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Introduction: energy for a sustainable future

By David A. King

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I published a paper in *Science* (King 2004) a couple of years ago in which I said that 'climate change was the biggest challenge facing us this century, bigger even than the threat of global terrorism'. An outcome of all of this was the decision by the Prime Minister that, during the UK's presidency of the G8, we would place climate change at the top of the agenda, alongside Africa. These two are of course interconnected. In the run-up to our G8 presidency in 2005, the Prime Minister asked for a meeting to be held here in Britain to bring together the scientific community from around the world, so that the year of his presidency could be informed by the current state of the science. At that meeting, the situation emerged to be rather more complex and more threatening than we had understood from the previous report from the Inter-Governmental Panel on Climate Change (IPCC).

I will begin with an overview of the science and then discuss UK Government policy and international action.

Figure 1 illustrates a picture that originated in the work by the French mathematician, Jean Josef Fourier, in 1827. Fourier is really saying 'I should be able to calculate the average temperature of the Earth's surface, because I know that it's heated up by sunlight, that yellow stuff coming in from the left, and I know it's cooled down by radiation going back into space, and all I have to do is equilibrate these two, and I know that the radiation going back into space is a very sensitive function of the surface temperature'. Hence he calculated the average temperature of the Earth's surface, but the answer he obtained was approximately 30°C too low. He also surmised what would happen if we turn off the incoming Sun's rays, namely that there would be a vast amount of heat going back out into space, and so the surface of the Earth should cool very rapidly over a 10 h period. This is a typical night-time period, and he calculated that the temperature would cool by perhaps another 15 or 20°C. Hence, two parts of his calculation were wrong: both the absolute temperature he calculated and also the difference between night- and daytime temperatures, and so Fourier concluded that he would have to bring in another factor, and it was the blue stuff across the background of the figure, namely the atmosphere. This is Fourier really bringing in a fudge factor because he did not know how much of that radiated heat was absorbed by the atmosphere; he put in a value for this coefficient which gave him the right number of approximately 15°C.

One contribution of 13 to a Discussion Meeting Issue 'Energy for the future'.

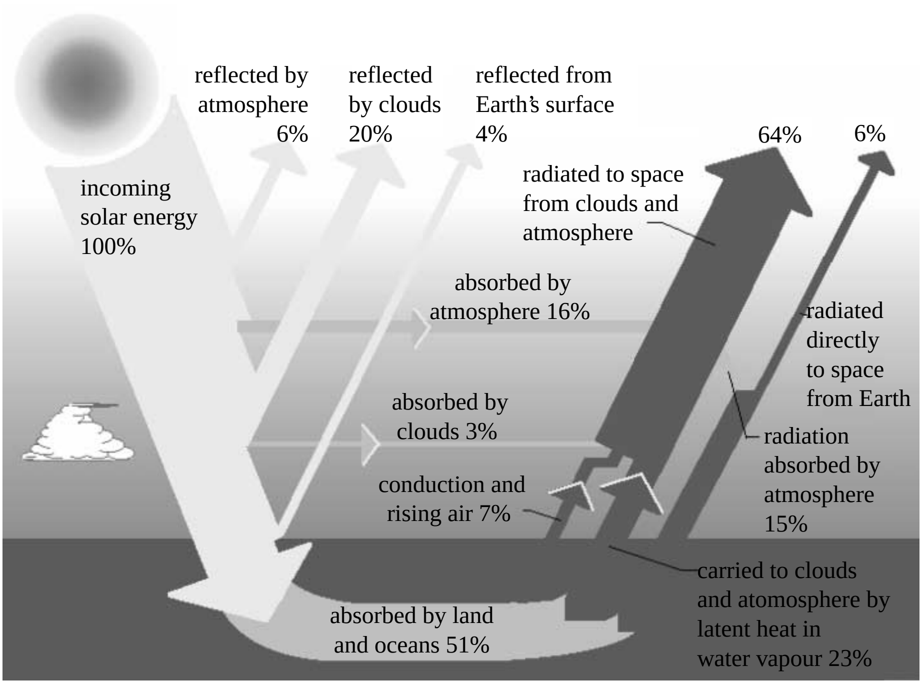

Figure 1. Illustration of incident sunlight and reflected radiation at the Earth's surface. Source: NASA.

Later that century, a British scientist, John Tyndall, a Fellow of the Royal Society, comes along and says, ‘Oh I can actually do an experiment to see what that absorption is of that infrared heat radiated out from a hot body’, and so he sets up a cylinder, and being a careful scientist, he first of all clears up the air in the cylinder, and in so doing takes out all the carbon dioxide and water vapour, and he finds that there is no energy absorbed by the atmosphere, so Fourier's coefficient apparently is zero. Now, of course this was a very important discovery: using his purified atmosphere, he obtained a value for Fourier's coefficient that is very close to zero and concluded, critically, that it is the minority gases in the atmosphere which are absorbing the infrared radiation. Indeed, with these gases present, he was able to reproduce Fourier's assumed coefficient. We now know that homonuclear diatomic molecules such as nitrogen and oxygen (which make up nearly 100% of the atmosphere) do not absorb infrared radiation. But carbon dioxide and water molecules and indeed methane (another gas we should be concerned with) do absorb infrared radiation, and these provide Fourier's greenhouse effect. Hence, we now have a fairly complete understanding by 1860.

