Prof. John R. Krebs "Science and Sustainability"

Introductory Remarks

It is a great honour and privilege to be here today to deliver the 11th Queen's Lecture. This evening's Lecture is especially significant because it marks the resumption of the Queen's Lectures after a gap of 22 years.

I am also especially delighted to be here in Berlin, a great city with which I have many connections. In my own research I have collaborated with scientists in Berlin for many years and more recently, I have been working with the Advisory Board of the Wissenschaftskolleg, a superb example of an organisation that fosters interdisciplinary research and brings together bright young people from around the world.

Further back in my family history, my father, the biochemist Hans Krebs, spent a crucial part of his career in Berlin, in the late 1920s, working with Otto Warburg. In his autobiography, my father recalls his time in Berlin with great affection and acknowledges the enormous influence that this period had on his scientific development.

My theme for today's lecture is *Science and Sustainability*. I think this is an especially appropriate theme for an international occasion such as this. The language of science is inherently international: scientists can walk into a laboratory in their field in any country in the world and immediately understand at the highest level what is being done. Sustainability also transcends national boundaries. It is a concept that is relevant to all nations and one that has to be embraced by all for it to work.

Three key messages

My message in this lecture consists of three parts: (1) the environment is central to sustainability, (2) science is one of the keys to sustainable development, and (3) a principle role of science is to reduce uncertainty.

(1) Sustainable development has been defined in many ways, but here I use the recent definition of the UK Round Table on Sustainable Development: **"Development that meets the needs of the present without compromising the ability of future generations to meet their needs"**.. Most commentators describe the elements of sustainable development as "the three Es ": Environment, Equity and Economics. Central to all three is the relationship between mankind and the environment. Achieving the right balance in this relationship is arguably the single biggest challenge facing global society today and it will become an even

bigger challenge in the future as a result of population and economic growth. Each month an equivalent of New York City is added to the world's population, or to put it another way, by the time I have finished this lecture, the global population will have increased by 10,000 individuals. Whilst the industrialised nations currently use two thirds of the natural resources and create four fifths of the world's pollution, this balance will shift as the large developing countries become richer and more populous. Unlike issues of health and poverty, which are pressing for some sectors of the human population but not others, the environment is truly pervasive and inescapable. For example, some commentators have identified water shortage as the most likely cause of international conflict in the next century.

(2) If we are to rise to the challenge of managing our affairs in such a way as to pass on a healthy environment to our children, their children and their children's children, we require three things. First, *scientific understanding* to illuminate the "What? Why? and How?" of sustainability: "What is happening to our environment? ", "Why is it happening? ", "How can adverse or unsustainable changes be reversed, ameliorated or prevented in the future?" Second the appropriate *social and economic conditions* to effect changes. Third the *political mechanism* to implement change. Although there is an argument that sustainability is essentially a political issue rather than a technological one, I will argue that science and technology have a central role to play.

(3) A central role of science is to generate understanding in order to predict the future consequences of our actions and thereby to *reduce uncertainty* about the future. Science, through reducing uncertainty, also points the way to the solutions for sustainable development.

The health of our environment

I have said that the environment is the biggest single challenge facing global society today. If you look at the daily newspapers or television, you will be bombarded by stories about environmental problems. The local, regional and global impacts of pollution are ever more apparent. Habitats and species are being destroyed at unprecedented rates, desertification is increasing in many arid parts of the world. Resources such as water, fish and hydrocarbons are being rapidly depleted or exploited more rapidly than they replenish themselves. Perhaps most significant of all, human activity is now almost certainly influencing the climate of the planet on which we live. The Intergovernmental Panel on Climate Change (IPCC) in their

1995 report concluded that "... The balance of evidence suggests a discernable human influence on global climate ".
Of course there are those who hold a contrary view, and it is true that some of the more extreme claims are, if not exaggerations, extrapolations based on a great deal of assumption. In his book *Small is Stupid* Wilfred Beckerman shows a Table entitled *"How we used up all the resources that we had and still finished up with more than we started with"*. In 1970, for example, the estimated global reserves of oil were 550 million metric tonnes. Today the estimate is 900 million metric tonnes, even though in the meantime 600 million metric tonnes have been consumed! Beckerman argues, in fact, that the whole concept of known reserves is dubious, because companies are unlikely to explore for new reserves until there is a market need.
More generally, the doubters, whether they are talking about extinction rates of species or global climate change, base their doubts on *uncertainties* in knowledge about the present and prediction of the future. This is one reason why scientific analysis, aimed at reducing uncertainty, is so important.

