4 Weak uncertainty

Risk and imperfect information

As should be apparent from chapters 2 and 3, the Greenhouse Effect itself is a scientifically well-founded phenomenon, but questions arise as to the extent of and speed with which human enhancement of that effect is taking place, and with what consequences. There is a positive global warming trend, and a general consensus that atmospheric CO_2 has increased due to fossil fuel combustion. The increasing atmospheric concentration of the cocktail of greenhouse gases is known to be changing atmospheric chemistry. However, beyond these 'facts', there are problems with establishing a trace-gas-cause climate-change-effect relationship. The imprecision of prediction grows as more detail is attempted in the description of the impacts of global climate change, as the move is made from physical to socio-economic concerns, from global to regional or local, and the further into the future events are predicted to occur.

The aim of this and the next chapter is to explore and question the way in which such uncertainties are standardised and characterised. Different types of uncertainty should be recognised, especially because public debate often interprets risk and uncertainty as meaning the same thing and referring to unknowable outcomes (strong uncertainty), while the professional debate by economists and scientists tends to restrict attention to known events which are uncertain (weak uncertainty). The concepts to be discussed in this chapter are grouped under weak uncertainty and concern the realm of normal science and standard economics. The realm of weak uncertainty is in specifying the probabilities of future events. Weak uncertainty can be contrasted with strong uncertainty where knowledge is actually lacking due to partial ignorance and because outcomes are indeterminate. These are topics to which I return in chapter 5.

In the current chapter, the weak uncertainty approach is outlined in the context of global climate change using a characterisation of mean temperature increases as an example. This raises the need for filling in gaps in our knowledge and improving estimates of future changes and their probability. The extent to which different types of uncertainty pertain to the measurement and prediction of climate change is discussed. Modelling is seen as necessary to help inform prediction and the nature of that modelling in science and economics is then analysed. This leads to a concern for the role of scientists and economists in the policy debate, and the way in which their models are reported as 'factual'.

The probability of the enhanced Greenhouse Effect

If standard scientific methodology and burden of proof are followed, an intricate chain of cause–effect relationships is required to establish the nature of potential outcomes from increased GHGs. A key controversy has been the extent to which anthropogenic additions to the atmospheric concentration of GHGs will raise Earth's surface temperature. Much of the debate centres upon the role of feedback mechanisms', e.g. whether or not increased temperatures will lead to greater cloud cover and so backscatter of incoming radiation, which causes cooling. If a range of climate change scenarios could be agreed upon then the physical results for other aspects of the global biosphere would need to be calculated in order to derive predictive consequences. Calls for a rigorous scientific proof of human-induced changes due to the Greenhouse Effect involve evidence of increasing concentrations of trace gases being linked directly to specified changes in climate, which in turn are estimated to cause physical damages: for example, the prediction of an increased probability of hurricanes in the southern US followed by the realisation of that probability in specific weather patterns and resulting loss of man-made capital. The physical events would therefore be linked to economic models which require their own calculation, estimation and abstraction, creating associated errors and so adding to the potential inaccuracies of the predictions. An increased frequency of hurricanes may fail to cause damages (by occurring off-shore) or the damages may be minimal from the standard economic viewpoint (being unrelated to human utility).

The probability density function

In trying to observe whether climatic change is underway only the initial step of the above process of proof has been undertaken with any rigour. This step emphasises changes in climatic variables predicted as a result of increasing greenhouse gases, most obviously increased global mean temperature. Figure 4.1 takes actual temperature data (Jones *et al*., 2000), as used in figure 2.6, and expresses this in terms of the frequency with which given anomalies have occurred. The anomalies are measured as variations from the mean temperature for the period 1961–90. Data have been divided equally into four 36-year periods to show how the distribution has been shifting. Thus, the last period (1964–99) has a range of observations from –0.23 to +0.59°C while the first period (1856–91) ranges from –0.53 to 0.0°C. This distribution of observed global temperatures implies an increasing probability of above average or relatively warm climatic conditions.

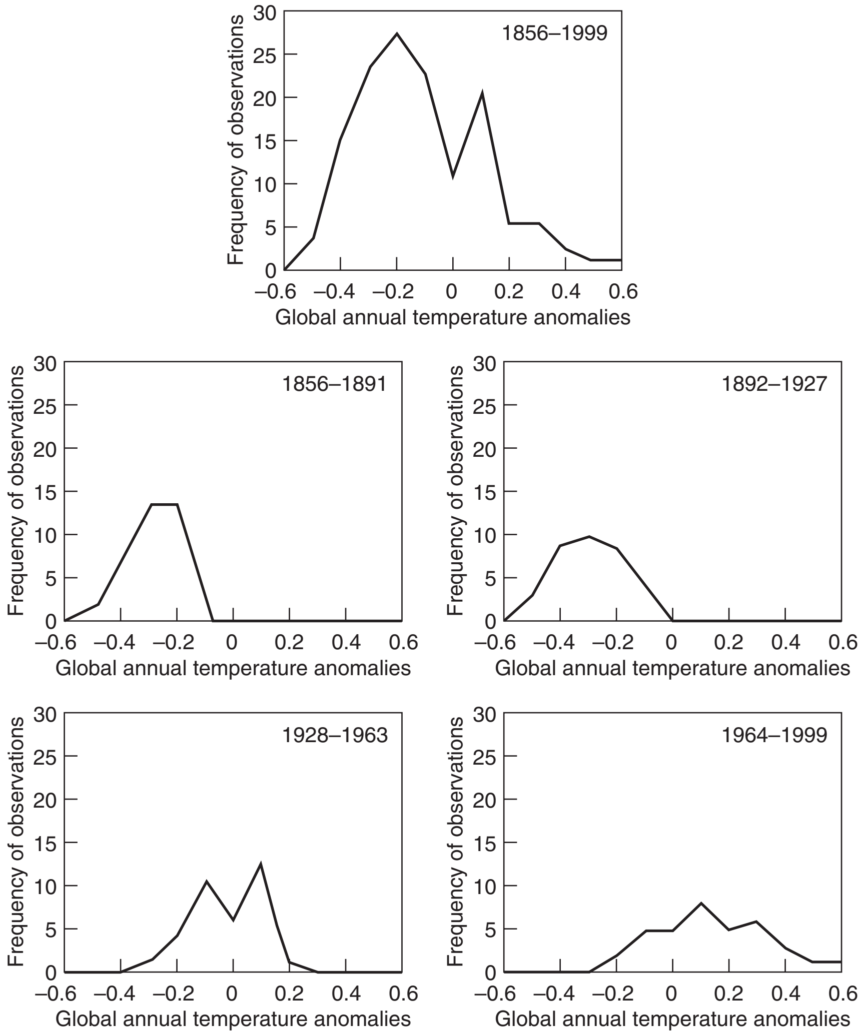

Figure 4.1 Frequency distribution for temperature, 1856–1999
Data source: Jones *et al*. (2000).