In 1896, we come to the Nobel Prize winner Svante Arrhenius. He pointed out that by burning fossil fuels we are increasing the level of one of those greenhouse gases quite substantially, namely carbon dioxide. He put up the suggestion, which was fantastic at the time, that we might even double the amount of carbon dioxide in the atmosphere, saying ‘and I can use Fourier's equations and Tyndall's coefficient now to calculate what would happen to the surface temperature…’ and he found a temperature rise of approximately 5°C.

In the century which has elapsed since then, a lot of detail has been worked on. Clouds and the aerosols provide a massive complication for any

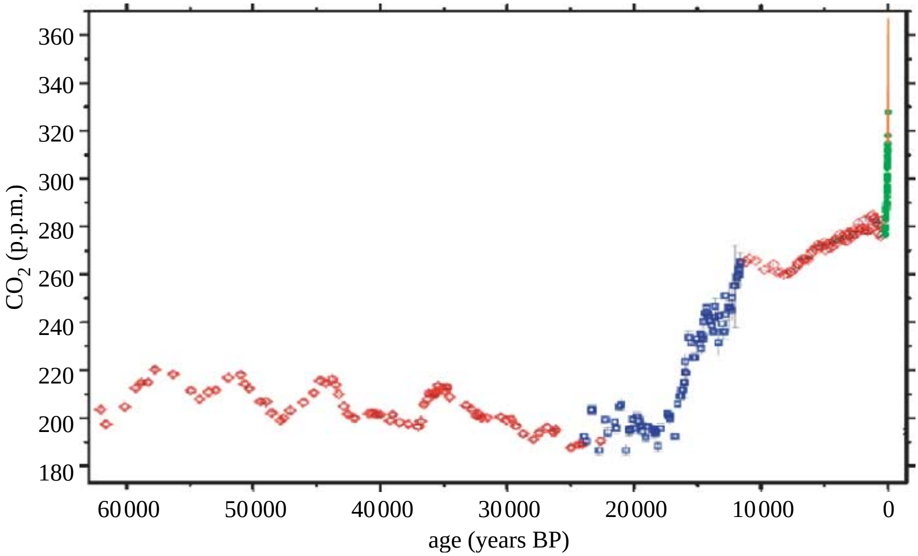

Figure 2. Concentration of CO_2 in p.p.m. in the Earth's atmosphere over the last 60 000 years. Source: University of Bern and National Oceanic and Atmospheric Administration.

theoretician trying to model Earth's temperature; over the last century, we released a lot of aerosols into the atmosphere. Aerosols reflect incoming solar energy and hence tend to have a cooling effect on the planet. We also need to consider changes in land use, for example what is happening to the extent of green growth around Earth's surface; we also need to worry about urbanization and how this affects planetary temperatures. Volcanic and solar activities also need to be factored in.

The Hadley Centre in the UK provides one of the world's leading groups in modelling the atmosphere which makes use of the Earth's biggest computer, the so-called Earth Simulator, in Japan, which is now running vast programmes to model the Earth's climate system. Back in 2001, I brokered with the Japanese government the agreement for our scientists to use this computer. We can now compare the results of this modelling with Arrhenius' 5°C prediction for the elevation of the Earth's temperature. The error margin has been determined to be 5 ± 2.5°C. Hence with my physics background, I would say basically Fourier and others had got the physics roughly right by the end of the nineteenth century.

Approximately 55 Myr ago, CO_2 levels were in excess of 1000 p.p.m., there was no ice on the planet and sea levels were approximately 100–120 m higher than they are today. How did the CO_2 get removed since that time? Figure 2 shows how the carbon dioxide has changed in the atmosphere during the last 60 000 years from which we see that carbon dioxide levels have remained between 180 and 280 p.p.m. until around the time of the Industrial Revolution. Figure 3 illustrates the dynamics involved: quite simply, photosynthesis and mineralization (rock formation) absorb CO_2 whereas respiration and decomposition return it to the atmosphere. Importantly, carbon in the form of hydrocarbons has been naturally sequestered for many millions of years and are the fossil fuels, oil, coal and gas that we have been burning as rapidly as we can. Thus, we are destroying a carefully balanced system.

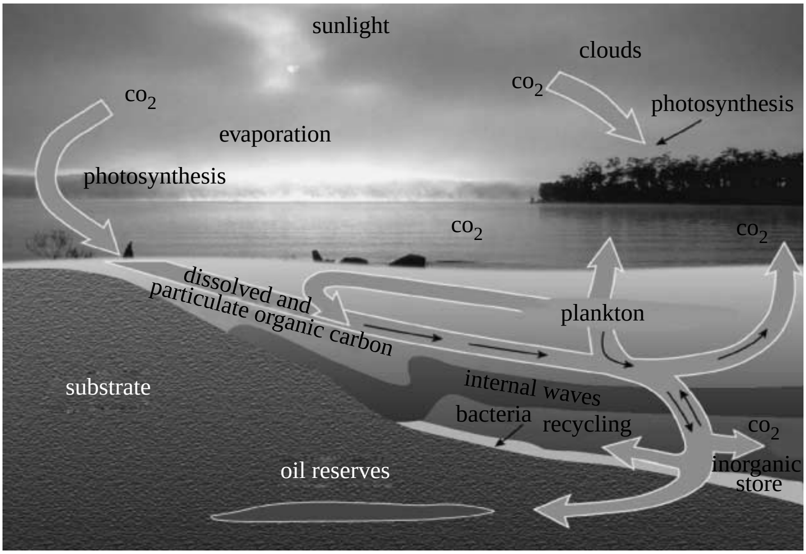

Figure 3. Illustration of the uptake of carbon dioxide by photosynthesis, replacement in the atmosphere by respiration and breakdown of organic matter, and natural sequestration as coal, oil and gas.

