tell you my view at the moment. My view is that personal sacrifices, like depriving yourself of that holiday abroad because the transport will generate CO_2 emissions, are not going to make any significant impact on long term global warming. Turning off the stand-by function on your TV or sound centre is about as effective as putting small change into a jar in order to save for your old age. Yes, it will make a contribution but so tiny that it's not an effective solution to the problem. If the action lulls you into thinking you're solving the problem, it may be worse than doing nothing.

I'll put it another, if slightly depressing, way. Saving CO_2 emissions by, for example, not flying somewhere isn't going to stop mankind using the fuel, even if the entire plane is grounded. It may cut back on fuel use this year but the crude oil that might have supplied that fuel isn't going to stay in the ground for ever as a result of your decision. Mankind is going to extract it. It will just be a bit later rather than sooner. So your actions won't prevent that oil being used. It's true that the most effective form of carbon sequestration is to leave the stuff underground where it's sitting in the first place but alternative energy generating capacity and infrastructure isn't coming on-stream quick enough to do this, and it doesn't look as if it will unless there are major world policy shifts. The inevitable consequence is that all the fossil fuel resources of the Earth will be used in due course, in fact most of them before the end of this century, and so we have to plan for the resulting CO_2 being released. To see how much that will be, see the notes called 'the numbers game' in the blue panel of our main met web page. In short, there is absolutely no alternative to promoting alternative energy generation, for the simple and irrefutable reason that fossil fuels will run out. If you look at the figures in 'the numbers game', you'll see that this will be much sooner than you would have wished for. Perhaps it's a consolation that even if we wanted to, we can't keep using fossil fuel for a long time at the same rate we are using it now. It's a message that hasn't got through to a lot of influential people.

The Copenhagen summit meeting in December 2009 concentrated on CO_2 reduction targets. Not a lot was achieved. My own view is that this is putting the cart before the horse. Society needs to invest in alternative energy provision as the top priority, which in effect means you and I paying for it through taxes that fund developments and incentive schemes, through company profits being ploughed back to research, development, investing in alternative energy even though it's not the cheapest and reducing the payout to shareholders; through higher electricity costs while the technology is being developed; through acceptance of alternative electrical generation in the landscape, etc. I came to Aberdeen by train today, a distance of some 200 km, and didn't see a single wind turbine in the whole journey. I saw tens of thousands of houses, all using electricity. Where do people think the electricity will come from in future? It won't all come from wind but when we have alternative energy, decarbonising will be comparatively easy. Updating these notes in 2012, I can add that some sizeable wind turbines are now visible on the journey from Edinburgh to Aberdeen – progress, if only a little. The facts of the case are that Scotland is one of the windiest countries in Europe. In decades' time, most of our energy will be delivered electrically. If we intend to participate in civilisation then we shall need to generate electricity on a substantial scale and for reasons of independence, standing on our own feet, making good what we have and just common sense then wind turbines are going to be part of the landscape of the future. We'd better get used to them and turn them into positive symbols. This isn't a carte-blanche argument for putting them up anywhere but unless the dark ages are thrust upon us again, Scotland will have more wind turbines than Holland had windmills. We should see them as symbols of self-sufficiency, modernisation, part of our contribution to the new world order. I say this as someone who has enjoyed the unrivalled Scottish landscape for decades with only the occasional, derelict, wind-powered field water pump in sight; in future I'll enjoy the unrivalled Scottish landscape with wind turbines. My guess is that those born in mid-21st century and later will hardly notice them because "they've always been there".

The Durban December 2011 Summit meeting indirectly supported the words I'd written above. The *New Scientist* wondered if the meeting "confirmed that climate diplomats have finally lost touch with scientific reality". Its broad result was that participants agreed that by 2015 they would set legally binding targets that would come into force by 2020. At least Emperor Nero was enjoying himself fiddling while Rome burned but there is no indication the politicians are even enjoying themselves. However, as the *New Scientist* also pointed out, there is a huge rise in the development of alternative energy technologies, driven in the main by long-term profit motives or military self-sufficiency, not particularly by altruism. Whatever the driving forces, putting in place alternative energy technologies does seem to be the logical step to reducing carbon emissions, not trucking box-loads of legal documents to international courts. As a rolling update of these notes, I'll add that the 2013 Polish 'Summit' continued the theme of damp squib meetings. The President of the next meeting of the UN Framework Convention on Climate Change, to give the august body its proper name, said in December 2014 "*here in Lima, governments have left with a far clearer vision of what the draft Paris agreement will look like as we head into 2015 and the next round of negotiations in Geneva.*" The phrase 'leading from the rear' comes to mind. December 2015 has come and gone. The Paris agreement there signed by 195 nations was hailed as 'historic' – for 195 nations to agree on anything is pretty historic – but informed commentary suggests that it's strong on goals and aspirations but short on specifying action that will achieve the goals. The agreement and publicity, though, has got many more people pulling their heads out of the sand and realising that a carbon-based energy future is unsustainable. The rolling updates continue to roll without much to show. The Katowice Climate Change Conference in December 2018 basically secured the agreement of 194 counties to uphold the promises of the Paris agreement. Two UN led meetings in 2019 elicited pledges from some participants to do something in the future. If anyone ever had any doubt that the rich, powerful and short-sighted hold the reins of political power then climate change inaction should be evidence enough.

