

# Climate Change Prediction

A challenging scientific problem

Institute *of* **Physics**



This paper, produced on behalf of the Institute of Physics by Professor Alan J. Thorpe, explains how predictions of future climate change are made using climate models. It is hoped that the paper will increase believability in these models and be persuasive that anthropogenic activity is likely to be causing global warming. It aims to convince policy-makers, the general public and the scientific community that the threats posed by global climate change are real.

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## A challenging scientific problem

By

Professor Alan J. Thorpe

Climate change is one of those issues where science is crucial in determining government and international policy-making. Like the weather, everyone has a view on climate change but, as will be discussed, not all such views, such as the one reproduced below, are equally defensible on scientific grounds:

*“The claim of man-made global warming represents the descent of science from the pursuit of truth into politicised propaganda. The fact that it is endorsed by the top scientist in the British government shows how deep this rot has gone.”* Melanie Phillips, *Daily Mail*, 12 January 2004.

Climate change is a fundamental problem involving basic science including physics. There is much research still to be done before we get to a position of sufficient certainty about all the aspects of climate change that are required by society to plan for the future. Predictions of future climate change, based on numerical global climate models, are the critical outputs of climate science. Whilst much has been written about the details of the predictions themselves, scepticism about the prediction models is rife and this is why this paper is devoted to de-mystifying the prediction methodology. Consequently this paper focuses on the scientific basis of climate change prediction. As for all problems in science, uncertainty and its quantification are a fundamental part of the scientific process and thus they will figure largely in this paper. There is little doubt that a lack of knowledge about how climate change is predicted and the associated uncertainties are amongst the main reasons for ill-informed comment on climate change.

## What is climate? Evidence of change

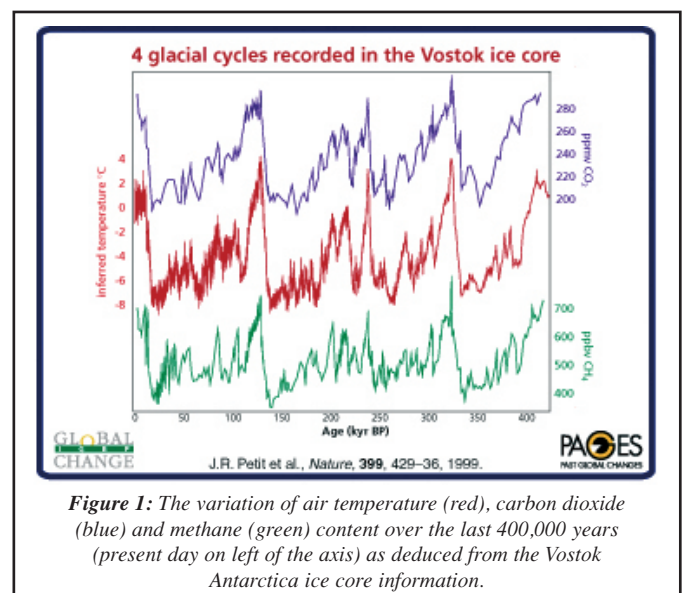
Weather is the state of the atmosphere at a given time whilst *climate* is the average weather over a period of time. The state of the atmosphere is usually given in terms of its temperature, atmospheric composition (for example, water vapour, liquid water or carbon dioxide content), wind speed and direction, pressure and density. In addition the intensity of solar and terrestrially emitted radiation are fundamental determining factors. The characteristic timescale of the variability of the atmosphere at various spatial scales is critical in deciding whether and how the future state of the weather and climate might be forecast. It is the presence of relatively slow time and large space scale phenomena in the atmosphere which means both that accurate forecasts can be made and that society can benefit from them.

As the atmosphere interacts with the underlying surface – oceans, land, and ice – the term *climate system* is used to encompass both the atmosphere and the influence of the Earth's surface on climate. Understanding and predicting both the climate and other properties of the atmosphere, the surface and sub-surface media are now referred to as *Earth System Science* reflecting a holistic view of the system. The long timescale of mixing and transport of heat in the oceans is a key factor in determining the timescale of climate variations.

Climate is a time-average of weather, but what makes it complex is that this average varies in time. Clearly if we average over the complete history of the Earth's atmosphere there is a single climate state. However any finite average varies significantly on all longer timescales. The reason for these variations is crucial in understanding the physics of climate and of climate change. It is commonplace to look at climate averages over weekly, monthly, seasonal, annual, decadal, centennial, millennial and longer time periods and figure out how climate, so defined, varies on all longer timescales.

Knowledge of past variations in the Earth's climate has been acquired from a wide variety of both direct measurements and other indirect or proxy information. This reconstruction of the climate record shows that climate, for example, annual or decadal averages, has varied significantly on a wide range of timescales. Information about the variation

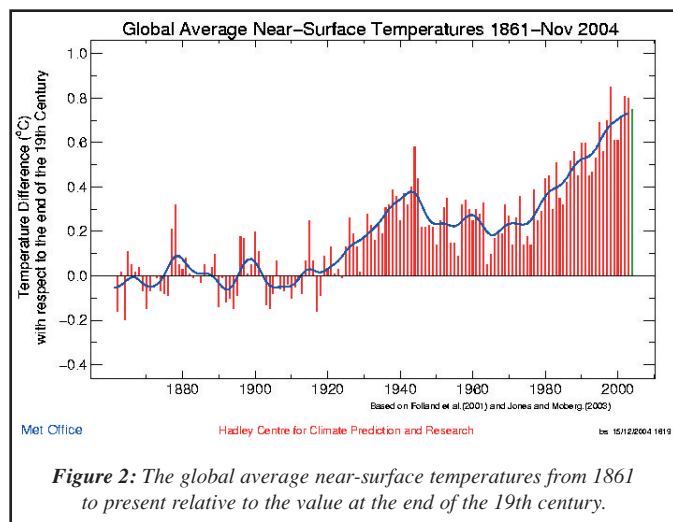
of temperature in Antarctica is available from the Vostok ice core records over the past 400,000 years; see Figure 1. This is a period that covers only about 0.01% of the lifetime of the Earth's atmosphere. During these 400,000 years there are variations in Antarctica from about  $-10^{\circ}\text{C}$  to  $+4^{\circ}\text{C}$  relative to present day values. The periods with the lowest temperatures are the ice ages whilst warmer epochs, such as at present are interglacials. There has been a relatively regular pattern of four ice ages and five interglacials over this period. The transition from an ice age to the warmest temperatures in the following interglacial is relatively rapid ( $\sim 10,000$  years or less) followed by a much more gradual cooling, interrupted by significant fluctuations, over  $\sim 100,000$  years or more towards the next ice age.