The blue points of figure 2 show where carbon dioxide levels started rising 18 000 years ago. It seems that the rising levels of carbon dioxide go together with rising temperature, interplaying in a complex, nonlinear fashion but in general keeping with Fourier and Tyndall. Since that time, the average global temperature has risen by around 5–8°C. So we emerge from that Ice Age into what is commonly called a warm period, beginning approximately 12 000 years ago.

During the current period of our civilization, we have had constant sea levels. If we go back 20 000 years, there was a complete connectivity across the Baring Strait, for example, because the geography of the planet changed quite substantially as the sea level changed. That sea level change was around 100 m. But we, comfortably, have not seen sea level changes and so we have been building our major cities around the edges of our land masses—80% of our major cities and population are sitting at those edges. Thus far, over the period of our civilization, those have been pretty safe places to have cities. The green data points in figure 2 show what has happened since the Industrial Revolution. There are some interesting scientific questions about that rise, from approximately 8000 years ago until 1860. It could be that this rise is attributable to land use changes produced by humankind, in which case what we have is the beginning of the anthropocene, the period in which the climate system of the planet is determined by humans. As the green data points show, humans started doing that in a very dramatic fashion, after the Industrial Revolution.

Atmospheric CO_2 is currently at 383 p.p.m. and rising at 2 p.p.m. per annum, so in 10 years time, we know that we are going to pass the 400 p.p.m. point.

Figure 4 shows detailed data from the Scripps Institute initiated by, among others, Charles Keeling, who passed away last year. It is a great tribute to his remarkably accurate measurements, that they have attracted attention to this particular problem. When he began measuring, it was at around 315 p.p.m. and when he passed away, we were up at 380 p.p.m.

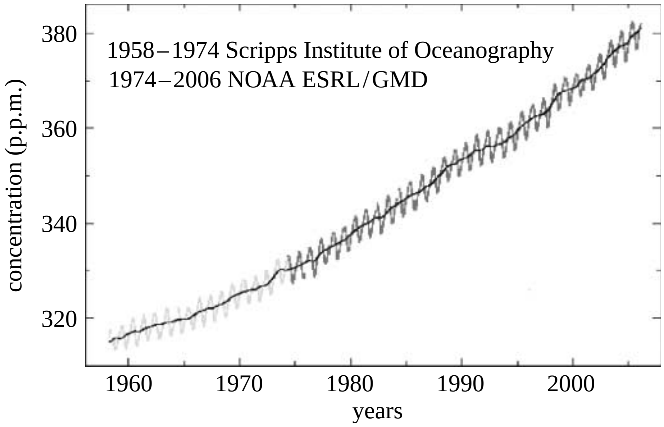

Figure 4. The concentration of atmospheric CO_2, as measured from the Mauna Loa observatory.

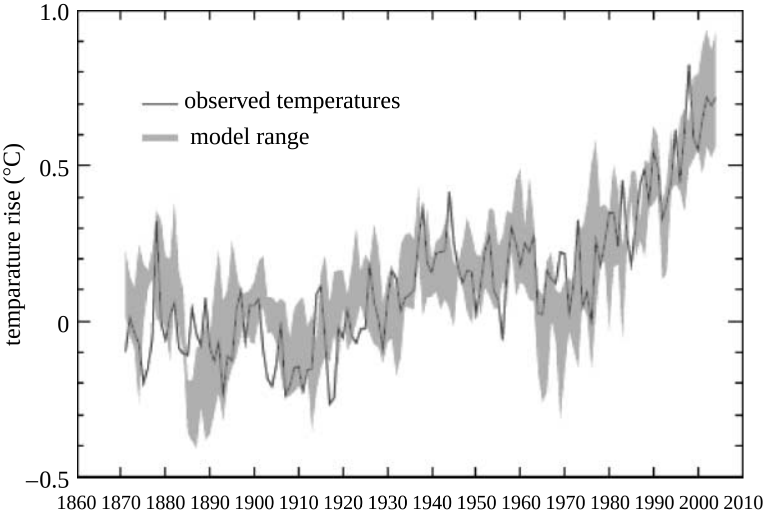

Figure 5. Simulated and measured global warming, from the Hadley Centre.

The zigzag that can be seen is not noise, but corresponds to the difference in land mass in the northern compared with the southern hemisphere: during a summer in the northern hemisphere, there is more pumping of carbon dioxide by the green matter, so the carbon dioxide level is lower, and then during our winter, it rises as the leaves fall.

There are some analysts who look at the changes in slope in fine detail, considering the influence of financial crises, the drop in use of oil and so on, but what is really important to gain from this figure is that our generation and use of energy is driving this upward. The other important fact is that we have a rather good correlation between the observed temperature rise up to the start of the points shown as a thin dark grey line in figure 5. These are the global average temperature rises, going back to the 1860s, when the British Met Office began collecting data from 300 weather stations around the world, so this is a rather good dataset.