The dominant weak uncertainty approach takes such information and fits it within a probability density function. If the climatic variables of concern for the prediction of global climate change are assumed to be continuous and random, showing a distribution that is normal then some of the problems surrounding their expected range can be easily explained. This approach is illustrated below and can be found in Fukui (1979), Hare (1979; 1985), Parry and Carter (1986) and Riebsame (1989: 6–7). For example, the estimation of average temperature in the Northern Hemisphere might be the variable

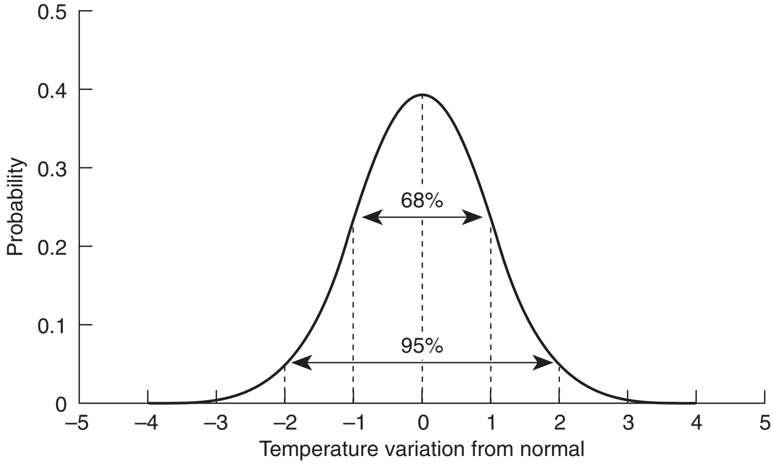

Figure 4.2a Hypothetical probability distribution

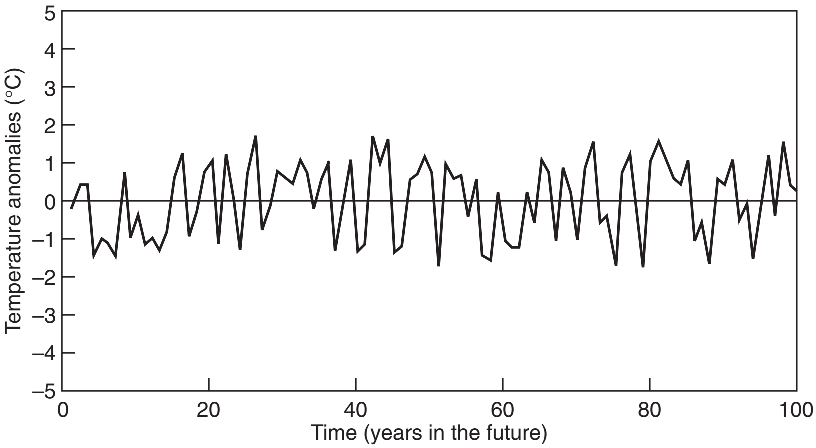

Figure 4.2b Hypothetical temperature variations

which is to be predicted. In figure 4.2a the variation of temperature from usual is characterised as a Gaussian distribution. The mean in figure 4.2a is zero and the standard deviation one, giving what is called a standard normal distribution.

The concept of a usual, typical or normal temperature is derived from observations over time. A time series data set for a given period (e.g. observations of temperature over the past 100 years) gives the average or mean temperature which will be used as a reference value or status quo. As new observations are collected they can be compared to this status quo to test whether there is evidence for global warming. Thus, imagine the year is 2100 and a set of data has been collected over the past 200 years, the results could be displayed as in figure 4.2b which provides a set of hypothetical observations for the period 2000–2100. In order to test whether global warming has been occurring this data might be compared to the average temperature from 1900–2000. Interest is then focused upon the probability of variations from the norm as experienced in the twentieth century, which can be shown by expected temperature deviations from the mean; in this way the mean becomes the zero reference point, as was shown previously for actual data in figure 4.1.

On the basis of the particular normal distribution in figure 4.2a, the expected values of temperature variations can be specified; that is, approximately 68 per cent of the temperatures, shown in figure 4.2b, fall within ±1°C of the mean, 95 per cent within ±2°C and over 99 per cent within ±3°C. Alternatively, the probability of some threshold temperature of interest might be expressed: for example, the chance of a temperature greater than 2°C can be specified as just over 2 per cent. As mentioned in chapter 2, the mean temperature of the Northern Hemisphere has varied no more than 2°C in the past 10,000 years, which would suggest a smaller standard deviation than the 1°C used in the hypothetical data of figures 4.2a and 4.2b.

Increasing mean temperature

Much attention in the literature has focused upon the double CO_2 scenario and its impact on temperature. The lower range of estimates give an increase of 1.5°C, thus a 1°C change might be observed in the near future. If this were the only change, the mean rise in temperature would then shift the normal distribution as shown in figure 4.3a, resulting in the chance of temperatures above 2°C becoming approximately 16 per cent (from just over 2 per cent in figure 4.2a). Such a change would be related to observations like those in figure 4.3b. That is, halfway into the next century a sudden increase in mean temperature might be observed. Currently, actual mean temperature has been estimated to have increased by 0.6°C. However, confirming that the mean temperature has in fact shifted is difficult because of the considerable area of overlap with the original probability density function. Thus, observed high temperatures could merely be part of normal variability and might be evened out by low temperatures in future years. In order for greater confidence to be expressed in the hypothesis that a shift in mean temperature has occurred, more observations above the original mean temperature are required.

Even a marked and consistent shift, as illustrated in figure 4.3b, can take decades to be substantiated. In this regard the nature of the transition from current norm to the higher mean is an important indicator of change. However, the nature of this change is unknown, and in fact neglected by equilibrium models (such as GCMs, and those in economic applications). There may be a smooth transition, a sudden shift (as in figure 4.3b) or a ‘surprise’.

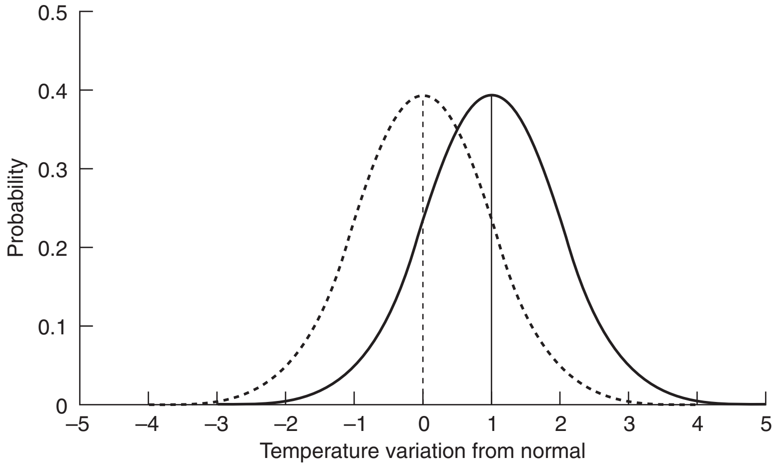

Figure 4.3a An increase in temperature mean

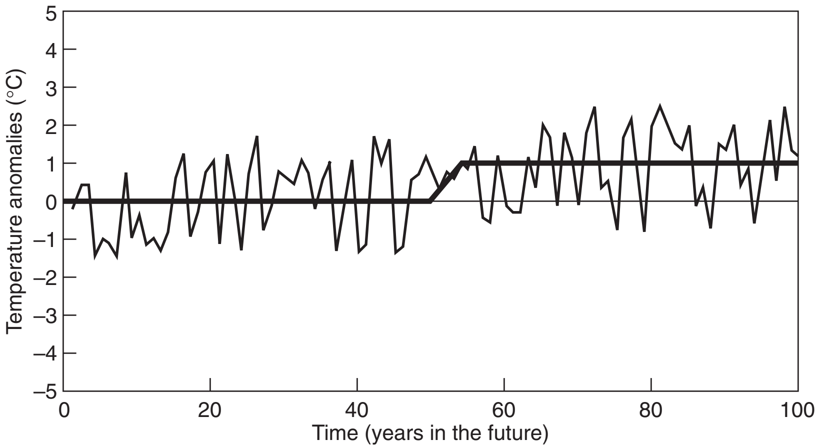

Figure 4.3b Hypothetical 1°C mean temperature rise

The importance of variability

Yet the picture is still more complicated, even though the restrictions of the normal probability density function are maintained. One complication is that the concentration on a shift in mean ignores the likely change in the variability of climatic factors. Concern has been expressed that temperature, precipitation, sea level and other variables will become more erratic, i.e. higher highs and lower lows will occur. Hence, the Small Island States are concerned about storm surges as much as mean sea level rise. An increase in variability can happen independently of a change in