**Figure 1:** The variation of air temperature (red), carbon dioxide (blue) and methane (green) content over the last 400,000 years (present day on left of the axis) as deduced from the Vostok Antarctica ice core information.

Whilst important for understanding the causes of climate change, such timescales are of less interest to the development of human societies. Considerable effort has been devoted to using proxy information, such as from tree rings, to estimate change over the past 1000 years or so and the climate appears to have been noticeably lacking in significant variations. The so-called instrumental record period, when there have been accepted meteorological instruments that can be utilised to measure climate, has been available since about 1860, which is a very small fraction of the lifetime of the Earth's atmosphere. There is an accepted **global** change over the last 100 years of nearly  $0.8^{\circ}\text{C}$  (with an uncertainty of  $\pm 0.2^{\circ}\text{C}$ , 95% confidence interval) in the global-average near surface temperature, with this rise – a.k.a. global warming – focused into the periods 1910 to 1945

and 1980 to present; see Figure 2. Regionally in 2004 this translates into a maximum warming relative to the end of the 19th century over, for example, parts of the Arctic by about 5°C and overall the land has warmed at about twice the rate of the oceans. These variations are noteworthy not least as they have occurred over a short time period and society is increasingly vulnerable to climate change both because of the huge increase in the total population and because of the way it organises itself.

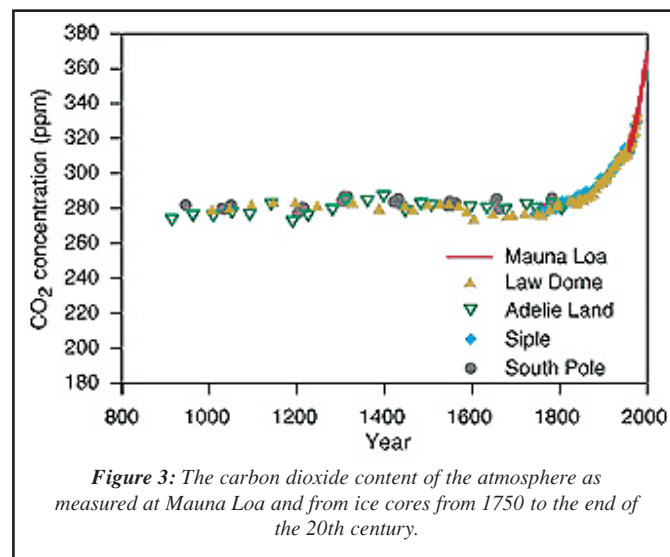


## The physics of climate

Weather and climate exist because of the distribution of energy from incoming short-wave solar radiation that drives the circulation of the atmosphere relative to the underlying surface. For a steady state, climate properties such as temperature can be supposed to result from a long-term equilibrium between received energy from the Sun and outgoing energy emitted by the warm planet. The existence of an atmosphere that is capable of absorbing and re-transmitting certain wavelengths in the electromagnetic spectrum means that there must be a so-called *greenhouse effect* whereby the atmosphere traps outgoing infrared radiation, thereby increasing the atmospheric temperature (see box insert and Andrews 2000). This was first postulated by Jean-Baptiste Fourier in 1827 and further elaborated upon by John Tyndall in 1860 and Svante Arrhenius in 1896. It was Arrhenius who first noted that, say, a doubling of the carbon dioxide concentration in the atmosphere could lead to an increase in surface temperature of some 5 to 6°C.

Atmospheric absorption in the infrared is caused by the presence in the atmosphere of gases (so-called greenhouse gases) such as water vapour, carbon

dioxide and ozone. These gases occur in the present-day atmosphere in small concentrations and so they are referred to as minor constituents. Pre-industrial concentrations of carbon dioxide were about 280 parts per million (ppm) whilst the current day value is around 370ppm – the difference being attributable to human emissions from, for example, the burning of fossil fuels; see Figure 3.



To simplify significantly, the equilibrium temperature at the surface depends on three factors: the concentration and vertical distribution of the minor constituents that determine the magnitude of the greenhouse effect, via  $\tau$ ; the Sun's output of radiation, via  $S$ ; the reflectivity of the Earth to that incoming solar radiation determined by surface, aerosol and cloud properties, via  $a$ . These three parameters tell us a lot about the climate change problem. Solar output leading to  $S$  is not a constant but note that it is independent of the atmosphere. The concentration of minor constituents is being changed by human activities such as fossil fuel burning but also by changes in the flora and fauna and volcanic out-gassing etc. The planetary reflectivity, or albedo, depends on the internal dynamics and physics of the atmosphere and in particular the cloud content, as well as land use, which is controlled by human activities. The human input of aerosols to the atmosphere reflects back incoming solar radiation and may make clouds more reflective – it is thought this has acted to partially offset the amount of global warming (sometimes called global dimming). The fact that the amount of cloud is altered, in principle, by temperature shows that there is the possibility of feedbacks in the climate system. Other feedbacks include: (i) the melting of sea-ice leading to reduced albedo and

## Greenhouse Effect

Using radiative transfer theory we can relate the intensity of outgoing infrared radiation at a given frequency at the top of the atmosphere,  $I_{TOA}$ , to surface and atmospheric properties:

$$I_{TOA} = I_{SFC} \tau + \int_0^{z_{TOA}} B(T) W(z) dz \quad (1)$$

where  $I_{SFC}$  is the infrared radiation emitted by the Earth's surface at temperature  $T_{SFC}$ ;  $\tau$  is the atmospheric transmittance at a given frequency;  $B(T)$  is the Planck function;  $T(z)$  is the height ( $z$ ) dependent atmospheric temperature;  $W(z)$  is the height dependent weighting function governed by the vertical distribution of constituents of the atmosphere responsible for absorption and emission of infrared radiation by the atmosphere itself. The fact that  $\tau$  is less than unity (and  $W \neq 0$ ), because of the presence in the atmosphere of absorbing greenhouse gases, means that the atmosphere exerts a significant influence on the global temperature – the greenhouse effect.