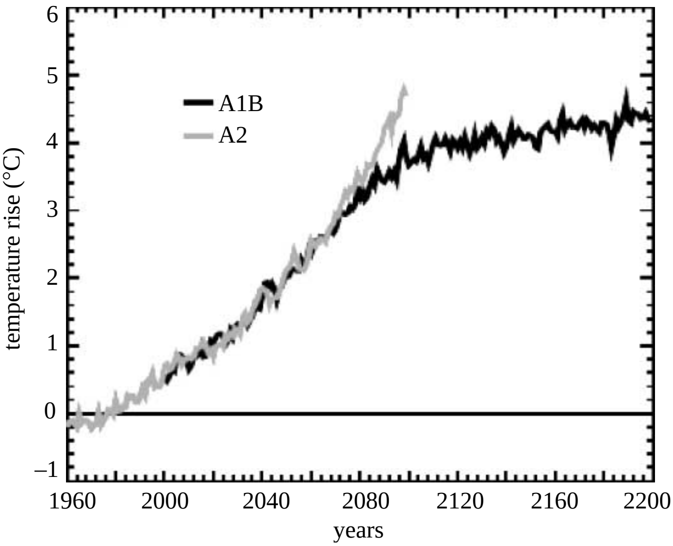

Figure 6. Global average temperature rises simulated for two different emissions scenarios, called A1B and A2.

Figure 5 shows in grey the output from the current Hadley Centre model. It is important to point out that the last 15 years of data has been obtained subsequent to the first publication of the model data. The model therefore demonstrates that you can provide a clear explanation of the temperature rise from left to right in this diagram, provided you include carbon dioxide increases. If you keep the carbon dioxide in the atmosphere constant over this period, the ups and downs due to volcanic and solar activities are reproduced, but the general trend from left to right of an increase in temperature is not reproduced. This increase in temperature is now just over 0.7°C.

Figure 6 shows, for two different emission scenarios, the extrapolation from 1960 forwards of the latest output of the model depicted in figure 5. The curve A2 demonstrates the emissions scenario of 'business as usual', where there is no global agreement on fossil fuel usage. This is not out of the question since, of course, we have enough coal, for example, under the surface of the planet to drive carbon dioxide levels up to well over 1000 p.p.m., probably close to 2000 p.p.m., so we can go well beyond the doubling that Arrhenius was worried about. The curve A1B shows what can potentially be done if we limit emissions, but of course the concern is that even in this case, the plateau the average temperature rises to is 4°C above the 1960 level. So even to the year 2050, to mid-century, this dataset is predicting a temperature rise in the region of 3°C. It is very important that we understand that if action begins now, it will take some time before the impact is seen on these data. The reason is quite simply the carbon dioxide level is rising so rapidly that we have pushed the system out of equilibrium, and so the inertia from the Earth's climate system is probably about three decades. Hence, if we were to stop emitting carbon dioxide now, we still have 30 years on these curves ahead of us, and any action we therefore take to reduce emissions is going to play through in terms of advantages, and very big advantages, in the longer term.

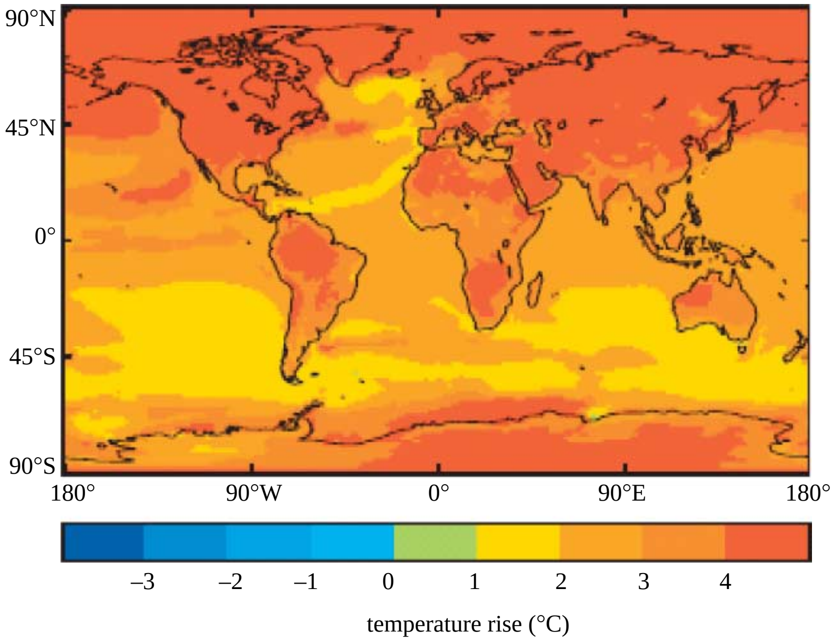

Figure 7. Predicted change in average temperature rise between the present day and the late twenty-first century, according to a particular emissions scenario termed A1B (see text and figure 6).

What all of this indicates is that our objective, which in British Government terms was to reach the ceiling at no more than 550 p.p.m., and which we thought was quite a tough objective to reach, really needs to be re-evaluated if we are to meet the objectives of the UN framework convention that we should not exceed the possibility where we get dangerous climate change. I am afraid under these scenarios, even the best one here, we are heading towards what would be described I think as dangerous climate change.

The map of the world shown in figure 7 shows how this temperature change prediction shown in figure 6 for the ‘optimistic’ emissions scenario A1B is likely to be distributed. We are already seeing that the temperature rise in the Arctic region is roughly double the global average, and in the Antarctic region, it is roughly half the global average. So we are not seeing and nor should we anticipate seeing, an even rise in temperatures throughout the world.