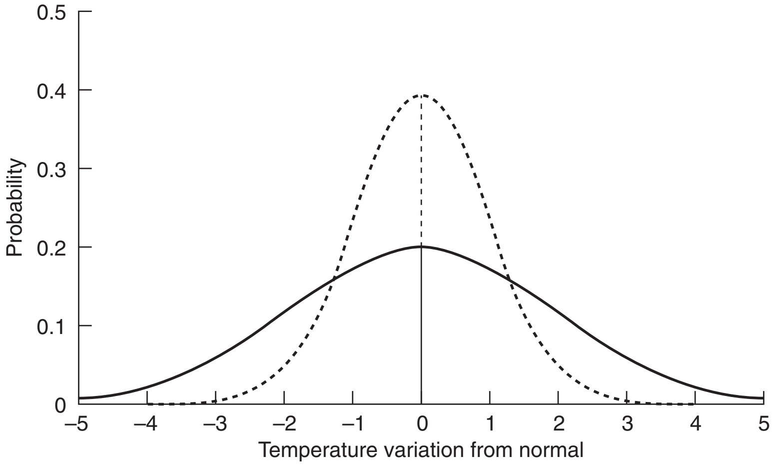

Figure 4.4a An increase in temperature variation

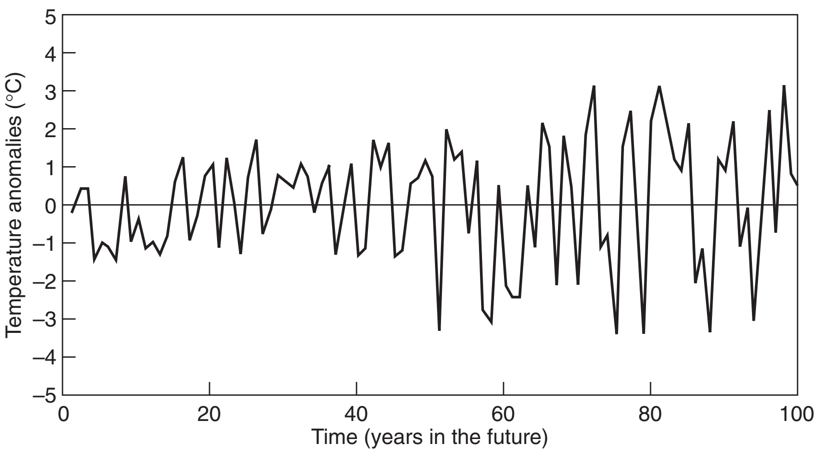

Figure 4.4b Hypothetical increase in variance

mean, as shown in figures 4.4a and 4.4b for temperature. In this case increasing the variability, while holding the mean constant, by doubling the standard deviation, results in the probability of a greater than 2°C temperature again becoming 16 per cent. Merely concentrating on mean temperature observations would ignore this change, i.e. a change in variance may fail to be detected if attention is focused upon the trend in mean values. Consider another example: in the case of rainfall, the result of climatic warming might be increased years of drought and years of flood but the average amount of rainfall would be the same as when neither of the extremes occurred. There is an increased risk of both excessive and deficient rainfall which an average would conceal.

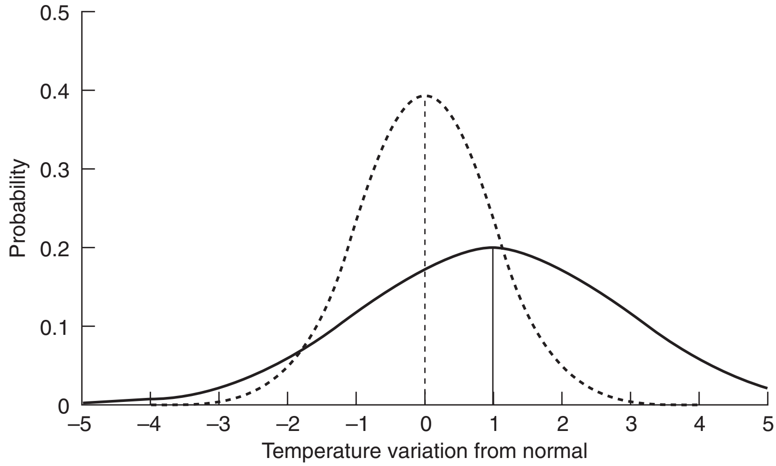

Figure 4.5a An increase in mean and variance

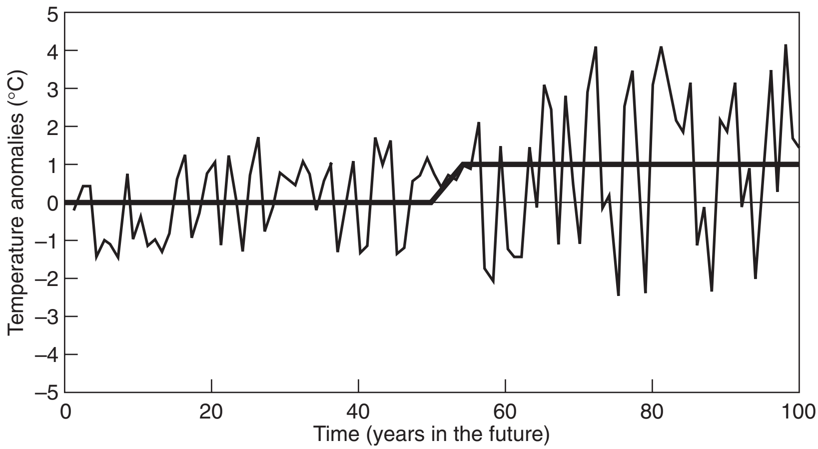

Figure 4.5b Hypothetical mean and variance shift

The relevance of variability seems to be easily neglected while the concentration upon averages can influence the policy debate. For example, Rowlands (1995: 242) notes the impact of the 1988 hot summer in North America in raising concern over global warming policy at that year's international conference in Toronto and Congressional hearings in Washington DC. The subsequent cold winters then eradicated memories of that hot weather, and dispelled fears of global warming until the next hot summer. The policymakers' misconception of the role of variability can be gleaned directly from transcripts of Congressional hearings. There Senator Ford is found asking Dr Hansen to explain why winters in the Ohio River area were, in his experience, more severe, as if this were counter-evidence to a global warming hypothesis (Hansen, 1988: 80). A decade or even a few years of colder temperatures

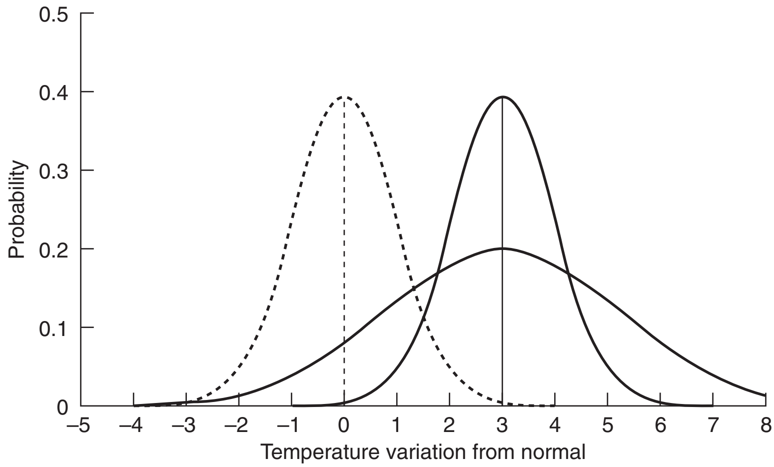

Figure 4.6 Double carbon dioxide scenarios

could have a dramatic political impact on the support for action on climatic change due to oversimplistic perceptions of what is possible.