If we simplify equation (1) by integrating over frequency, assume that the atmosphere has a characteristic (infrared brightness) temperature,  $T_A$ , and use Stefan-Boltzmann's law, then for radiative equilibrium:

$$\sigma T_e^4 = \bar{\tau} \sigma T_{SFC}^4 + (1 - \bar{\tau}) \sigma T_A^4 \quad (2)$$

where  $\bar{\tau}$  is an average transmittance and the emission temperature  $T_e$  is given by:

$$T_e = \sqrt[4]{\frac{(1-a)S}{4\sigma}} \quad (3)$$

where  $S$  is the total solar irradiance at the mean distance of the Earth from the Sun ( $\sim 1367 \text{Wm}^{-2}$ ),  $\sigma$  is Stefan-Boltzmann's constant and  $a$  is the planetary reflectivity, or *albedo*, to incoming solar radiation ( $\sim 0.3$ ). This albedo arises from reflection of solar radiation from bright surfaces such as snow and clouds; note that the atmosphere is relatively transparent to incoming solar radiation. Thus  $T_e \sim 255\text{K}$  and this would be the chilly temperature at the Earth's surface if there wasn't an atmospheric greenhouse effect (i.e., if  $\bar{\tau} = 1$ ). In fact the atmosphere absorbs up-welling infrared radiation and radiates infrared both upwards and downwards. Hence:

$$2(1 - \bar{\tau}) \sigma T_A^4 = (1 - \bar{\tau}) \sigma T_{SFC}^4 \quad (4)$$

Substituting equations (4) into (2) gives the following estimate for the temperature of the air near the surface of the Earth:

$$T_{SFC} = T_e \sqrt[4]{\frac{2}{(1 + \bar{\tau})}} = \sqrt[4]{\frac{(1-a)S}{2(1 + \bar{\tau})\sigma}} \quad (5)$$

Note that this simplified description (wrongly) ignores other heat transfer mechanisms. A value of  $\bar{\tau}$  consistent with current concentrations of greenhouse gases might be 0.2 and so equation (5) gives a crude estimate of the globally averaged surface temperature,  $T_{SFC}$ , in the presence of the greenhouse effect, of 287K, i.e., a greenhouse effect that warms the surface by about 32°C. If the atmosphere were entirely opaque in the infrared we would have,  $\bar{\tau} = 0$ . Then if there was no change in albedo in this simplified model,  $T_{SFC} \sim 303\text{K}$ .

further warming, and (ii) higher temperatures leading to more atmospheric water vapour and an enhanced greenhouse effect. It is the ability of humans to alter the greenhouse effect that shows that the term “anthropogenic climate change” is a meaningful concept.

The concentration of greenhouse gases also varies naturally over the geological history of the Earth. Over the period of the Vostok ice core record, back to 400,000 years ago, levels of carbon dioxide are

thought to have varied between about 180 and 280ppm with this variation mirroring that of the ice age-interglacial temperature cycles. It is believed that it is only prior to about 20 million years ago that carbon dioxide levels exceeded current day values with epochs hundreds of million years ago when concentrations were in excess of 5000ppm.

If there is a human-induced climate modification then present-day climate variations are a mixture of natural and anthropogenic contributions. The



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*detection* of climate change relies on measurements of recent past climate variations and the *attribution* of climate variations to anthropogenic sources attempts to find the contribution to observed or predicted change from these sources. Given that we have only one climate system to measure, it is extremely difficult to be definitive about attribution although this can be done using statistical and modelling approaches. The problem with attribution being that a natural trend can exist over certain time periods, even without human modifications, as part of a longer-term natural oscillation. It is particularly popular to ask questions such as “is the recent severe weather event caused by global warming?” and extremely difficult to answer them definitively.

### How is weather and climate forecast?

Whilst the debate about why climate change has been happening is often heated, that concerning predictions of future climate change can be vitriolic in the extreme. Being able to predict the outcome of an experiment is the touchstone for whether we have understood the underlying physics. So how do we predict climate change?

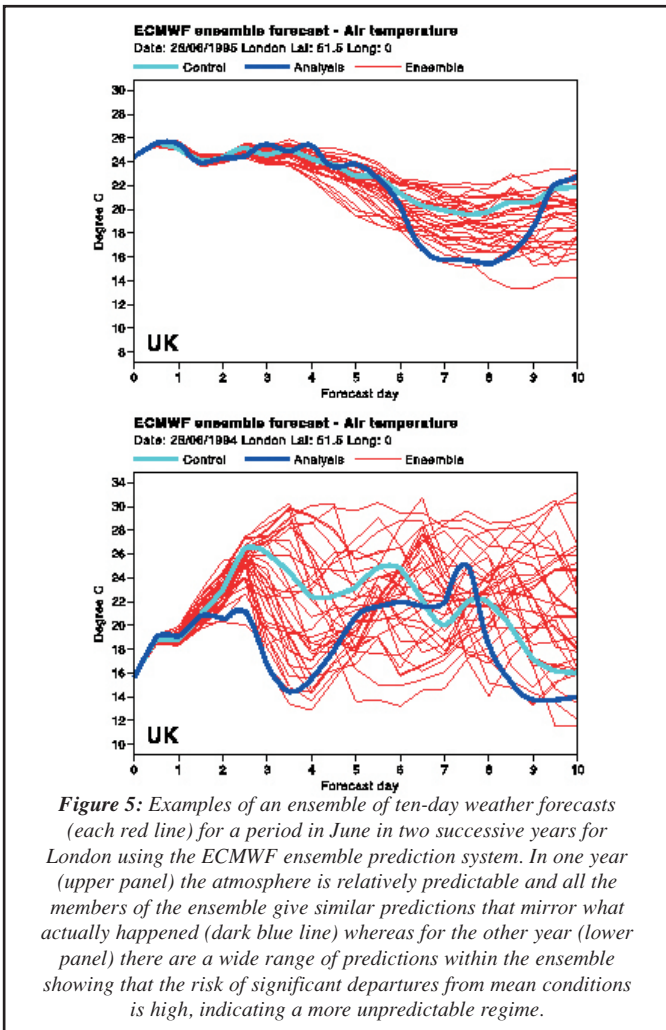
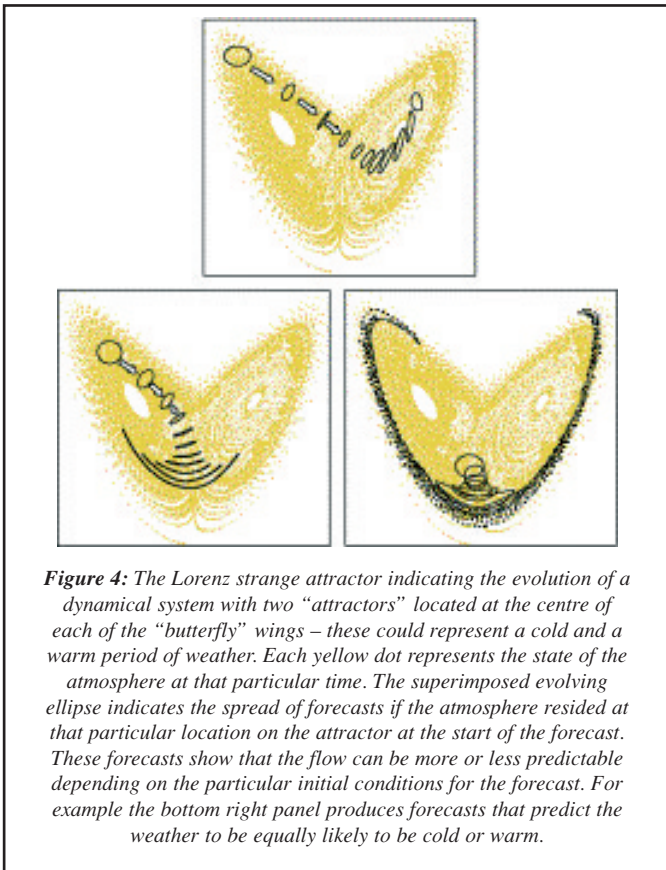
Weather forecasting is the best place to start because the forecasts are more familiar and the methodology is very similar in many important ways to climate prediction. A weather forecast involves numerically integrating forward in time equations that describe the evolution of the atmosphere starting from a set of initial conditions. The equations used are the classical laws of (fluid) mechanics and thermodynamics that are known to apply well to the atmosphere. The numerical solutions require the atmosphere to be divided up into a large three-dimensional lattice of *grid points* at which the atmospheric variables are held in the *model* and on which the equations are solved using finite numerical approximations. The initial conditions arise from *global measurements* of the state of the atmosphere interpreted using a prior short-range forecast of that state using the model forecast system. The measurements have an uncertainty because they are: (a) insufficient in number to initialise every variable at every grid point, (b) usually not located at grid points, and (c) have a degree of measurement error.