There has been much focus of attention on the Greenland ice sheets, and I simply show here recent satellite data. The modelling that was conducted by the Hadley Centre, the best modelling available at that time, published several years ago, indicated that you had to go above 550 p.p.m. to initiate the irreversible melting of the Greenland ice sheet. But now that we have got the satellite data in, we can see that the melting is occurring considerably more rapidly than the modelling had demonstrated. There is already a considerable increase in the extent of ice melt, shown in figure 8. The reason why is a massive challenge for the modellers, but it is likely to be due to the uneven nature of the melting that is taking place, the generation of large rivers and cascades on the mainland, and the possibility of these rivers running right down to land mass and therefore lubricating large chunks of ice and causing insipient carling; all of these

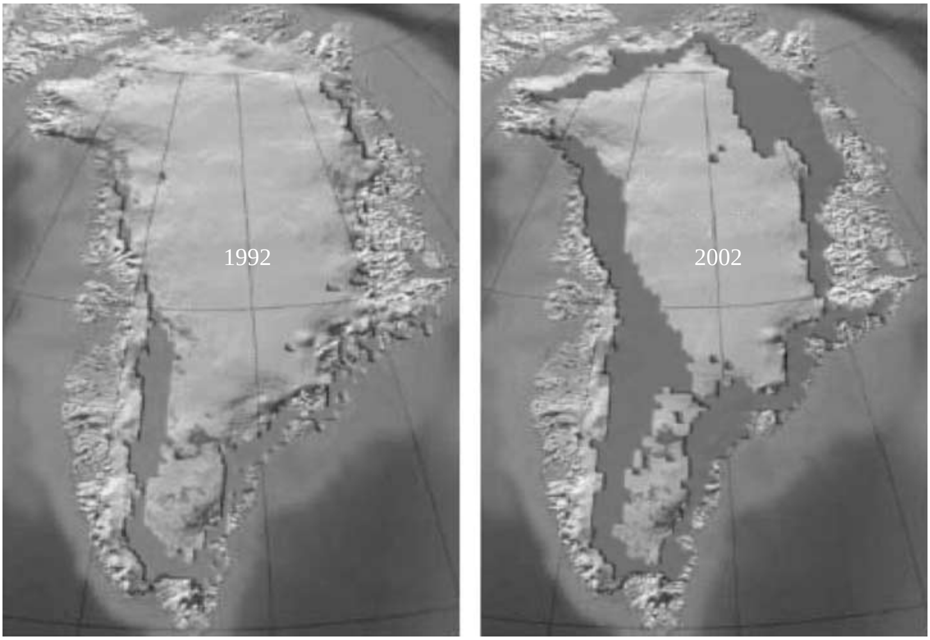

Figure 8. The Greenland ice sheets, in 1992 and 2002.

factors will increase the rate of loss of ice from Greenland. I do not want to sound alarmist, but if you look at the pictures coming back from the satellites, I can assure you, you would feel very alarmed.

Why should we worry about this? If we only focus on Greenland ice melting, the sea level would ultimately rise by 6.5 m. Now, of course, ice is melting from land mass elsewhere on the planet, and as recent gravitational measurements on the Antarctic are indicating a significant loss of ice from that region as well, any ice on the land melting into the sea is causing sea level rises, so we must anticipate, as we move forward in time, substantial sea level rises. At the present time, sea level rise is largely due to the warming, and hence expansion, of the oceans. This has the corollary that when we get extreme weather events, those extreme events are going to have more impact on the place of habitation of people around the coastlines than they would if sea levels were lower. In particular, as indicated in figure 9, again with data based on the Hadley Centre models, the top figure of which shows the biggest risk is going to be to people in Asia, India, Indonesia, Malaysia, Singapore and Japan. They will be very seriously at risk from increased sea level rises and hence increased impact of extreme events.

Figure 9*a* predicts the likely flooding extrapolated according to the 'business as usual' emissions scenario. The good news is that stabilization at 550 p.p.m., according to the Hadley Centre models, indicates that we can get quite a substantial mitigation of that effect. Figure 9*b*,*c* still predicts that mitigation will affect significant percentages of the number of people indicated in figure 9*a*. The suggestion is that although the sea level rise is going to take place over some period of time and therefore people have time to adapt to these measures, in countries where adaptation costs are too high, it will be seen that people will begin to move away from their place of habitation; this could lead to a potential destabilization of

Table 1. This table shows, for given plateau or stabilization levels of CO_2 (including the 'equivalent CO_2' which accounts for the presence of greenhouse gases other than CO_2), the predicted temperature changes by 2100 in the case of the third column by the IPCC 2001 modelling and in the fourth column by more recent Hadley Centre modelling. (Based on den Elzen & Meinhausen 2005.)

greenhouse gas stabilization level	greenhouse gas stabilization level	IPCC 2001 results	Hadley Centre ensemble results
CO_2 equivalent	CO_2 only level	temperature change in 2100	temperature change in 2100
450 p.p.m.	400–420 p.p.m.	1.3–2.7°C	1.8–3.0°C
550 p.p.m.	475–500 p.p.m.	1.5–3.2°C	2.2–3.6°C

the global political and economic system. This is one challenge we are faced with, and this from simply looking in terms of the impacts of sea level rise.