Why does the health of the environment matter?
If we accept that there is a problem, that we are interacting with our environment in a way that is unsustainable in the long run, why does it matter here and now? It is not a problem that we can leave for future generations, just as past generations have left us with their legacy of contaminated land, radioactive waste and so on? It matters for three reasons, namely human health, national and global prosperity and social equity.

Health
Environmental health is now recognised as influencing human health. Depletion of the "ozone layer " in the stratosphere 10-30km above the earth's surface has an effect on our exposure to ultraviolet radiation, increasing the risk of skin cancer and cataracts (a sustained reduction of total stratospheric ozone of 1% could lead to a 2% increase in the incidence of non-melanoma skin cancers). Certain potentially hazardous pollutants in the environment are now known to persist through the food chain and therefore eventually end up in our own diets. The early warning signals of these potentially adverse effects on human health have generally come from the study of natural populations: Rachel Carson in the 1960s in her book "Silent Spring " first highlighted the idea that pesticides might persist through the food chain.

Economics

The health of the environment also has an economic dimension. Normally, we measure the economic health of a country by its per capita GDP. However, now attention is increasingly turning to alternative measures, which take into account the health of the environment and stock of natural resources.

One such index developed by the Stockholm Institute, is the "index of sustainable economic welfare " (ISEW).

For the UK, whilst per capita GDP has increased steadily over the past 30 years, the ISEW has been declining since the 1970s. Whilst the details of measures such as ISEW may be disputed, the general question raised is whether we are getting richer in part by building up debts for the future. An alternative approach to the economics of the environment is through attempts to place a value on the economic "goods and services " provided by Nature. A recent overview by Constanza and others puts the value of the global ecosystem at $33 trillion, approximately twice the estimated global GDP of $18 trillion.

These goods and services break down into three categories: (i) *amenity value*, (ii) *natural resources*, such as minerals, forest products and fish, and (iii) *"regulating the balance of materials"*, which account for the lion's share of ecosystem value. This includes the movement of water around the planet, the dispersal and breakdown of pollutants and the fluxes of energy which determine climate and weather. The technique for estimating the value of these services is to calculate what it would cost to replicate them were they not provided free by Nature.

Whether or not the figure of $33 trillion is correct, the overall message is clear: the long term health of the environment has very significant economic implications. What is important is not the absolute values, but the way in which these values would change as a result of different policy options.

Social equity

In addition to its human health and economic dimensions, concern for the health of the environment is an ethical and equity issue. As temporary occupants of the planet, we have a responsibility to future generations to hand it on to them in a condition that allows them to enjoy the same benefits as we do.

This long term view is the essence of the concept of sustainability. Our inherent tendency is to "discount the future " very strongly. We would rather enjoy a small benefit right now than the promise of something bigger and better in ten year's time, a perfectly reasonable stance given that the long-term promise may not be delivered. However for environmental sustainability, a long term view is essential. For example carbon dioxide, a major contributor to the greenhouse effect has a lifespan in the atmosphere of 100 years, so decisions we take now will imply very long term commitments.

The most difficult parts of the environment for sustainable management are the "global commons ": the oceans and atmosphere that belong to all of us but no-one in particular. Because they are no-one's responsibility they are especially prone to unsustainable exploitation, which is why, in the North East Atlantic, two thirds of the major fish stocks are overexploited, some to the point of collapse. However the problem of sustainable exploitation of resources is not restricted to the commons: the economically rational way for an owner to exploit a piece of rainforest is to cut it down, and invest the profit in the stock market, where returns are higher.

In summary, the health of the environment impinges on all of the three Es of sustainable development: environment, equity and economics.

The Science of Sustainability

The central challenge of the science of sustainability, or Earth System science as it is sometimes called, is simply this: to understand how the "Earth System " works and therefore, how it responds to perturbation. The "Earth System " means the interconnected living and non-living components of the atmosphere, oceans, freshwater (including ice), and solid earth. The properties of any one part of the system depend in a complex way on the other parts and cannot therefore be understood in isolation. For example the chemical composition of the atmosphere depends on interchange of gasses involving the oceans, rocks, living organisms, ice and freshwater. This principle was graphically illustrated, albeit in highly artificial conditions, in the attempt to create a self-contained Earth System at Biosphere 2 in Arizona. Soon after sealing off the Biosphere, levels of oxygen and carbon dioxide in the atmosphere fell, oxygen being depleted by the metabolism of soil microbes whilst the carbon dioxide was interacting with the concrete components of the structure to form calcium carbonate.