From the viewpoint of knowing whether the physics in the model is correct, the fact that weather

forecasting has been done routinely every day for about the last thirty years is significant. Many, many weather states have been forecast over that period and so experimental repetitions certainly exist – although one could argue that few states have been sampled compared to the lifetime of the atmosphere! On the whole, weather forecasts are both incredibly successful and useful to society, which is why they continue to be produced even though they involve considerable expense. Numerical weather predictions have an element of uncertainty and meteorological science has devoted considerable effort to understand why. The answer has led to a major shift in the way classical physics is understood.

The numerical model introduces uncertainties because of the finite approximation to the continuous equations. This approximation has two related aspects – one that there is a truncation error because of the numerical method and the other because the effects of scales of motion smaller than the *grid resolution* (the distance between neighbouring grid points) on the resolved scale flow must be included. The representation of these sub-grid-scale effects is called *parametrisation*. Secondly the measurements of the atmosphere introduce an uncertainty because of their insufficient number and inherent inaccuracies. Uncertainty in initial conditions means that two forecasts started from almost identical initial conditions will diverge slowly at first but then radically such that the two predicted states become as different from one another as two observed states picked at random. This sensitivity to initial conditions and to model formulation, are prime examples of *chaos*, about which much has been written following on from its introduction into modern physics by the meteorologist Ed Lorenz; see Figure 4. The realisation of the pervasive relevance of chaos to physics has been a reminder that whilst physicists might like to imagine that classical physics is understood in principle, there are fundamental aspects still left to be uncovered in its practice.

Knowledge of uncertainty has been turned to our advantage. By calculating a set of multiple forecasts – an *ensemble* – the members of which differ only slightly in their initial conditions and in their parametrisations, forecasts can now not only predict the most likely future weather but also the risk that nature will deviate from this most likely predicted



state. So we are now in the era of predicting **both** the most likely weather to come but also the chance that the forecast is wrong; see Figure 5. This ability to predict in a probabilistic way represents a profound advance in the science that is often overlooked or misinterpreted.

On both empirical and theoretical grounds it is thought that skilful weather forecasts are possible perhaps up to about 14 days ahead. At first sight the prospect for climate prediction, which aims to predict the average weather over timescales of hundreds of years into the future, if not more does not look good! However the key is that climate predictions only require the average and statistics of the weather states to be described correctly and not their particular sequencing. It turns out that the way the average weather can be constrained on regional-to-global scales is to use a climate model that has at its core a weather forecast model. This is because climate is constrained by factors such as the incoming solar radiation, the atmospheric composition and the reflective and other properties of the atmosphere and the underlying surface. Some of these factors are external whilst others are determined by the climate itself and also by human activities. But the overall radiative budget is a powerful constraint on the climate possibilities. So whilst a climate forecast model could fail to describe the detailed sequence of the weather in any place, its climate is constrained by these factors if they are accurately represented in the model. Physicists are used to such ideas – the kinetic theory of gases allows average properties of the system to be accurately quantified even though the location and momentum of each molecule need not, and cannot, be predicted accurately.

The analogy with the kinetic theory of gases tells us that it is probably possible to describe certain gross aspects of climate (for example, global average near-surface air temperature) without recourse to detailed numerical models and the radiative transfer calculation given earlier is an example of this. But if we want to predict local properties of the climate system and their evolution in time, we need to use a numerical climate model.

How does a climate model differ from a weather model? Currently computational limitations restrict climate models to be run with grid points significantly further apart than weather models.



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Also a climate model requires the interactions between the atmosphere, the oceans and the land/ice surface to be included. The atmospheric part is a global weather model, extended to be able to include the temporal evolution of key atmospheric constituents, whilst the ocean component consists of a similarly structured fluid-dynamical model of ocean properties such as currents, heat and composition. The land/ice surface properties are included particularly as they determine the reflectivity and other key aspects of the climate system.

Putting these components together to make a climate model is a complex task. Critical for belief in the science of climate change predictions is the demonstration that such climate models are capable of producing accurate predictions for the right reasons. Physicists will want to describe a given system/experiment with theories/models with a range of complexity and it is the consistency of understanding amongst these theories/models that is powerful in allowing us to believe that we have a credible physically consistent explanation. The fact that we have simplified descriptions, such as that based purely on radiative considerations, for the greenhouse effect is crucial and enhances the credibility of the predictions from detailed climate models.