We are also observing measurable acidification of the oceans due to carbon dioxide partitioning itself between ocean and atmosphere, and we are also of course seeing temperature rises, resulting in changes around the planet in rainfall patterns and desertification.

The Indian monsoon is a critical part of the Indian economy. If the monsoon in one year is exceeded by 10% in terms of total rainfall, there is a massive flooding problem around the country. If it is less by 10% in another year, there is massive crop failure. Hence, the Indian economy and its growth depend critically on the monsoon. The African monsoon again is equally important. The African monsoon is already showing tremendous changes, and in the Indian area, it is anticipated that the extent of the monsoon will increase, so it is difficult to see how adaptation measures can come into place on the 'business as usual' scenario.

Table 1 lists the ensemble results of modelling by (third column) the IPCC and (fourth column) the Hadley Centre. The results are stated in terms of the greenhouse gas stabilization level, that is, the ultimate plateau of carbon dioxide concentration reached, represented as CO_2 equivalent, to account for the presence of the other greenhouse gases. For example, methane gas emissions have been rising largely due to our use of animals as a food system. The table shows that even if CO_2 concentration plateaus at 450 p.p.m., quite substantial temperature changes are predicted by 2100. If the plateau level is 550 p.p.m., then the temperature change by 2100 is predicted to be higher by the new ensemble results from the Hadley Centre than the IPCC had published in 2001.

Returning to the Greenland ice sheet, it had been estimated that a temperature rise exceeding 2°C would be enough to begin the irreversible melting of the Greenland ice sheet. It may take 1000 or even 2000 years to complete, but the Chinese Academy of Science last year published a very detailed report of the state of ice on the Chinese mainland, and this suggests that due to the loss of summertime (so-called permanent) ice there, we understand that sea levels will be rising due to this general loss of land-based ice around the planet.

The challenge to achieve a stabilization level at 550 p.p.m. is shown in figure 10 in terms of getting our emissions of carbon dioxide under control as a function of time, and you will see that the 'business as usual' scenario (the IPCC A2 curve) has to be shifted from fairly soon if we are going to be on that curve. We need global action urgently: by 2012, we need global action to bring this

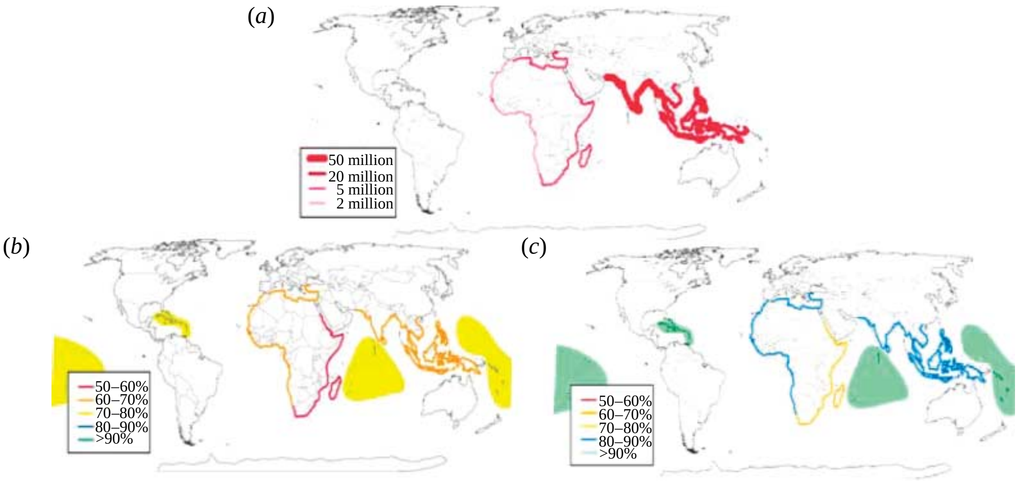

Figure 9. Predictions of annual number of people flooded, based on Hadley Centre models. (*a*) Change from the present day to the 2080s: unmitigated emissions. Reduction in change due to mitigated emission scenarios: (*b*) stabilization at 750 p.p.m. and (*c*) stabilization at 550 p.p.m.

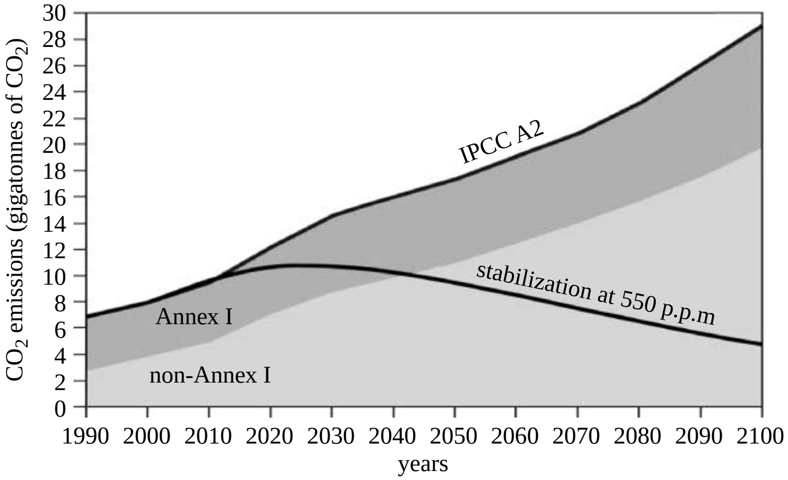

Figure 10. Illustration of the relation between gigatonnes of CO_2 emitted into the atmosphere, and the achievement of a stable plateau concentration at 550 p.p.m.

down. The darker grey-coloured region represents the contribution the developed countries, described as Annex 1 in the Kyoto Treaty, could make if they take full action. But even if those countries do take full action, we are going to see that the problem will not be contained. Since the growth in emissions is coming very largely now from the non-Annex 1 countries, we need to bring them into play, which is precisely why the Prime Minister invited the heads of state of China, India, Mexico, South Africa and Brazil to the G8 meeting at Gleneagles. We are trying to continue that process of the ‘G8 plus 5’ as a means of getting action and engaging both the Annex 1 and the non-Annex 1 countries.