The key questions for Earth Systems science are: "Is the Earth System in any sense homeostatic? ", "What is its resilience to perturbation? ", "Does it have multiple stable states, so that a perturbation may lead the system to flip to a new state? " These questions are the most challenging intellectually, and the most significant for our common future, of any in science today.

Understanding the Earth System is not only an intellectual, but also an enormous technical challenge.
The phenomena under study are on a massive scale in space and time: patterns of ocean circulation, temperature changes over millions of years, carbon assimilation by the whole world's vegetation. Often measurements can be made only indirectly, for example the measurement of past climate and atmospheric composition by studying isotopic ratios in ocean sediments or in air bubbles trapped in ice. Increasingly, measurements will be made from space. For example instruments are now able to measure the composition of the atmosphere, changes in sea level and temperature of the sea surface.
Environmental systems often involve many feedbacks and non-linearities. This means that the perturbation of one element of the system may have unexpected consequences on other parts, and that changes may be sudden rather than incremental. As a result, the behaviour of the Earth System is explored by scientists through the medium of complex mathematical and simulation models. The models themselves, through their success or failure in replicating the behaviour of the system, tell us whether or not our understanding is adequate. To give one example, the models that are used to predict climate change are based on the idea of the mathematician, L F Richardson, who developed the concept of numerical weather forecasting. His method involved imagining the earth's surface to be covered with a square grid, like a gigantic chessboard, and calculating physical factors that influence weather in every one of these squares. The conditions in any one square (eg wind, storm clouds) affect what happens in its neighbours, so the calculations are enormously complex. Richardson's first numerical forecast predicted the weather over Munich, and the prediction was wrong. However the concept was gradually accepted and now numerical forecasts, both for weather in the short term and for climate in the long term, are the norm. Richardson imagined the calculations being done in a large theatre full of mathematicians, whereas nowadays they are done by supercomputers.
Present-day changes in the Earth System that scientists are trying to detect are often relatively small in relation to past variation: the signal is against a noisy background. For example the question of whether or not we are in a period of unusually high extinction rates can only be answered by knowing about the overall pattern of extinction in the geological record. Equally, the conclusions as to whether or not the current changes in carbon dioxide and average temperature are man-made has to be informed by knowledge of past changes.

Climate change

In the past thirty years it has become clear that human activity can influence the Earth System not just on a local and regional scale but also at a global level. Global change encompasses aspects such as loss of habitat, desertification, changes in biodiversity, and, of course climate change.

The pressing importance of the last of these is underlined by the Kyoto summit in a few days time.

The following facts about climate change are now widely accepted:

1. Global temperature has risen by about 0.6 degrees in the past 130 years.
2. The composition of the atmosphere has changed: carbon dioxide levels have increased by about 25% in the past 200 years, methane has doubled in 100 years and nitrous oxide is increasing at a rate of 0.25% per year.
3. Most of these increases are probably a result of human activity, the gasses arising from industry, energy generation, agriculture and transport.
4. The gasses all have a greenhouse effect of trapping more solar radiation within the earth's atmosphere. Carbon dioxide accounts for about half the additional greenhouse effect from human activity.
5. Other products of human activity, especially particles that form so-called "aerosols ", have a cooling effect by shielding the earth from incoming solar radiation.

Current global climate models, in which many of the chemical and physical processes influencing climate are represented, show that, all other things being equal, the consequence of these changes in the composition of the atmosphere will be to cause the average global temperature to rise by another 1 to 2 degrees Celsius by the middle of the next century. All the scientific evidence has been synthesised, analysed and appraised by the Intergovernmental Panel on Climate Change (IPCC), which contains the best climate scientists worldwide. However there are still major uncertainties both in determining the nature of present changes in the climate system and in predicting their future consequences.

The earth's climate has changed dramatically in the past. Over the past 20 years, studies of a variety of "climate proxies " including the isotopic composition of ice cores, sediments from the bottom of the ocean and the distribution of fossils, have shown that not only has the climate fluctuated substantially and rapidly in the past, but that the past 10,000 years have been unusually stable. In order to be sure that present change is man-induced, we have to distinguish anthropogenic from natural variation.

Part of the argument for a man-induced effect is that changes to the atmosphere from burning fossil fuels can be directly calculated. It is known that the human population produces about 5-6 billion tonnes of carbon dioxide per year (equivalent to one tonne per person, world wide).