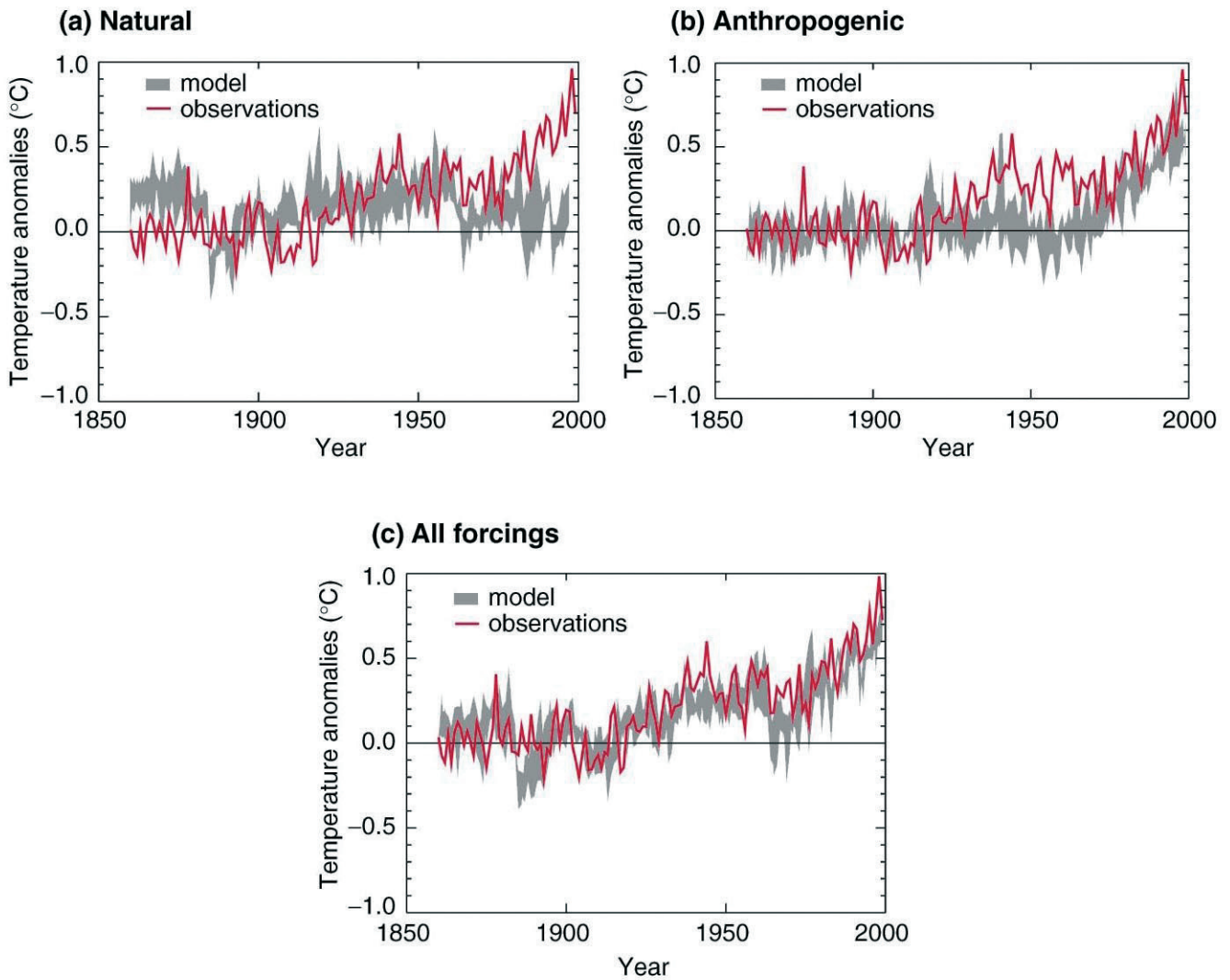
There are, of course, significant uncertainties in the parametrised physical, chemical and biological processes in climate models. Physical processes represent the difficult parts of the physics – we are sure that Newton’s laws of motion apply but the precise details of how to represent the multiplicity of forces that exist and how they depend on atmospheric, and other, properties is extremely challenging. One example, of many, concerns the drag coefficient that determines the degree of frictional retardation of the flow as it moves across the rough Earth’s surface. This is known to within a tolerance of say,  $\pm 10\%$ . The method to explore the way in which such uncertainties in the model effect the predictions is to create a climate ensemble prediction in much the same way as is done for weather forecasting. The climate ensemble uses a set of similar but slightly different initial conditions and model formulations to span this uncertainty space. Then the risk of possible climate change can be evaluated explicitly. The uncertainties of the initial conditions and model formulations are a measure of

the level of knowledge we have about the physics of the climate system. However quantifying the effect of these uncertainties on the climate predictions themselves is a vital aspect of the scientific method. Many commentators imagine that this implies we cannot believe the output of climate models. But they have misunderstood the critical nature of uncertainty and risk in science, particularly the science that feeds directly into policy.

How can we evaluate whether these climate predictions are credible – or to put it another way, how can we estimate the information content of the climate forecast? The fact that a weather forecast model is at the heart of the climate model and this is independently shown to be valid is an important feature. Also climate models can be run for current day climate conditions assuming no further human-produced increase in greenhouse gases. This should reproduce the statistics of current climate and not drift because of imperfections in the overall modelled radiation balance. In addition the model can be run including the known varying concentration of greenhouse gases over the period 1850 to present and other external forcing factors such as volcanic eruptions and variability in solar output (also used to simulate past climates in the geological record). The “hindcasts” made in these ways reproduce many aspects of the (relatively well) observed climate over that period. Indeed it is possible to show, by including each forcing separately, that the solar variations that have occurred cannot explain the recent few decades of warming and that human input of greenhouse gases are most likely responsible for this warming; see Figure 6. A more complete ensemble may show, however, that there are a number of different ways such climate models can balance processes to pass this test.

It is sometimes imagined that such tests of the model are rigged in some way because, as has been discussed, there are various empirical and other parameters in the parametrisation components of the model that are to a degree uncertain and so perhaps these could be tuned to get the “right” answer. It is wildly over-simplistic to suppose that a few parameter values can be adjusted to reproduce the many diverse attributes that constitute the complex behaviour of the climate system. If it were possible to do this we would indeed have emerged with a climate “theory of

## Simulated annual global mean surface temperatures



**Figure 6:** Hindcast of twentieth century global temperature record with the Hadley Centre model. The red line is from the observations and the grey band is the range of model predictions; (a) includes only natural climate forcings such as solar output and volcanoes, (b) includes only human input of greenhouse gases and aerosols, (c) includes all forcings.

everything"! The very complexity of the model (maybe three-quarters of a million lines of computer code) tells us that it is almost certain to be impossible to cheat in this way.