Of course, a change in both the mean and variance of a climatic variable is another prospect. An increase in annual average temperature could result in greater fluctuations between years and a generally warmer climate. This kind of change is shown in figures 4.5a and 4.5b, where the probability of a temperature greater than 2°C is now 31 per cent. An interesting point to note here is that, despite the shift in mean temperature, the frequency with which years below the previous norm occur is also 31 per cent. Thus, a generally warmer world can include colder years than currently occur on average and, if variability increases, extreme cold years become even more likely.

Thresholds, niches and critical values

Another complication is evident in a paper by Fukui (1979) who points out the importance of critical ranges of rainfall for agricultural crops and illustrates this with a normal distribution. This role of critical values can be generalised to other variables and their relationship to individual species or entire ecosystems. Thus, in figure 4.2a the range of temperatures between ±2°C could be critical for a given species, i.e. temperatures above or below 2°C of current mean temperature will cause that species to die out. Now, if the warming under double CO_2 equivalent is 3°C (possible by 2050), and variability is unchanged, the probability of temperature being within the necessary species survival range falls from 95 per cent to 16 per cent. This is shown in figure 4.6. If, in addition, variability also increases, then the probability improves to 30 per cent. Thus, survival of species in the next century will be crucially dependent upon the mix of changes in mean and variability and the range of climatic variability within which a species can survive. Timing of events is also crucial for species and ecosystems (e.g. cold winters, rain in spring, summer sunshine). The range or niche can also change and may be reduced by, say, increasing stress due to habitat loss or greater parasitism due to warmer climates. Knowledge of the changing vulnerability of species is an example of the complications involved in assessing the impacts of climate change.

How useful is the probability approach?

In summary, the probability approach appears to provide some insight into aspects of climate change and be a useful characterisation of the weak uncertainty imposed by climate change. For example, the concentration on mean temperature changes can be exposed as misleading despite common use in economic studies, policy discussions and the media. However, the reduction of unknown futures to risk must also be recognised as an extreme simplification. The probability approach as a description of imperfect knowledge gives the perception that the concern of scientific research is to increase the confidence level with which possible future states of the climate and their implications are predicted. The job of scientists is then to define the possible future states and the probability of their occurrence.

According to this view, defining frequency distributions for the main variables is the key to convincing the still sceptical of the dangers, or otherwise, of global warming. Hence IPCC Working Group I (2001: 17) calls for the improvement of 'methods to quantify uncertainties of climate projections and scenarios'. IPCC Working Group II (2001: 17) calls for further research 'to reduce uncertainties' and although recognising the need for multiple metrics emphasises risk assessment, quantification and monetary valuation. Thus, the areas in which our knowledge is currently deficient are to be identified and that deficiency removed by further research. Economists also often voice such an opinion. For example, while discussing the economic costs of CO_2 reductions, Manne and Richels (1992: 1, 86) express a belief in the resolution of scientific uncertainty and better information leading to better decisions. Similarly, Adger and Fankhauser (1993: 117) regard more scientific research on costs and impacts as the best response to 'a high level of uncertainty', and state that 'all uncertainties can be resolved', although action may be necessary before then. IPCC Working Group III (2001) also believes in the 'reduction of scientific uncertainty' (p. 11), and in particular 'developing decision analytical frameworks for dealing with uncertainty' (p. 13). So next, let us look at issues relating to the measurement and prediction of climatic change to see how far the gaps in knowledge conform to this perception.

Measuring and predicting climatic change

Standard concerns over the impact of information on prediction can be relate to two areas: first, the ability to measure variables with minimal error, and second, imperfect knowledge about systems and how they change over time. In this section, the first area is shown to be concerned largely with estimable risk, while the second moves into the area of strong uncertainty. In order to see how these information issues relate to the enhanced Greenhouse Effect, the two main sources of information for confirming human-induced global warming GCMs and actual climate observations are considered. In doing so the main problem, as outlined in the probability approach above, is to be regarded as finding evidence for climatic variations which show as substantial differences between reference periods.

In assessing the accuracy of observational data on temperature Harrison (1991) has suggested four points be considered. First, the measurement of temperature and sea level are subject to errors. Second, the span of the climatological record is at best about 200 years and for many areas less than 50 years in terms of reliable direct measurement, which is very short in terms of estimating unusual disturbances. Third, the extent of background variations is unknown, so that the observed trends may be incorrectly attributed to humans or expected trends may fail to show because of environmental variation. Fourth, environmental systems are best described as complex networks rather than simple cause–effect relationships. These points are worth considering in turn.

Measuring variables

Examples of measurement error can certainly be found easily enough and are associated with specific confidence ranges given along with any climatic data. For example, measurement from land-based weather stations can suffer cumulative observation errors depending upon the calibration of thermometers, observer diligence, maintenance of thermometer shelters, local topography and the proximity of features such as urban areas or open water. Harrison points out that the result is accuracy within $\pm 0.5°C$ at any individual station, but he neglects to mention that as long as errors are consistent trends in temperature would be unaffected. Local measurement errors can also be specified and corrected.

Whether temperature, precipitation, gas concentration or some other climatic variable, repeated observation can allow identification of influencing factors. For example, the Mauna Loa site measuring CO_2 is considered one of the best locations because local influences are minimal and can be observed and excluded from the records. The methods and equipment used to obtain the Mauna Loa measurements have remained essentially unchanged since the late 1950s when the monitoring programme was initiated (Keeling and Whorf, 2000). Where equipment has changed and practices altered over time the number of factors affecting measurement comparability increases. In such cases figures are recalibrated to match the impacts of different techniques. Thus, repeating a measurement with different equipment allows for comparison and estimation of bias. The ability to observe from repeated experience means probability functions can be constructed and precise error estimates calculated.

Observational evidence

While observational data is indeed a short time series for prediction this fails to recognise the availability of alternative data sources. The composition of the atmosphere estimated from ice core samples has given a climate record extending back 420,000 years (Petit *et al*., 2000) with a resolution of a few decades (Jouzel *et al*., 1994). The changing terrestrial vegetation has left a record in lake bottoms and bogs which allows analysis of climates back to a 100,000 years ago (Boulton, 1994). Research in recent decades has reconstructed detailed records of climate cycles extending up to 500,000 years ago from high resolution ocean sediment cores, land-based sediments, pollen records, ice cores and coral reef sea level records (Goodess, Palutikof and Davies, 1992: 20). Tree rings can be used to reconstruct variability in complex climatic factors, e.g. precipitation, stream flow, warmth and humidity (LaMarche, 1978). Other principal sources of historical climates are glacier fluctuations, fossil beetle remains and fluctuating snowlines and treelines. Collation and cross comparison of existing observational records can also improve data sources. For example, during the 1990s the observational global average monthly temperature measurements were extended back from 1881 to 1856 (compare Vinnikov, Groisman and Lugina, 1994; Jones *et al*., 2000). This is an area in which scientific research has been successfully reducing the imprecision of the basis for climatic comparisons, and looking for repeated experiences.