It doesn't seem that long ago to me – it was the late 1990s – that the year 2020 seemed well in the future and the need for results by 2020 was an easy target. 2020 is here now, very little of political significance has happened in 20 years and 'it will be all right on the night' seems to have been the unspoken attitude, clearly missing the fact that it will only be alright on the night if all the preparation has been done. 2020 now looks like a target for the start of big changes rather than a date where their impact should be conspicuous.

There is a very real issue that society has embraced change in the past because change has brought improvement. That's happened not just in our lifetimes but for thousands of years.

Now we're being asked to embrace change for no obvious improvement, in fact in countries like the UK we're being asked to make huge investments just to maintain what we already have. For example, the majority of families in the UK own a car. We'd like to own a car in 40 years time but it will most likely be an electric car, powered by fuel cell or lithium battery or some other technology. None of these options have been adequately developed yet. We like travelling abroad, perhaps on holiday or to see family or participate in international research or business but if we are to do that in 40 years time the kerosene will need to come from biofuel, and land suitable for growing food will need to be dedicated to biofuel production in one way or another. 'Everyone' complains of rising electricity bills but in fact in spite of using electricity for lighting, entertainment, domestic chores, some heating, maybe some gardening and perhaps cooking, the quarterly electricity bill is only a few percent of family income. If we want equally cheap electricity in 40 years time we need to invest in sustainable generation. People are wary of being asked to change just to keep what they already have but that is the new reality.

[At the risk of producing a fine example of bathos, I'm tempted to insert here three controversial paragraphs about light bulbs that I wrote about the year 2000. "Nowadays you can't find a 100 W bayonet-fitting filament bulb in the shops in this part of the world, of the kind that any decent-sized room would have used in its ceiling lamp. I think you can still buy 40 W versions but economising on light is bad for your eyes and hopeless for reading small print. Is this forced energy saving? If so it's misdirected. I'm told I should fit a 100 W equivalent energy-saving (fluorescent) bulb in place of the old 100 W filament bulb. They are poor products: large, quite expensive, usually terrible looking, can take minutes to come to full power especially when they are not new and don't seem to last as long as they claim to. I shan't even go into the comparative resource they take to make or what should be done with the mercury that's still in them when they do expire. I'm not completely against them, for we have quite a few at home in places where the light can be left on, such as in the corridor. The reply to the criticism that they take minutes to warm up is that they should be left on if you're likely to come back to the room within 15 minutes. Well, maybe I'll come back, maybe I won't so lights get left on in rooms where no-one is present, eating up some of the power saving. (Updating these notes in 2016, I'll add that LED technology light bulbs are a different matter altogether. They produce full light immediately, even more light for the same power and should have lifetimes of many tens of thousands of hours. I expect them to replace 'energy-saving' fluorescent bulbs in due course but my original criticism below still applies).

My main gripe against energy-saving bulbs is that they will actually save no energy. The light from a light bulb is free. All the energy ends up heating the room. From a 100 W filament bulb you get 100 W of heat, nothing less. On the way to heating the room you get about 5 W of light that is turned into heat when it is absorbed by the contents of the room. If you reduce this source of heat, say by replacing three 100 W filament bulbs by three 20 W 'energy saving' bulbs, then if the room is to stay at the same temperature your room heater has to make good this 240 W of lost heat input. So the central heating works a bit harder. The same is true for other rooms in your house. No-one seems to count this into the energy balance equation and that's bad science. Worse, in a way, the central heating from gas or oil generates CO_2 while producing this 240 W (and more when you've added in other rooms) at least some of the electricity that the light bulb uses is generated from renewable sources. The light bulb generates the heat when it's dark and, by and large, outside temperatures are cool and the heat is needed. So it's heat at the right time in the right place that's increasingly coming from renewable resources. People who strongly support 'energy saving' bulbs have to agree that no energy is actually saved. They counter by saying that generating heat using electricity from a non-renewable fired power station is a 'no-no' and indeed the heat is better generated on-site by one's own central heating system. This isn't necessarily true because central heating is a pretty blunt instrument with quite crude thermostatic control that has to heat or reheat all the water in the system every time it fires up. Electricity is a sharp instrument providing localised heat in the room where you are. In short, I'd say that on the whole energy-saving bulbs are not a worthwhile contribution to the reduced carbon economy, never minding the issue of the resources it takes to make them. Please, policy-makers and manufacturers, can I have my 100-watt filament light bulbs back again? I'm sure the answer is 'no'! When the central heating oil and gas runs out we'll all be heating our houses with special electrical heating lamps – combined light and power, and they won't be as feeble as 100 W.