It is clear, however, that climate forecasting does not have the luxury of the quantity of multiple independent forecasts to prove its overall level of accuracy that is available to weather forecasting. In addition we may need to wait for some time before we can test fully the predictions of future climate change. But this does not mean the predictions are necessarily either inaccurate or not credible as is sometimes implied. There is little doubt that there is still some way to go to simulate accurately all facets of the climate system with such models. The era of ensemble climate prediction is only just beginning

now. But we will soon be able to say more quantitatively what level of uncertainty we attach to predictions of various facets of the climate system – the fact that some are more uncertain than others does not mean that all predictions are to be treated as worthless.

What are the future prospects for reducing uncertainty in climate predictions? There are very substantial improvements that will be made possible by increasing the resolution of the models utilising next generation supercomputer power. As reported recently in the press, UK scientists are collaborating with Japanese colleagues to use the Earth Simulator supercomputer in Yokohama to carry out ground-breaking climate simulations. This means we will have, for the first time, sufficient

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information to provide realistic estimates of the change in the frequency and intensity of the weather systems under climate change. This is critically important, as climate impact on society crucially depends on these extreme weather events. In addition scientific knowledge is accumulating rapidly on the critical areas of uncertainty associated with biogeochemical cycles and ocean circulation and this will be incorporated in the models as soon as it is available.

### **Predictions of climate change over the next century and climate change policy**

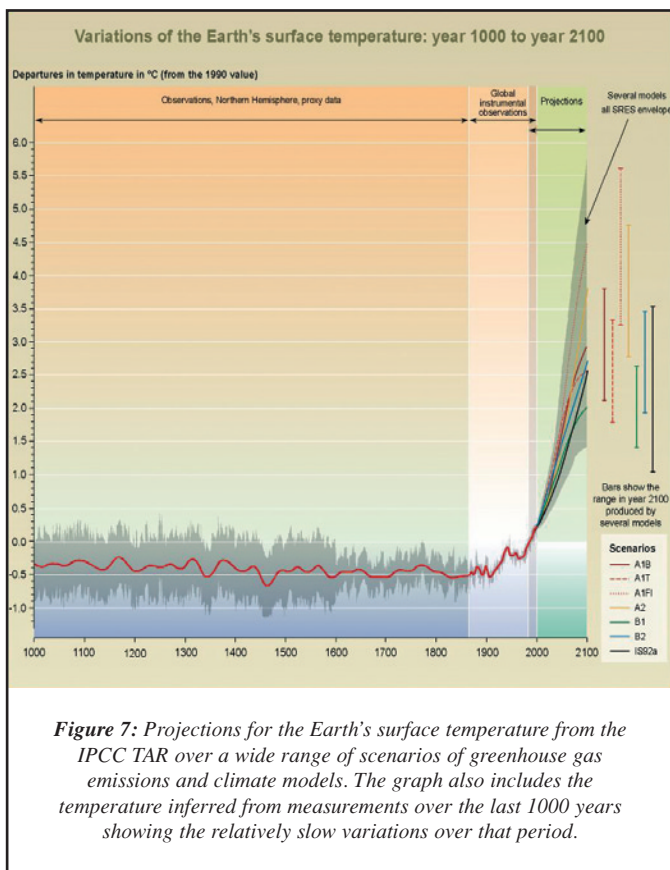
The importance of climate change to society makes the stakes very high in making predictions with climate models. This fact, amongst others, led to the establishment by the World Meteorological Organization and the United Nations Environment Programme of the Intergovernmental Panel on Climate Change (IPCC), in 1988. IPCC has issued a series of assessments including the state of the science of climate change. This has involved a process of drawing together all published research and assessing the degree to which there is a consensus and to identify the areas of remaining uncertainty. In 2001, IPCC issued its third assessment report (TAR) of the science of climate change, and this is widely used as the authoritative view of the predictions and of the science. Scientists and policy-makers use it as a reference; see IPCC 2001a and 2001b. The TAR describes the level of uncertainty with statements such as “it is likely” or “it is very likely that...” where these words have a percentage of likelihood associated with them (66-90% and 90-99% chance respectively). These estimates are based on expert judgement but as ensemble climate prediction develops we expect to have more objective criteria. There are facets of the future evolution of the climate system that we can be reasonably sure about whereas other facets are much more uncertain. For example, there are sound meteorological reasons why rainfall predictions have a larger degree of uncertainty than those for temperature. This is because rainfall is highly variable in space and so the relatively coarse spatial resolution of the current generation of climate models is not adequate to fully capture that variability. But this does not mean we cannot believe, for example, the larger scale aspects of the water cycle in the models. This cycle depends on the average effects of rainfall systems, amongst other

things, and climate models are capable of capturing this with an acceptable level of accuracy. This variation in accuracy depending on which property of the system is being considered is perhaps one reason why some commentators are too negative about the accuracy of climate predictions.

The spatial resolution of current climate models is, to a large degree, determined by the availability of supercomputer resources. The models assessed in the TAR typically used a horizontal resolution of about 250km. The typical horizontal scale of the cyclonic storm systems, that are such a ubiquitous feature of tropical and extra-tropical weather, is about 1000-2000km but with significant sub-structure occurring at fronts, for example, on much smaller scales. To describe comprehensively the details of the interaction of such weather systems and the large-scale global circulation of the atmosphere, it is thought necessary to have a model resolution in the order of 100km or better. Consequently there is currently low confidence in the ability of these models to quantify the change to the frequency and intensity of such storm systems. As most of the impacts of climate change on society and the economy arise from the winds and rainfall (such as leads to local flooding) associated with such systems, this remains a key research problem to be addressed. The relentless advance in the power of computers means that we are in sight, over the next decade or two, of being able to simulate the global climate with a horizontal lattice with grid points separated by as little as a few kilometres, thus removing the need for many of the parametrisations used currently. This will help reduce substantially major uncertainties such as those associated with the effects of clouds.