Fingerprints, signal and noise

The evidence for greenhouse warming from climate observations suffers the problem of discerning a signal from the background noise. Watts (1982: 447–8) has summarised several features of Earth's climate history which show the difficulty of observing changes in climate as being 'abnormal':

(i) the globe is currently experiencing unusually warm temperatures compared to the last million years;
(ii) warmer centuries than the 1900s have occurred as frequently as cooler ones since the beginning of human history;
(iii) the variance of Northern Hemisphere climate has been 1°C since the ancient Greeks to the present temperature;
(iv) within this 2°C range are the Little Ice Age (fifteenth to sixteenth centuries) and current high temperatures;

(v) the rate and magnitude of greenhouse warming over the next century could equal or exceed historical human experience of climatic warming.

The observed changes in the twentieth century were faster than previous records show but generally remained within historical bounds. Thus, this year's Ethiopian drought, or last year's flooding in Bangladesh, are difficult to identify as results outside of 'normal' climatic variations, at the present time.

The US Department of Energy funded an attempt to detect early signs of anthropogenic climate change (Santer, 1994). The identification of variables which are expected to show a clear link between past GHG levels and climate change would provide what has been termed an enhanced Greenhouse Effect 'fingerprint'. Describing and separating GHG signals from noise of natural background variability is a key task. This noise is solely due to the internal dynamics of the atmosphere and ocean, and unrelated to the effect of GHG concentrations on climate variability. Noise could easily mask climate change. As shown earlier, extreme cold years can occur even in a warmer world without signifying warming has failed to materialise, and conversely severe droughts with a low frequency of occurrence, perhaps every 300 years, can be mistaken for global warming. A fingerprint might show up as theoretical predictions of the pattern of surface air temperature, under a double CO_2 equivalent scenario, which differs from any dominant natural variability pattern identifiable from observations or theoretical models of current and historical climates. The aim is then to find these distinct variables and patterns and try to collect data with sufficient accuracy to provide evidence of GHG-induced climate change. Thus, modelling uncertainty and measurement risk become relevant to the fingerprint exercise.

Feedbacks, complexity and prediction

There is a danger in simplifying systems knowledge and, most relevantly here, failing to accept limits to our ability to understand complexity. For example, feedback mechanisms can either amplify a small change via a positive feedback, or pacify the same change via a negative feedback; treating the systems in a simplified way can therefore lead to the misinterpretation of observational data. This problem relates most seriously to predicting future climate as opposed to defining past norms.

During the 1970s the concern amongst climatologists was as much for global cooling as global warming. The emission of CO_2 was seen to be an important influence upon the operation of the Greenhouse Effect but the outcome was disputed, specifically due to the relative strengths of various feedback mechanisms. In a survey of 24 climatologists, conducted in the late 1970s, 35 per cent expected cooling of between 0.05 to 1.20°C by the year 2000 and the same per cent expected warming of between 0.25 to 1.80°C, with the remaining 30 per cent predicting a status quo of –0.05 to +0.25°C (National Defense University 1978, cited in Kelejian and

Varichek, 1982). Bray (1991) attempts to pour derision on all concerns over the susceptibility of climate to human influence by quoting several eminent scientists who published warnings of global cooling between 1973 and 1976. This concern for cooling was supported by observation of a cooling trend in the decades after the Second World War, now attributed to volcanic activity, which then reversed itself in the late 1970s. Extrapolating trends to the future from relatively short time period data is highly likely to give erroneous forecasts. The implication is that scientists (like everybody else) can be too ready to simplify complex issues, in which case large-scale, irreversible schemes, recommended to solve media-inflated issues, should be avoided. However, the underlying relevance of human impacts on the atmosphere, which has been of consistent concern, is in danger of being written off as just another media 'event'. In addition, outlining a range of scenarios from cooling to warming need only signify honesty about strong uncertainty rather than incompetence as a scientist. The attitude of critics is that there is only one correct scenario and if you back the wrong one you deserve ridicule. This simplistic view of prediction shows the importance of expanding the conception of uncertainty and debating the role of both science and economics.

The experience of the 1970s also signifies one of the main limitations of observational data which is in terms of telling where climate is heading. More generally, there is in principle no reason to expect the past to be a good guide to the future in regard to human perturbation of climatic systems. Looking at, say, the 1930's drought in the US as an analogy for likely impacts in a warmer world may be a useful exercise (see Crosson, 1993), but the way in which systems change in the future due to GHG releases may bear little or no relationship to the processes responsible for historical droughts (and social responses would also be different). The rapid change in atmospheric gases which has occurred this century has no direct historical or paleoclimatic precedent. Paleoclimatic data, from sources such as tree rings or ice cores, while providing a reference norm, are useless for predicting regional and seasonal climate patterns or the rate of change over the coming centuries. The global experiment is unrepeatable. Thus, in order to predict climatic changes, a theoretical model is required and for the natural scientists that means using GCMs. In addition, social scientists have their own models, which attempt to characterise potential futures.

The role of modelling

Scientific models of climate change

One of the main sources for predicting the impacts of global warming is climate simulation modelling using GCMs. While these models tend to be in broad agreement at the global level, significant differences arise between models as results are examined on successively smaller scales, eventually focusing on subcontinental regions. GCMs treat the world as uniform blocks, ignoring topographical and meteorological variations within these blocks. For example, a typical grid might represent as a single average all of Greece, including the Aegean Sea, or an entire region such as Mexico including mountains, plains and deserts. Of the five individual GCMs which have dominated the literature the most detailed grid size has been OSU (4° latitude by 5° longitude), but such high horizontal resolution has only been achieved by simplifying the atmospheric model (two rather than nine layers), although the ocean model is multi-layered (Goodess, Palutikof and Davies, 1992: 77–80). Clearly there are restrictions on the detail which GCMs can obtain and different groups of scientists and modellers decide on the areas in which their models will have the greatest resolution, e.g. oceans, atmosphere or regional scale.

GCMs were designed for basic research in the atmospheric sciences, and thus have drawbacks in their modelling of other systems, e.g. the oceans and biota. As commonly cited, the role of oceans as modelled in GCMs has typically lacked detail. Oceans are known to be both an important sink for CO_2 and a heat sink, but their size in these roles is unclear. For example, the amount of biomass stimulation due to CO_2 enrichment could play a significant role in continued CO_2 uptake by phyto-plankton. Within the atmospheric system the exact role of each trace gas is unknown, and their interactions are complex. While source inventories for CO_2 are reasonably well defined, those for CH_4 and N_2O are vague, and the budget for CO_2 still remains a point of debate.

Yet GCMs are extremely complex, typically solving 200,000 equations on each run, using computers that perform half a billion operations each second. Current examples have developed from using single averages as representative of conditions everywhere to including realistic wind development; cloud formation, precipitation and disappearance; air flows over mountains; moisture exchange with the ocean surface; soil moisture accumulation and evaporation; and snow and ice fluctuations by season and altitude (Firor, 1990: 76). Despite the potential for model variations, results from comparative studies show the results from different GCMs often agree well with each other, and with historical temperature data, over large scales (global, hemispherical, zonal). More than 100 independent studies have given estimates of average global warming within the 1.5°C to 4.5°C range, for a scenario indicating a doubling of CO_2 equivalent, with values near 3°C tending to be favoured (MacDonald, 1988: 437).