I've been slightly provocative. Maybe you don't agree with what I've just written. I was told some time ago that the use of filament bulbs in Australia is now banned. Is this an example of bandwagon legislation by the poorly informed, or is it so hot in Australia that most people never have to heat their house? My only personal experience of Australia is a few hours spent in Brisbane and Sydney airports in transit but I was told the other day by an Australian that actually most Australians don't have house heating, because cooling is a higher priority than heating. This hasn't stopped our own legislators following the Australian example. In fact to update the comments above, the manufacture and import of 100 W filament bulbs became illegal in Europe in September 2009 and even selling standard 60 W bulbs was made illegal in 2011. In my view this is legislation worthy of an episode of 'The Simpsons', a sad example of how not to respond to the issue of global warming, namely pushing forward ill-conceived legislation based on a poor analysis of the situation that will make a negligible contribution to the issue and create unnecessary inconvenience in the process. I'd be surprised if we didn't see more of this kind of thing in the coming years. The root cause of the trouble surely lies in the name 'light bulb'. It's true that we buy them to produce light and they're bulb shaped but they're really glowing heat bulbs. 'Glowing heat bulb' is hardly a marketing man's dream name but saddled with a misleading name they are now the poster pin-up of what was allegedly wrong with old technology. To put a glowing heat bulb in a street lamp is clearly silly, for outside in the open air we want light without heat, so there's plenty of demand for hi-tech efficient lights without the need to vilify the incandescent light bulb. As hinted above, my prediction is that 'glowing heat bulbs' will return as a domestic and industrial light source of the future, electrically generated heat with free light thrown in – an electric fire that illuminates the room for nothing. Electric heaters that do nothing other than heat a room are surely the future targets for reducing the inefficient use of power. Don't we want a range of heaters that are large TVs, powerful computers, tech that can make tea, refrigerate provisions, cook food and provide many other services 'for free' on the way to heating a room? Heat is the ultimate commodity produced by all electrical goods. Generating heat along with light is not the real problem. The real problem is keeping heat within a house and not radiating it uselessly into the surroundings. That's an issue worthy of research, development and legislation. Raise your points in the class and other related issues will likely come to light."]

Returning to the main more serious theme, weather may be a local, almost personal, experience but climate is a global issue. Climate is no respecter of nationalism, military power, economic interests or religious sensitivity. Millions of people, perhaps billions, now see the need for change but who is going to drive the changes needed? Who is going to manage the planet-wide issues involved? It's my belief that the main power of the people will be in steering governments and industry in the right direction. I personally think that the biggest drivers of change will have to be governments, government bodies and international bodies answering to governments. It was encouraging that the UK Government had a Department of Energy and Climate Change (DECC), at least it did at the time of writing this, but Tory Prime Minister Theresa May abolished it soon after taking office. "Plain stupid" was the widespread criticism.

It does highlight the issue that any plan that assumes Government is staffed with far-sighted individuals who can steer the country in the right direction is doomed to failure. A better starting point is to assume the Government is stuck in the mud and needs the push of millions of citizens to get it moving. That means several million voting citizens must buy into the need for climate change action and mitigation at a personal level. As I update these notes in 2020, this now seems to be happening. Big industry needs to be on-board but the timescale of change of the magnitude needed is measured in decades and big industry operates on a shorter timescale; its main remit is to look after itself, not steer society, and even big industry hasn't got the hundreds of billions to invest with no commercial return that will be necessary to change the infrastructure of society away from our present carbon-based economy. Moreover, it is only governments who can introduce the legislation required, set national goals, impose taxation incentives and penalties and, through local government involvement, control planning. This brings me back to the point I made above, namely that 'zero-cost' initiatives such as reducing the heating in your house, turning off lights when you're not in a room, sharing your bath with your partner, etc. may make you feel involved but in fact they aren't going to contribute much to the solution or the changes required. They will, though, through personal involvement in the process likely get you voting for the political party offering timely and sensible policies on climate change legislation.