It is well known that a range of climate models, using a range of representative scenarios for the continuing human input of greenhouse gases and aerosols, predict a global-average surface warming by 2100, relative to 1990, of between about 1.4 and 5.6°C; see Figure 7. The models predict many other regional properties of the system, such as temperature, wind speed and direction, humidity, rainfall, snowfall, sea level, sea-ice and ocean currents. The warming is not uniform, having a general increase towards the Poles, particularly the North Pole; see Figure 8. This pole-ward increase may be connected to the reduction of sea-ice as warming occurs and the



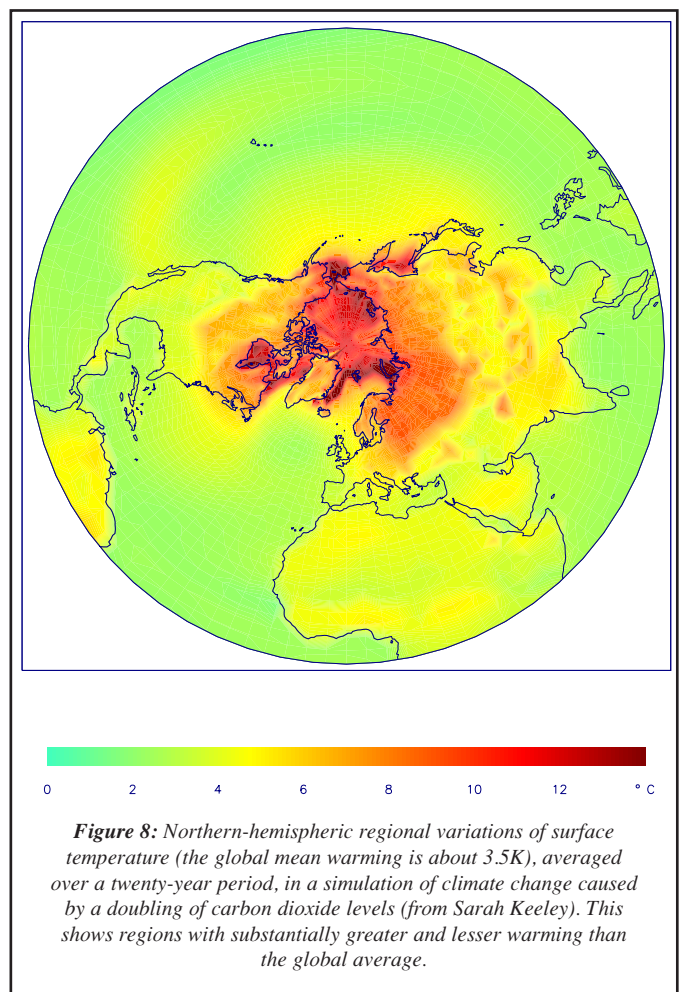


**Figure 7:** Projections for the Earth's surface temperature from the IPCC TAR over a wide range of scenarios of greenhouse gas emissions and climate models. The graph also includes the temperature inferred from measurements over the last 1000 years showing the relatively slow variations over that period.

consequent positive feedback as the reflective ice surface is replaced by the essentially non-reflective sea surface. Also the near-surface air over the land warms more than that over the oceans. As temperature rises near the surface the air holds more moisture and the hydrological cycle becomes more intense.

The ocean circulation is also predicted to change and sea level is expected to rise at a rate of about 1.7mm/year as the ocean expands (and glaciers melt enhancing river flow) as heat is gradually diffused downwards in the ocean. Predictions of sea level rise show that, perhaps surprisingly, it varies substantially regionally but also the rise will continue for several hundred years even if we could stop emitting greenhouse gases into the atmosphere now. This is because of the commitment to sea level rise arising from warming of the atmosphere that has already occurred. This feature is one of the most robust and potentially damaging aspects of the predicted change to the climate system arising from human activities.

An important aspect of the ocean circulation is the *thermohaline circulation* (THC) that is driven by spatial variations in the density of sea water, which is determined by its temperature and salinity. The



North Atlantic Ocean plays a fundamental role in the development and maintenance of the THC. Warm salty upper ocean water moves northward and eastwards towards northwest Europe and this is known as the Gulf Stream. The Gulf Stream and the atmospheric storms moving across the North Atlantic, transport heat north and keep the climate of northwest Europe relatively warm compared to other places at similar latitudes. This water is then cooled as heat is given up to the atmosphere. The water then sinks rapidly in the Greenland and the Labrador Seas before returning south at depth. This is the Atlantic component of a global THC circulation; see Figure 9. Comprehensive climate models predict that the intensity of the THC may weaken by as much as 30% as climate warms but not actually shut down. This is important for the climate of northwest Europe as a complete shutdown would imply a local reduction in the predicted warming and in fact may actually lead to a cooler climate. Despite the 30% reduction, current models suggest that there will be an overall warming of the climate in this region. There have been periods in the geological past when climate has cooled relatively rapidly, for example, the Younger Dryas period, and