The process of GCM construction seems to create a scientific consensus and internal validity. A central issue has been the role of feedback mechanisms which could be either stabilising or destabilising depending on the relative dominance of alternative mechanisms. For example, albedo could be reduced in a warmer world, as the area of snow and ice cover is reduced, leading to further warming. Alternatively, a warmer world may increase cloud cover, cause greater backscatter of incoming solar radiation, and so reduce tropospheric temperatures. The scientific consensus, as witnessed by the dominant warming predictions of GCMs, is that the positive feedbacks will dominate negative feedbacks (Crosson, 1989: 109) and this has been reconfirmed by the IPCC reports (Houghton, Jenkins and Ephraums, 1990; Houghton *et al*., 1996; IPCC Working Group I, 2001).

Yet, as far as greenhouse economics is concerned, there are problems with the type of data GCMs generate. In order to assess economic impacts variance is more useful than means, and regional impacts more useful than global. Where the concern is for scales below the regional extent for which an average is estimated, adopting the average value can be misleading. Two models can have precisely the same average for a regional variable but still give significant spatial differences for that variable within the region. Thus, GCMs have been regarded as inadequate for quantitative prediction even at the level of a multi-state region, let alone a particular state, county or city (Grotch, 1988: 253). The aim has therefore been to link these with regional atmospheric models with correspondingly scaled ecological, hydrological and mesoscale ocean models, although, the IPCC 1995 report warned that: 'Regional modelling techniques, however, rely critically on the GCM performance in simulating large-scale circulation patterns at the regional scale, because these are a primary input to both empirical and physically based regional models' (Kattenberg *et al*., 1996: 345).

The degree of expected error multiplies dramatically as predictions move from global to continental to country to state levels, because GCMs currently treat the world as uniform blocks, ignoring topographical and meteorological variations within these blocks. Yet the more detailed predictions are those required for rigorous proof of the Greenhouse Effect. In addition, questions must be raised about the process of internal validation without reflection upon external concerns. There are, quite simply, unknown factors which scientists are unable to estimate, but about which they are forced to make judgements.

Socio-economic models

In the estimation of socio-economic impacts of climatic change another set of judgements is introduced. Even with 'perfect knowledge' from the scientific models the prediction of future states of the world would be dependent upon the estimation of such factors as population growth, technology and the nature of demand for products. Thus, imperfect information in relation to the implications of the enhanced Greenhouse Effect must consider knowledge about socio-economic effects. For example, while forests are regarded as a physical sink for CO_2, global deforestation currently makes this a net source of that gas. The unknowns pertaining to the socio-economic outcomes of global climate change, while dependent upon the scientific knowledge of physical effects, also feed back upon the physical systems. Thus, the interrelationship of the physical and socio-economic variables increases the inability to predict future events in accordance with the principles of weak uncertainty.

In the face of such complexity economists attempt to simplify the problem by holding factors constant and considering one issue at a time. However, as Kelejian and Varichek (1982: 225) have pointed out, the sum of the partial effects can be completely different from a combined effect occurring simultaneously. They gave the following example: annual increases of CFCs by 10 per cent, CO_2 by 5 per cent, and N_2O by 2.5 per cent as a sum of partial effects on wheat production in the US would be +0.4 per cent. In contrast, the total combined effect of these pollutants being simultaneously released was estimated to be –13.1 per cent.

The practice of analysing the effects of change in only a part of an economy, partial equilibrium analysis, is common in economics. For example, the study of western US agriculture by Adams *et al*. (1988) is typical of this methodology. The successful application requires ignored sectors to be relatively benign in terms of the variables under analysis. Thus, this approach can be misleading if relative prices in secondary sectors are changed by the relevant climatic variables, because all benefit estimates calculated on the basis of stability in those prices are brought into question. This problem can be extended as a critique of regarding inherently dynamic systems as static. Yet the extent to which changes in other sectors affect the results and at what stage such exogenous factors become significant is unclear. In a comparison of partial equilibrium and general equilibrium analyses of climate change, Kokoski and Smith (1987) found very divergent descriptions of the economic impacts where such a large-scale change in environmental conditions affects production activities. Thus, the results of many studies, such as those on agricultural impacts, are brought into question, along with the partial methodology for conducting environmental economic assessments of the enhanced Greenhouse Effect.

Paradoxically, the variations in environmental and socio-economic conditions around the world mean local information is critical for understanding the implications of climate change, e.g. local evaluation of probable species extinction. This would mean assessing national and international risks and potential costs and benefits largely on the basis of induction from numerous local and regional studies (Frederick and Rosenberg, 1994), i.e. partial equilibrium analysis.

In contrast, others have approached the issue from the level of global aggregates, often favouring abstract neo-classical modelling. Continuing efforts are aimed at global cost–benefit analysis of the enhanced Greenhouse Effect. Amongst these attempts that of Nordhaus has been noteworthy.[1] For example, Rowlands (1995: 138) refers to the earlier work by Nordhaus as a prescription to the US administration to avoid co-operative action which commanded significant respect and currency in that country. Others have noted the influence of this work in supporting the US position in international negotiations against emission reduction. The work also exemplifies several points with regard to economic modelling and the treatment of uncertainty.

In his summary volume, Nordhaus (1994), an optimisation model is presented which is purposefully designed to run on a personal computer; this is a stark contrast with the scientific input to the issue which employs Cray supercomputers to run GCMs. While GCMs are, as has been pointed out, still criticised for being too abstract and simple, Nordhaus rejects complex models in favour of 'transparency'. On the surface this appeal seems reasonable because of the tendency for excessive detail in modelling leading to results that are extremely precise but precisely wrong. Unfortunately, the transparency is rhetorical and the outcome is similar to previous models by Nordhaus in that the management of quantitative uncertainty and value-commitments are concealed (Funtowicz and Ravetz, 1994: 203).

The optimisation model approach requires 'developing' the scientific information to obtain 'highly simplified aggregate relationships' (Nordhaus, 1994: 23). Despite this bringing into question any policy relevance of the model or its predictions, Nordhaus claims these studies suggest avoiding a massive effort to slow climate change. This is particularly interesting given the assumptions made in constructing the model on both the physical science and economic sides, which are briefly considered next. Various other problems have been noted in Nordhaus's work (e.g. see Ayres and Walters, 1991; Daily *et al*., 1991; Funtowicz and Ravetz, 1994) and are discussed further in chapter 6.

The scientific assumptions appear to go beyond mere simplification. The deep ocean is assumed to be an infinite carbon sink while the 'missing sink' for CO_2 is ignored. Price (1994) calculates that the unrealistic assumptions about ocean uptake of carbon used by Nordhaus result in the benefits of CO_2 control being under-estimated, at low discount rates, by a factor of four. Climate change is represented by global mean surface temperature, although a better range of variables for impact assessment are precipitation, soil moisture, sea level rise and measurement by seasonal patterns, rate of change and variance (rather than mean). Most attention is paid to CO_2 on the basis that it contributes 80 per cent of global warming (p. 15), although the IPCC only attributed 55 per cent of warming to this gas at the time (Houghton, Callander and Varney, 1992); methane and nitrous oxides are considered to be external to the Nordhaus model. With little explanation a mixture of 1990 IPCC scenarios was chosen for the no action base case; thus CO_2 and N_2O are 'business as usual', CFCs are phased out under the IPCC accelerated policies scenario, and methane emissions occur at the low-level scenario.