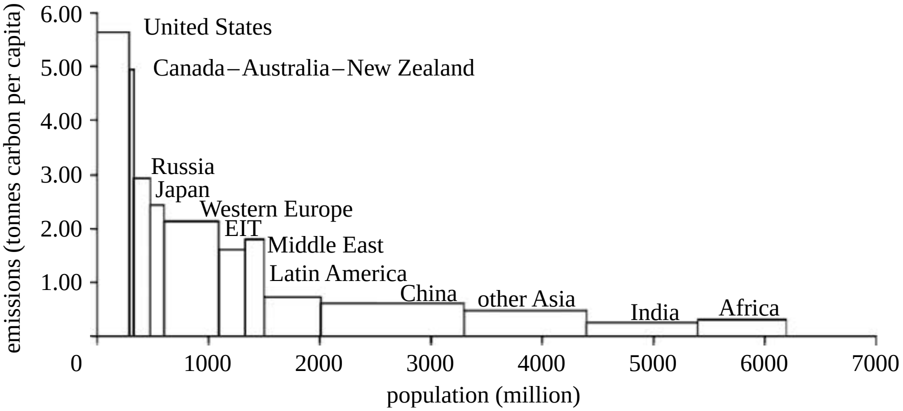

Figure 11. The per capita emissions and population by region in 2000. Source: the Carbon Trust.

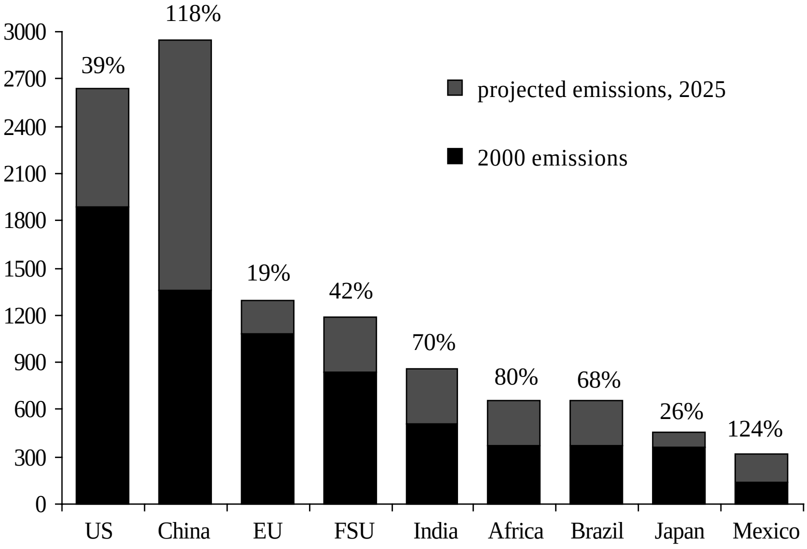

Figure 12. The projected emissions of carbon in millions of tonnes. Note that to convert to emissions of CO_2, one should multiply by 3.664, the atomic ratio. This plot shows that the larger developing countries account for much of the forecast rise in emissions.

The global dimensions of the problem are illustrated in figure 11, which shows that in 2000 while the United States had emissions of around 5.7 tonnes of carbon per person per annum, in Europe there were 2.2 tonnes of carbon per person per year, while Africa and India and China were at much lower figures. Note that to convert to emissions of CO_2, one should multiply by 3.664, the atomic ratio.

Figure 12 shows the sum per country, that is the per capita emissions multiplied by the population, indicating that China currently occupies second place, because of its large population, but moving forward to first place in 2025.

Based on the current projections of growth and energy demand, China is predicted to become the country that will be emitting the most carbon dioxide.