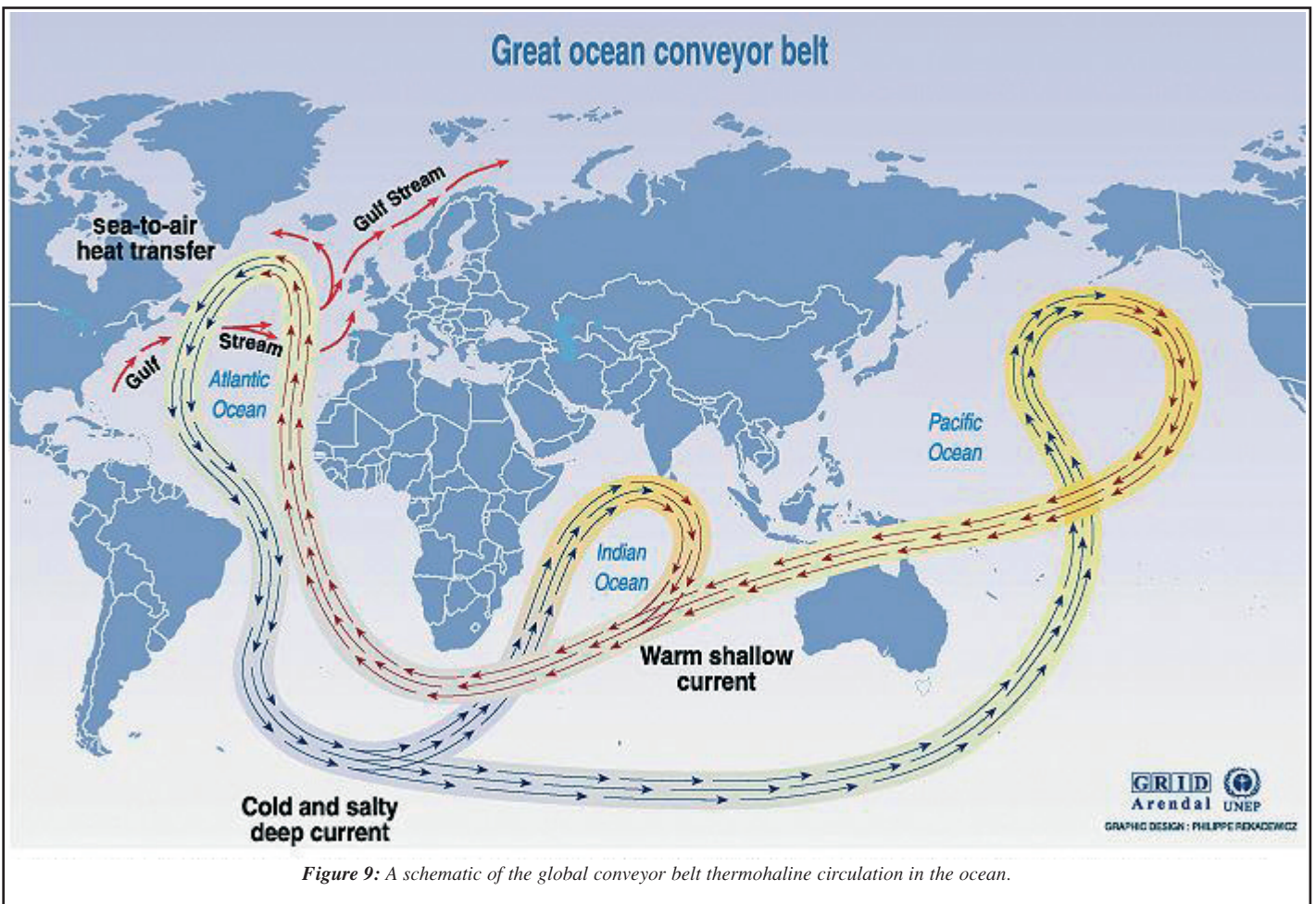


Figure 9: A schematic of the global conveyor belt thermohaline circulation in the ocean.

this may be, at least in part, explained by changes to the THC. It is still an open scientific question as to the circumstances in which the THC might shut off completely and how rapidly this might happen. There has been speculation that this could occur as rapidly as a few tens of years but this is highly uncertain at present.

The human input of carbon dioxide needs to be put into the context of the natural carbon cycle. Current climate models attempt to represent the carbon cycle with, most recently, the inclusion of a dynamic vegetation component that allows for feedbacks between the biosphere and climate change. The effect of land use changes, such as deforestation and the potential partial amelioration of global warming by reforestation, can be included in the models. Current knowledge suggests that the carbon cycle is very sensitive to climate change with, for example, a recent Hadley Centre calculation showing that dieback of the Amazon rainforest because of a reduction of rainfall as warming occurs, represents a major potential positive feedback as the carbon from the forest is released back into the atmosphere. Such dieback processes represent another potentially rapid (and large) climate change

but the risk of this happening is still very difficult to quantify because of uncertainties in the biogeochemical feedback processes.

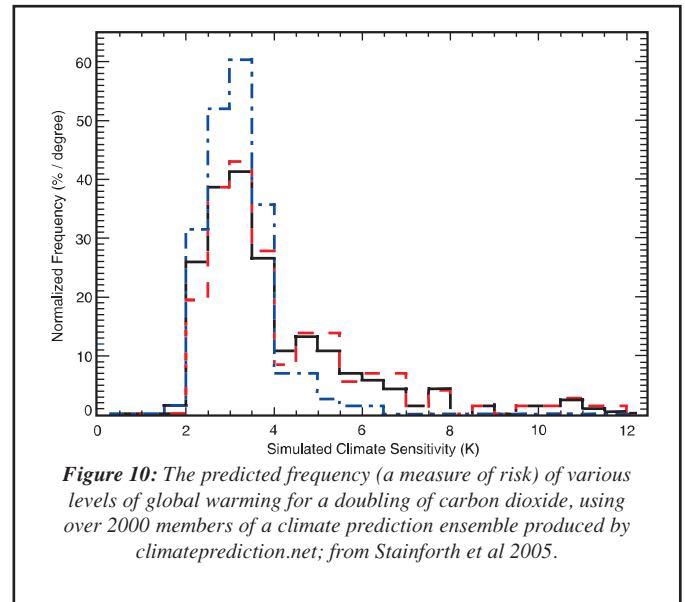
Societal vulnerability to climate change, including that caused by human input of greenhouse gases, is potentially large depending on the characteristics and organisation of each region. This led to the creation of the United Nations Framework Convention on Climate Change. Arising from this is the Kyoto Protocol that seeks to cut each country's greenhouse gas emissions to a level that in total, within the commitment period 2008-2012, will be 5% less than 1990 levels. This international and legally binding agreement on signatory countries in the developed world entered into force in February 2005. The effect on atmospheric concentrations of carbon dioxide is likely to be small. However the Kyoto Protocol is regarded as being highly significant from a political viewpoint even if the amelioration of global warming is likely to be too small to make a real difference. A sustained reduction of emissions would require major changes to the way in which, for example, energy and transport are structured.

## In conclusion

So why do commentators imagine that top scientists are deluded about anthropogenic climate change? The stakes are high and rarely are scientists under such scrutiny. Scientists are appalled that they could be suspected of distorting the evidence to enhance their reputations or funding opportunities. Of course scientific hypotheses and analysis can be refuted by later discoveries but this is not the same as complicity. The fact that everyone experiences weather and climate may explain why non-scientists feel confident in attempting to refute the scientific evidence. The complexity of the climate system and its many interacting and compensating physical processes means that simple arguments that gloss over this complexity have to be approached with a significant degree of scepticism. A common method of arguing starts by identifying a single cause or physical process that either has not been included or has been included in an imperfect way, into climate models. But the climate changes because of a multiplicity of interacting processes and any one process alone cannot be the whole story. The search for the one and only cause of climate change is doomed to failure. Climate modellers attempt to include in the models all the processes that are even remotely likely to have a detectable effect – any newly discovered process will quickly find itself incorporated into the models!

The multitude of non-scientist comments and views about climate change is important and to be welcomed as they represent society's engagement and participation in the scientific process. An

exciting initiative in this regard is the availability from <http://climateprediction.net> of a comprehensive climate model that can be run on anyone's personal computer in the background to predict climate change using idle time on the computer. The results from this very large distributed-computing ensemble will be used to evaluate, in an improved way, the uncertainty in current predictions of climate change; see Figure 10.



Few if any scientific problems have had such a huge degree of scrutiny by specialists and non-specialists and, whilst one can never say never, it would seem to be perverse not to take the risk of human-induced climate change very seriously indeed. At the very least the possibility of human-induced climate change is a known unknown but arguably it is close to making the transition to becoming a known known!



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