Next consider some of the economic assumptions. These include all countries having competitive industries, producing perfect substitutes, with identical Cobb–Douglas production functions,[3] all of which apparently has no effect on major conclusions (Nordhaus, 1994: 8), although one result would be no need for international trade. World estimates of damages are extended from estimates for the US economy, and regional distributions are largely ignored. Impacts are restricted to agriculture, coastlines, energy and 'other' and then bounded in model runs by the percentage of GNP these sectors are judged to contribute to the economy, e.g. agriculture is valued at 2.52 per cent of 1981 GNP ignoring the value of the related food sector. A change in the value of any sector due to increasing relative scarcity or cross-sectoral impacts are ruled out by assuming constant relative prices. The overall outcome is to recommend an optimal policy which leads to a 3.1°C global average temperature rise by 2100.

The way in which uncertain future events are characterised is also particularly revealing. The main treatment of uncertainty is the considerable effort put into sensitivity analysis. There is discussion of difficult-to-calibrate catastrophic scenarios '... which might be equivalent to the damages from a major war, or from a half century of Communist rule' (Nordhaus, 1994: 115). Rather than unknown surprises, such 'catastrophes' are then treated as known threshold events, at which large losses of GNP occur. That is, it is assumed that the states can be known, can be avoided and while large are bounded. There is considerable optimism concerning the ability to assess the risk of future events and the belief is expressed that many of the uncertainties are ones which can be resolved by further study or at least by the passage of time (Nordhaus, 1994: 169).

Overall this type of approach seems to present political argument as the outcome of an objective scientific modelling process. There are clearly a set of implicit values behind the work. For example, the idea of preserving Nature at the expense of economic growth is termed 'ultraconservative'. Nature is described as exogenous and to be regarded as threatening with the potential to 'deal us a nasty hand'. The emphasis is upon a specific model of political economy which is, however, never explicitly described. This study is indicative of more general issues concerning environmental assessment in economics, which is the subject of chapter 6, but also raises the problem of how economics has limited its view of uncertainty.

Conclusions

The approach to characterising uncertainty in relationship to climatic futures under the enhanced Greenhouse Effect has relied upon standard probability theory. This has the ability to show the importance of changing the frequency of events at different extremes and how thresholds may be exceeded or unusual climatic events become more common. Yet a sole emphasis on this approach to uncertainty neglects how knowledge and the ability to understand are limited.

Problems arise in the application of standard risk assessment and probability theory because of the complexity of climate change and its possible consequences. For example, the current size, age and species composition of many ecosystems are unique and have been strongly affected by human activities. Hence, strong uncertainty pertains to ecosystems functions in addition to risk. Biological systems vary over time and space due to physical factors to which they are related in a non-linear fashion. In order to study the effect of changes in atmospheric chemistry upon biological systems, data analysis must be based upon fluxes, variances, extreme events and 'noise', rather than concentrations, smoothed means and steady states (Williamson, 1992: 32).

A search for evidence about the implications of GHG emissions has led to modelling exercises to reduce strong uncertainty. Reliance for prediction has concentrated on simulation models (e.g. GCMs) as opposed to historical analogue because global temperatures are expected to occur at unprecedented rates. This need for artificial scenarios is a recognition of indeterminacy and partial ignorance. However, the extent to which models are then expected to provide answers seems to ignore their limitations. For example, the Northern Hemisphere, having most of the land area, is liable to heat more rapidly than the Southern Hemisphere, with most of the oceans; the result could change the general circulation of the atmosphere but would fail to be recognised by GCM models working on steady-state calculations, i.e. assuming shifts from one stable equilibrium to another (Firor, 1990: 78). A feature of non-linear systems is that small changes in a forcing variable can lead to abrupt and large changes in a dependent variable. Examples are the disruption of the El Niño systems or the North Atlantic Gulf Stream. The El Niño is an unusual warming of the water in the Equatorial Pacific appearing every three to five years and having a strong influence on weather patterns. The late 1990s saw intense El Niño causing extreme weather events in the Americas, Australia and Africa (May, 1997). Similarly, small changes in regional transportation of heat by oceans (a major heat reservoir) can have large but unpredictable impacts on local climate. The interactions between climate, atmosphere and oceans are areas of strong uncertainty (see on-going scientific research by Christiansen *et al*., 2000). In this regard concern has been expressed for any disruption of the Gulf Stream which transports heat to the British Isles.[2] As the UK government's chief scientific officer has stated: 'The possibility that this might be significantly reduced, much less turned off, is an awesome prospect' (May, 1997: 5).

The idea that uncertainty can be reduced, and even eradicated, by more research, seems common amongst both natural scientists and economists. However, several points can be raised against such a prognosis: the persistence of weak uncertainty due to measurement errors; the persistence of strong uncertainty due to differences in the interpretation of given 'facts'; the methodological problem that evidence can only disprove but never prove a theory; the existence of irreducible ignorance; the lack of any single metric for damage assessment; and the persistence of unknown cause–effect relationships. The type of work being produced by economists exemplifies how implicit value-loaded boundaries are drawn in terms of designating which knowledge is employed. While the social aspect of economic knowledge may be deemed to make it implicitly subjective, a similar methodological problem also faces natural scientists. That is, how environmental problems are characterised is seen to be determined by assumptions which restrict the focus of any given research.

The alternative to trying to define risk states is to accept that global systems are inherently unpredictable so that many different outcomes are equally likely. Strong uncertainty must then be regarded as a property of the system rather than a failure of scientific method which can be removed in the long term or by increased research budgets. Yet the main approach to uncertainty being put forward by both scientists and economists limits itself to weak uncertainty and fails to discuss the meaning or content of strong uncertainty.

Notes

1 The faith of Nordhaus in the potential of neo-classical modelling is witnessed by his stating that: 'Our future lies not in the stars but in our models' (Nordhaus, 1994: 6).

2 The heat being delivered amounts to 27,000 times the total power-generating capacity of the UK. Increased precipitation in the region flowing into the North Atlantic would reduce surface water salinity. This less dense water would fail to sink as easily so changing the fluid dynamics, impacting deep ocean circulation and the Gulf Stream.

3 A particular type of production function of the form:
$Q = b_0 x_1^{b1} x_2^{b2} \ldots x_n^{bn}$
Where Q is output, x are factors of production (e.g. capital, labour) and b are parameters. The name derives from the authors Cobb and Douglas who introduced it in an article published in the *American Economic Review* in 1928. The function has been widely used in economics especially in the form where the parameters add to one.

References

Adams, R.M., B.A. McCarl, D.J. Dudek and J.D. Glyer (1988) 'Implications of global climate change for western agriculture', *Western Journal of Agriculture Economics* **13**(2): 348–56.

Adger, N. and S. Fankhauser (1993) 'Economic analysis of the greenhouse effect: optimal abatement level and strategies for mitigation', *International Journal of Environment and Pollution* **3**(1–3): 104–19.

Ayres, R.U. and J. Walters (1991) 'The greenhouse effect: damages, costs and abatement', *Environmental and Resource Economics* **1**(3): 237–70.

Boulton, G.S. (1994) *The spectrum of recent climatic change and its reflection in the biosphere*. Presented at The Royal Society of Edinburgh, 2 February 1994.

Bray, A.J. (1991) 'The ice age cometh: remembering the scare of global cooling', *Policy Review* **58**: 82–4.

Christiansen, H.H., L.E. Mortensen, T. Nielsen, T.L. Rasmussen and O. Humlum (2000) *Linking Land and Sea at the Faroe Islands: Mapping and Understanding North Atlantic Changes*. Copenhagen: University of Copenhagen.

Crosson, P. (1989) 'Greenhouse warming and climate change: why should we care?', *Food Policy* (May): 107–18.