In case this sounds a lot to you, just pause to calculate how many tonnes of carbon dioxide you, collectively, may have produced by travelling here tonight. Suppose you each used a litre of petrol, which burns to produce about three kg of carbon dioxide, it would take 300 of you to have produced a tonne of carbon dioxide. If there was a quota of one tonne of carbon dioxide per person per year, an idea suggested in the run up to Kyoto, you, as a group, would have used up an individual's annual allowance in one evening!

The other part of the argument for anthropogenic change is that the rate of change in atmospheric composition is faster than that typically observed in the "fossil" record of the atmosphere in ice and sediments.

The major uncertainties in predicting the future are predominantly because of the feedback loops and non-linearities in the Earth System to which I referred earlier. (One is tempted to refer to the sign on the fortune-teller's booth saying "Closed due to unforeseen circumstances ", or the aphorism attributed to Sam Goldwyn: "Never prophesy, especially about the future").

Perhaps the greatest uncertainty in climate prediction relates to clouds and water vapour. Most climate scientists agree that one consequence of warming will be that the hydrological cycle will speed up: there will be more evaporation and precipitation. What is less clear is whether the consequent changes in water content of the atmosphere will have a positive or a negative feedback effect on climate. Different cloud types, for example, could act as a shield against incoming solar radiation or as a blanket to keep the heat in.

Other examples of feedbacks that are unknown in magnitude are changes in the absorption of heat by the earth's surface (as snow and ice melt through warming, the darker surface of rocks and vegetation will absorb more heat), and the release of stored carbon in soils and ice (as soils warm and ice melts, carbon dioxide and methane that are currently locked up may be released into the atmosphere). In the UK, for example, the carbon stored in soils is 30 times greater than the total annual carbon dioxide emissions for the country as a whole.

Uncertainty is even greater when we turn to the regional and local effects of climate change. To express climate change as a one or two degree increase in the average global temperature is somewhat akin to describing the effects of influenza simply in terms of a one degree rise in body temperature. It is only part of the story.

Increased regional fluctuations in temperature, rainfall and storminess may well turn out to be more important than the average global temperature rise for Northern Europe. Although it is still too early to say with confidence, some climate scientists predict that there will be greater extremes of weather, with longer droughts, more severe storms and more serious floods. In Britain, not a country known for its lack of rain, we are in the middle of the driest period of weather for 150 years. Could this be linked to global climate change?

Northern Europe benefits from "central heating " from the oceans. The region is comfortable to live in only because of an incredible annual delivery of free heat from the Atlantic ocean, an example of the free goods and services that I referred to earlier. The UK receives, every year, free heat equivalent to nearly 30,000 times the total output of the power generating industry. This heating system is driven by the so-called Atlantic conveyor belt, which brings warm water northwards at the surface. As this water travels north, evaporation causes the water to become more saline (hence denser), at the same time as it cools at high latitudes. This cold, salty water sinks and recycles southwards at great depths. It is thought that, in the past, this conveyor belt has abruptly changed its course, precipitating ice ages. One scenario is that global warming could lead to melting of the Arctic ice cap, which in turn could dilute the northern Atlantic waters. This could reduce the density of the water sufficiently to prevent it sinking, hence turning off the conveyor and precipitating glacial conditions in Northern Europe. Although there are no signs yet of the conveyor turning off, it has recently been observed that the deep water outflow from Nordic seas has doubled and then halved again over the past 40 years, indicating that very major changes are possible in a short space of time.

This scenario is still too speculative for you all to rush out and buy down jackets and snow shoes, but it illustrates how the feedbacks and non-linearities in the Earth System are still not well understood. Hence predictions about the long term future are still uncertain.

With such uncertainty, you might conclude that Earth System science is not yet mature enough to influence policies for sustainable development.

Indeed, the headlines leading up to the Kyoto summit suggest that political factors and lobbying may have a bigger impact than the science of climate change on the outcome. Even if this is true, it is important to understand that there would be no climate debate or Kyoto summit were it not for the scientific evidence that has demonstrated with enough certainty that there is an issue to be confronted. As the story of the ozone hole illustrates, when there is the right combination of factors, including scientific evidence, a rapid international response is possible.