My conclusion? Mankind needs to put in place plans to both cope with global warming ('adaptation') and to mitigate it. The focus these days on CO_2 emissions leads people to forget that there are a range of natural climate drivers as well. Cutting CO_2 emissions from what they could be if we didn't do anything at all may reduce global warming but won't stop it in the lifetime of anyone alive today. As it's sometimes put, the climate system has a lot of 'unrealised warming' in it that's still to come from the continuing effects of the changes already present, even if we don't increase our CO_2 emissions at all. It's necessary to put substantial effort into coping with the results of global warming as well as effort into building reduced carbon economies. It's very fortunate that many of the mitigation options are the same ones as we need to put in place because fossil fuels will be depleted this century. Since this section of these notes has included a fair dose of my personal opinion (for you to debate), I'll end up by saying that if I were in charge of world policy I'd make the first item on the agenda to leave as much of the stuff in the ground as possible and put the development of alternative energy sources and devices, and all that these imply, as the number one issue, followed closely by planning to cope with the effects of the global warming that is already on the way. Not mining coal, oil and natural gas is the best form of carbon sequestration of all. I did say above that simply reducing consumption won't make this happen and unfortunately if I had to bet on any result it would be that mankind will in fact use up all the available resource. On the positive side, industrialists are realising along with many other people that it doesn't matter whether you believe in global warming or not, green technologies are the only sustainable ones in the long term and new technology and new ways of doing things means business, and business sustains national economies. This doesn't mean we should believe everything the green lobby says, for they are just as capable of over-simplifying, exaggerating and misleading as any vested interest. The often implied over-simplification that cars and planes are 'bad' and bicycles are 'good' is one example. Whatever scenario does pan out, the changes in our lifestyles will greatly affect everyone and change the shape of society. I'm not sure if David Attenborough was right to say global warming is the 'greatest problem facing mankind' but it's certainly an issue that's likely to have the biggest impact on our personal futures.

[*Final* d*igression:* In recent years there has been a distinct rise in the number of people passionate about the adverse effects of global warming, some with the fervour of a preacher believing that the congregation is about to be cast into the flames of hell unless they follow his message. The basic situation is much more complicated than that. The implication that global warming is bad for the Earth and needs to be prevented at all costs is a topic you can discuss at leisure over a drink. You have to admit that huge areas of ice over Europe, Asia and North America have melted in the past 20,000 years. Sea levels have risen by around 100 metres from their lowest level, flooding land such as the bridge between Britain and mainland Europe. Another 5 to 10 m rise while the last of the ice melts is just the natural continuation of a global process begun thousands of years ago. Overall this de-glaciation has been ‘a good thing’, creating millions of square km of habitable land (Scotland included!). One hears a lot about curtailment of bio-diversity with global warming but the bio-diversity in places like Scotland has increased enormously as a consequence of the warming of the past 20 millennia. Were the process to reverse it would be deemed a global catastrophe. Why stop the melting now? Is it good for the Earth to have an entire continent coated in a thick ice sheet, not to mention some 2 million km^2 of Greenland and large parts of Northern Canada and Siberia? That’s a lot of otherwise habitable Earth. Put it another way. If these areas were all inhabited in a thousand years’ time and some world body came along and said “we’re going to use up half the CO_2 in the atmosphere and I’m sorry that most of the Earth above 60° N and below 60° S will be uninhabitably frozen as a result”, then it would never be allowed. Why do we condone it now? This is not a complete fantasy scenario. In fact, as mentioned earlier, for most of the Earth’s existence, the average temperature of the Earth has been higher than it now is and there have been no polar icecaps at all. Thought for the day!

On a much shorter timescale, the warming over the last couple of decades for countries like Scotland has decreased building heating bills, increased the growing season by over a week, increased ground water supply for farming and hydropower, decreased the disruption caused by snowfall, increased sunshine hours – all useful gains. The reality is that even if a warmer Earth was in principle better, the transition from the present state of affairs to the new state would be traumatic and would most likely destabilise societies around the world. Another thought is: what is the ideal average temperature of the Earth that will maximise the use of the Earth for mankind? Is that the same temperature as would benefit the greatest number of living species? The answers certainly depend on what we will use the Earth for but I don’t know the answer in any scenario. I did say that this was a discussion to be had with a drink in hand! Don’t throw it over your companions if they disagree with you.]

JSR