Crosson, P. (1993) 'Impacts of climate change on the agriculture and economy of Missouri, Iowa, Nebraska, and Kansas (MINK) region', in *Agricultural Dimensions of Global Climate Change,* edited by H.M. Kaiser and T.E. Drennen, pp. 117–35, Boca Raton, FL: St Lucie Press.

Daily, G.C., P. R. Ehrlich, H.A. Mooney and A.H. Ehrlich (1991) 'Greenhouse economics: learn before you leap', *Ecological Economics* **4**: 1–10.

Firor, J.W. (1990) *The Changing Atmosphere: A Global Challenge*. New Haven, CT: Yale University Press.

Frederick, K.D. and N.J. Rosenberg (eds) (1994) *Assessing the Impacts of Climate Change on Natural Resource Systems*. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Fukui, H. (1979) *Climatic Carriability and Agriculture in Tropical Moist Regions*. Presented at World Climate Conference, Geneva, 12–23 February 1979.

Funtowicz, S.O. and J.R. Ravetz (1994) 'The worth of a songbird: ecological economics as a post-normal science', *Ecological Economics* **10**(3): 197–207.

Goodess, C.M., J.P. Palutikof and T.D. Davies (1992) *The Nature and Causes of Climate Change: Assessing the Long Term Future*. London: Belhaven.

Grotch, S.L. (1988) *Regional Intercomparison of General Circulation Model Predictions and Historical Climate Data*. Washington, DC: Department of Energy.

Hansen, J.E. (1988) *Testimony to US Senate*. Presented at Committee on Energy and Natural Resources, Washington, DC, 23 June 1988, Alderson Reporting Company.

Hare, F.K. (1979) *Climatic Variation and Variability: Empirical Evidence from Meteorological and Other Sources*. Presented at World Climate Conference, Geneva, 12–23 February 1979.

Hare, F.K. (1985) 'Climatic variability and change', in *Climate Impact Assessment: Studies of the Interaction of Climate and Society* **SCOPE 27**, edited by R.W. Kates, J.H. Ausubel and M. Berberian, pp. 37–68, Chichester: John Wiley & Sons.

Harrison, S.J. (1991) *Global Warming: Predicting the Uncertain*. Department of Environmental Science, Stirling: University of Stirling Climate Services.

Houghton, J.T., B.A. Callander and S.K. Varney (eds) (1992) *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*. Cambridge, England: Cambridge University Press.

Houghton, J.T., G.J. Jenkins and J.J. Ephraums (eds) (1990) *Climate Change: The IPCC Scientific Assessment*. Cambridge, England: Cambridge University Press.

Houghton, J.T., L.G. Meira, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell (eds) (1996) *Climate Change 1995: The Science of Climate Change*. Cambridge, England: Cambridge University Press.

IPCC Working Group I (2001) *Climate Change 2001: Scientific Assessment; Summary for Policymakers*. Geneva: Intergovernmental Panel on Climate Change.

IPCC Working Group II (2001) *Climate Change 2001: Impacts, Adaptation, and Vulnerability; Summary for Policymakers*. Geneva: Intergovernmental Panel on Climate Change.

IPCC Working Group III (2001) *Climate Change 2001: Mitigation of Climate Change; Summary for Policymakers*. Geneva: Intergovernmental Panel on Climate Change.

Jones, P.D., D.E. Parker, T.J. Osborn and K.R. Briffa (2000) 'Global and hemispheric temperature anomalies: land and marine instrumental records', in *Trends: A Compendium of Data on Global Change*. Oak Ridge, TN: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy.

Jouzel, J., C. Lorius, J.R. Petit, N.I. Barkov and V.M. Kotlyakov (1994) 'Vostok isotopic temperature record', in *Trends '93: A Compendium of Data on Global Change* ORNL/CDIAC-65, edited by T.A. Boden, D.P. Kaiser, R.J. Sepanski and F.W. Stoss, pp. 590–602, Oak Ridge, TN: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy.

Kattenberg, A., F. Giorgi, H. Grassl, G.A. Meehl, J.F.B. Mitchell, R.J. Stouffer, T. Tokioka, A.J. Weaver and T.M.L. Wigley (1996) 'Climate models: projections of future climate', in *Climate Change 1995: The Science of Climate Change,* edited by J.T. Houghton, L.G. Meira, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell, pp. 285–357, Cambridge, England: Cambridge University Press.

Keeling, C.D. and T.P. Whorf (2000) 'Atmospheric CO_2 records from sites in the SIO air sampling network', in *Trends: A Compendium of Data on Global Change*. Oak Ridge, TN:

Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy.

Kelejian, H.K. and B.V. Varichek (1982) 'Pollution, climate change, and consequent economic costs concerning agricultural production', in *The Economics of Managing Chlorofluorocarbons: Stratospheric Ozone and Climate Issues,* edited by J.H. Cumberland, J.R. Hibbs and I. Hoch, pp. 224–68, Washington, DC: Resources for the Future.

Kokoski, M.F. and V.K. Smith (1987) 'A general equilibrium analysis of partial-equilibrium welfare measures: the case of climate change', *American Economic Review* **77**(3): 331–41.

LaMarche, V.C. (1978) 'Tree ring evidence of past climatic variability', *Nature* **276**(November): 334–8.

MacDonald, G.J. (1988) 'Scientific basis for the greenhouse effect', *Journal of Policy Analysis and Management* **7**(3): 424–44.

Manne, A.S. and R.G. Richels (1992) *Buying Greenhouse Insurance: The Economic Costs of CO_2 Emissions Limit*. Cambridge, MA: MIT Press.

May, R. (1997) *Climate Change*. London, Office of Science and Technology.

Nordhaus, W.D. (1994) *Managing the Global Commons: The Economics of Climate Change*. Cambridge, MA: MIT Press.

Parry, M.L. and T.R. Carter (1986) 'Effects of climatic changes on agriculture and forestry: an overview', in *Effects of Changes in Stratospheric Ozone and Global Climate* **I**, edited by J.G. Titus, pp. 257–98, Washington, DC: US Environmental Protection Agency.

Petit, J.R., D. Raynaud, C. Lorius, J. Jouzel, H. Delaygue, N.I. Barkov and V.M. Kotlyakov (2000) 'Historical isotopic temperature record from the Vostok ice core', in *Trends: A Compendium of Data on Global Change*. Oak Ridge, TN: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy.

Price, C. (1994) *Emissions, Concentrations, and Disappearing CO_2*. Bangor: University College of North Wales.

Riebsame, W.E. (1989) *Assessing the Social Implications of Climate Fluctuations: A Guide to Climate Impact Studies*. Nairobi, Kenya: UNEP, World Climate Impacts Programme.

Rowlands, I.H. (1995) *The Politics of Global Atmospheric Change*. Manchester, England: Manchester University Press.

Santer, B.D. (1994) *The detection of greenhouse-gas-induced climate change*. Research Summary no. 29. Oak Ridge, TN: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy.

Vinnikov, K., P. Groisman and K.M. Lugina (1994) 'Global hemispheric temperature anomalies from instrumental surface air temperature records', in *Trends '93: A Compendium of Data on Global Change* ORNL/CDIAC-65, edited by T.A. Boden, D.P. Kaiser, R.J. Sepanski and F.W. Stoss, pp. 615–27, Oak Ridge, TN: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy.

Watts, J.A. (1982) 'The carbon dioxide queston: a data sampler' in *Carbon Dioxide Review 1982*, edited by W.C. Clark, pp. 431–69, Oxford: Clarendon Press.

Williamson, P. (1992) *Global Change: Reducing Uncertainties*. Stockholm, Sweden: International Geosphere-Biosphere Programme.