Stratospheric ozone depletion

The "ozone layer " in the stratosphere is not actually a layer at all. Ozone is an extremely rare component of the atmosphere (on average about one part per million - if you were to collect all the ozone in the atmosphere together at ground level, it would form a layer about 3 millimetres deep) but it is most abundant some 25 km above the earth's surface in the stratosphere. Here, ozone is a vital shield against harmful ultraviolet radiation from the sun. This is partly why, when Joe Farman observed stratospheric ozone depletion over Antarctica in the late 1970s and early 1980s there was such a rapid response from the international community, leading to the 1987 Montreal Protocol on CFCs, now signed by more than 150 countries. As I will discuss later, other factors such as the availability of alternatives to CFCs, facilitated this rapid international response, but the scientific evidence was a key element.

The ozone story also illustrates several general lessons. When CFCs were first introduced, they were described as "among the safest chemicals in use in the home ", by the British magazine New Scientist: we should be alert to unexpected consequences of new products and processes!

A decade before Farman made his critical observations, Crutzen, Rowland and Molina had worked out the chemical route by which CFCs could destroy ozone, so that the observations of depletion were predicted by known chemical processes. Crutzen and colleagues had predicted that ozone in the stratosphere would be depleted by CFCs, but they did not expect such a dramatic effect.

The observations themselves were made by meticulous measurements using a well-established instrument, the Dobson meter, invented in 1926. At the same time data from space were being collected by the Total Ozone Mapping Spectrometer (TOMS) on the US Nimbus 7 satellite, but this instrument did not record ozone depletion. Only when Farman reported his findings, were the satellite data re-evaluated and found to show that there was after all ozone depletion: the extremely low values had been "filtered " out by the computer. Stratospheric ozone depletion over Antarctica now affects an area three times the size of the USA and the levels of ozone are about 40% of measurements made in the 1960s.

Last year, I was on my way to the House of Commons to give a talk on environmental science, including reference to ozone depletion. The taxi driver asked me what I was doing. When I mentioned that I would be talking to MPs about the ozone hole, he said it was rubbish to suggest that man-made pollution is to blame, because the hole is over Antarctica, where nobody lives. I didn't have time to explain, but of course the reason why the hole was first observed there is to do with the physical conditions that favour destruction of ozone by CFCs, including low temperatures, darkness and the fact that the CFCs become trapped in a vortex where they can persist for up to 100 years.

A question which is now the subject of active research is whether or not the same chemistry applies to stratospheric ozone depletion of 20-30% more recently observed in springtime northern mid latitudes. One hypothesis is that nitrogen oxide emissions from high flying airliners are partly responsible.

Biodiversity

For many people "the biodiversity crisis " brings to mind destruction of tropical rainforest and the consequent loss of species. It is true that tropical forests are home to some of the richest natural communities in the world and that these forests are disappearing at an alarming rate. However, for the next few minutes I want to talk about threats to biodiversity in the UK. The exact number of species that have gone extinct in the UK this century is not known, in part because the lesser studied groups of organism, for example marine bacteria, viruses and protists are simply inadequately documented.

However amongst the best known of all wild species, birds, there have been dramatic changes over the past 30 years: many species have declined in abundance by between 10% and 80%. To give you an idea of the scale: in Britain, the population of skylarks is now 3 million smaller than it was 30 years ago.

Because most of the species in decline live in farmland, it is thought that changes in farming practice are involved in causing the declines, perhaps by removing critical food supplies for the birds, or their nesting habitats, or by affecting survival in some other way. Many changes have taken place in the past thirty years including the increased use of pesticides, loss of hedgerows, land drainage, changes in crop types and cropping patterns. Because of these multiple changes it is not straightforward to prescribe a policy for reversing the declines in bird populations, which are similar in other Northern European countries.

At a general level it is known that the abundance and diversity of birds, butterflies and small mammals tends to be higher on organic than on conventional farms. If the mechanisms underlying this can be elucidated and generalised, there may be a scientific basis for changing the policy by which subsidies are given to farmers, in a direction that would encourage the preservation of biodiversity.

Concluding remarks

Using the examples of climate change, ozone depletion and biodiversity I have illustrated how scientific knowledge of what is happening to our environment, and why, is part of the essential underpinning of policies for sustainable development. In my concluding section I return to some more general points.

The importance of basic science

Firstly, there is no simple prescription for how scientific information will turn out to be useful. Whilst those in charge of science policy do, and should, form a view about priority areas for investment of public resources in scientific research, this view should be a fuzzy one and leave ample room for the unexpected. Processes such as the UK National Technology Foresight Exercise, in which scientists, industrialists and others identified the key priority areas of science for the next 20 years, are of considerable value in generating dialogue between scientists and users, but their use in determining priorities should be circumspect. Time and time again key scientific results for understanding the Earth System and therefore underpinning sustainability come from unexpected directions.