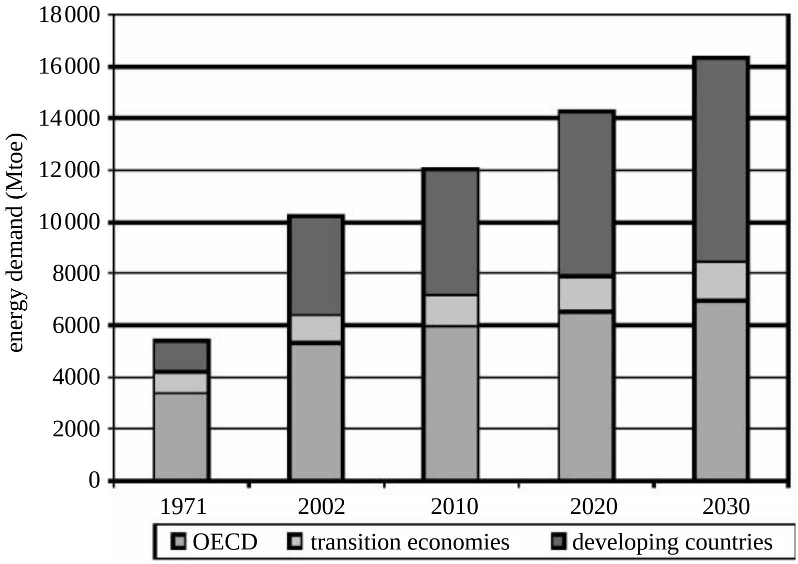

Figure 13. Depiction of the growth of different economies and implications for energy demand, in million tonnes of oil equivalent. (OECD: North America, Western Europe, Japan, Korea, Australia, New Zealand; transition economies: FSU, Eastern Europe; developing countries: all other nations, including China, India, etc.)

Concerning the growth of the different economies, figure 13 underlines the importance of bringing the non-Annex 1 countries into the discussion, but of course bringing them in sensitively so that a suitable conclusion is reached.

If we take our current geological knowledge, we know that there is a finite amount of fossil fuel resources on the planet. The current BP estimate, at the current rate of usage of 88 million barrels of oil a day, is 41 years of oil left. This includes the hard-to-obtain oil. The current Chinese usage of oil, extrapolated out to 2030, is 100 million barrels of oil a day; this is for China alone. Factoring all of this in, which of course cannot happen, would mean there would not be enough oil by 2030 for China to have 100 million barrels of oil a day. We can say oil is very definitely going to be used up. The problem is with coal, where we have at least 600 years of reserve at current rate of usage. If we convert coal to oil, as we move forward in time, and burn all of that, then I would suggest that we are in deep trouble with atmospheric CO_2 concentrations. Use of coal is what we have to bring under control.

There are various aspects of global action, as follows.

The *Inter-Governmental Panel on Climate Change* (IPCC) right at the top comprises the world's top climate scientists.

The *Kyoto process* provides a mechanism for taking their advice forward. This is a critically important mechanism because it contains fiscal drivers and it embodies a process of bringing developing countries on board in terms of clean development mechanisms.

In 2003, the *UK Government* announced within its energy policy, *a serious target of reducing its emissions by 60% by 2050*. That was a statement not that Britain can solve this problem alone, but that Britain intended to play a leadership role in this process, particularly as we led up to our G8 presidency in 2005. As we came through our EU presidency, we raised emissions trading there; emissions trading went from Britain to Europe within a year, and we now have the *European Trading Scheme* up and running. That is a cap and trade process.

The *Asia–Pacific Partnership* is welcome for their announcement on technology, but we know that the problem also requires fiscal process to bring the right behaviour on board.

Emissions trading is a critical part of the process. Any country looking at energy policy would see security of supply, emission reduction and energy costs, and maintaining competitiveness of the economy as the critical factors. These are the key drivers and what we are all trying to work on. Emission trading in Europe was introduced at €8 per ton of carbon dioxide, far too low to bring on board the right kind of behaviour, but the market knew better; the market drove it up to approximately €28 per ton, and several billion pounds have now been invested in this. I am now invited remarkably often into the City, the Square Mile, to talk about climate change, because this is now seen in the City of London as a massive investment opportunity. When the question is ‘what is the market going to push that up to?’ my answer is: ‘what would it cost to capture carbon dioxide at a coal-fired power station and store it?’ and this is one way of giving the price of carbon dioxide. In my view, we should be heading towards €50–55 per ton at today’s level, and so it is a good investment to make in carbon dioxide shares right now, because these are going to rise.

The UK Government set up an Energy Research Partnership, which I co-chair with Paul Golby. He is the chief executive of one of our biggest utilities, E.ON UK. Through this partnership, we have now announced the formation of an Energy Technologies Institute. This is a public/private partnership, in which the initial companies coming on board provide half the finance, with matching funds from the Government to a total figure of a billion pounds over 10 years. The initial companies coming on board are BP, Shell, E.ON and EDF. We have utilities and oil companies coming on board, and the Government has undertaken to give support pound for pound. The idea of the Energy Technologies Institute is to raise the profile of energy research all the way out to deployment.

We need to focus now on a sustainable future since we are looking at a planet that is finite in its dimensions and we are impacting on its atmosphere. Science, modern medicine and technology have since the Industrial Revolution provided us with societies in which we can live longer, healthier lives than in the pre-industrial period. Now we need to use our wealth and technology not only to manage our economies within finite natural resources, but also to adapt to a warming planet while reducing the extent of that warming by drastically reducing CO_2 emissions.

The following articles in this issue explore a range of possible energy solutions to the major problem we face; I consider that we need every tool in the bag to tackle this.

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NOTICE OF CORRECTION

The author's affiliation is now in the correct form. 14 March 2007

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Errata

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A physical model of the turbulent boundary layer consonant with mean momentum balance structure

By Joe Klewicki, Paul Fife, Tie Wei and Pat McMurtry

Line 19 of §3(f) is incorrect in the print version but is correct as follows.

It follows that an exactly logarithmic mean profile will occur when the locally normalized second derivative of the Reynolds stress (gradient of the Lamb vector) remains invariant over a range of y (i.e. for a range of β).

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Introduction: energy for a sustainable future

By David A. King

The author's affiliation in the print version of the paper is incorrect, and should read as follows.

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