Long term monitoring

My second point concerns the importance of long term data sets. Both Farman, who measured ozone, and Keeling, who measured atmospheric carbon dioxide in Hawaii, started a meticulous long term record in the International Geophysical Year of 1957. Without these long term data sets the crucial trends might not have been detected. Long term monitoring is not glamorous, but it is nevertheless an important part of the science of sustainability.

Perception and reality

You may at this stage be thinking of the following objection to my view that scientific knowledge is key for sustainable policies. You may argue that public perception of environmental risk and damage is more important than scientific reality. Take, for example, the Brent Spar. The scientific evidence showed that the local and global environmental impact of disposal of the Spar at the proposed Fenni Ridge site to the West of Scotland, would have been negligible. This was confirmed by an international group of experts that I set up to re-evaluate the evidence, at the request of the Minister for Energy and Industry (the group also questioned the "case by case " approach).

Yet the public perception of the disposal was that it would pose great risks to the destruction or pollution of a pristine environment, irrespective of the fact that natural seepage of oil and heavy metals into the oceans far exceed the quantities in the Spar.

Whilst we must take on board the fact that social and psychological factors have a key influence on public perception of environmental impacts, this is not an alternative to a scientific approach. The option of cultural relativism ("it all depends on your point of view, there are no absolutes ") will not help sustainability, just as it never helped to develop electricity to warm your house or antibiotics to cure illness.

Collaboration between disciplines

The science of sustainability is interdisciplinary. Whilst part of the benefit in sharing resources is to reduce costs, equally important is the fact that by pooling its intellectual resources, Europe is the second largest scientific player, after the United States, in the world. Individually Germany and the UK produce about 7% and 8% of the world's scientific literature respectively, but Europe as a whole produces more than 25%, placing it second behind the USA which produces some 35%.

A further benefit of collaboration comes from pooling data. Some of the major advances in understanding during the past 10 years have come through co-ordination of effort on a world wide scale, for example in synoptic measurements of ocean circulation, global carbon assimilation and past climate change.

From "What?" and "Why?" to "How?"

Let me finally turn from the science of *what* is happening to our environment and *why*, to the question of *how* science and technology can help to achieve sustainable behaviour. If targets for reductions in carbon emissions are agreed next week in Kyoto, how will they be achieved? The gains to date have not been easy, but they have in part resulted from specific opportunities (eg the switch from coal to gas in the UK). Future targets may well involve changes that have a much greater impact on all our lives, but in broad terms, three classes of short-term solution are possibilities: improved energy efficiency, carbon sequestration and tradeable permits.

As Lovins, Lovins and Weizecker have argued in their book *"Factor Four: doubling wealth and halving resource use"*, gains in energy efficiency can be made in many areas with existing technology.

Sequestration of carbon could be achieved in a variety of ways, but probably this will be no more than part of a larger package of measures. One approach is illustrated by Statoil's work on the feasibility of carbon dioxide sequestration under the seabed in places where oil has been extracted. Another possibility is tree planting, although rough calculations suggest that in the UK, virtually all the land surface would have to be planted with trees to gain the one-off benefit of carbon removal from the atmosphere to balance our annual emissions!

<u>Science and sustainability</u>

My thesis has been that sustainable development, an objective which is not only an aspiration but an absolute requirement for the survival of our descendants, must be based on a foundation of scientific understanding.

A comparison of the international response to ozone depletion and global warming is instructive. Within a very few years of the discovery of the ozone hole, an international protocol phasing out the use of CFCs had been agreed. The notion of global warming induced by burning fossil fuel was first proposed by the Swedish chemist Arrhenius in 1896, and we are still a considerable distance from achieving concerted action on limiting greenhouse gas emissions to the required level. Why? Partha Dasgupta has suggested two factors: (i) the ozone hole has an immediate and highly visible effect on human health, whilst the consequences of global warming are diffuse and long term, (ii) the cost of moving away from CFCs to alternatives was small whilst the reduction of carbon emissions will have huge impact on industrialised society. To these I would add that the scientific case for CFCs and ozone depletion was simple and watertight, whilst for global warming, the uncertainties are sufficient to allow prevarication.

The UN Commission on Sustainable Development, in listing the three impediments to sustainable development, refers to globalisation, official aid, and environmental concerns not being the top priority of governments. Scientific uncertainties are not identified as an impediment to progress. I hope that my talk has gone some way towards pointing out why scientific understanding of the interaction between the Earth System and the human population is central for the progress that must be made in the next few years towards sustainable development.