BRIEFINGS2

The science of climate change

The clouds of unknowing

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There are lots of uncertainties in climate science. But that does not mean it is fundamentally wrong

FOR anyone who thinks that climate science must be unimpeachable to be useful, the past few months have been a depressing time. A large stash of e-mails from and to investigators at the Climatic Research Unit of the University of East Anglia provided more than enough evidence for concern about the way some climate science is done. That the picture they painted, when seen in the round—or as much of the round as the incomplete selection available allows—was not as alarming as the most damning quotes taken out of context is little comfort. They offered plenty of grounds for both shame and blame.

At about the same time, glaciologists pointed out that a statement concerning Himalayan glaciers in the most recent report of the Intergovernmental Panel on Climate Change (IPCC) was wrong. This led to the discovery of other poorly worded or poorly sourced claims made by the IPCC, which seeks to create a scientific consensus for the world's politicians, and to more general worries about the panel's partiality, transparency and leadership. Taken together, and buttressed by previous criticisms, these two revelations have raised levels of scepticism about the consensus on climate change to new heights.

Increased antsiness about action on climate change can also be traced to the recession, the unedifying spectacle of last December's climate-change summit in Copenhagen, the political realities of the American Senate and an abnormally cold winter in much of the northern hemisphere. The new doubts about the science, though, are clearly also a part of that story. Should they be?

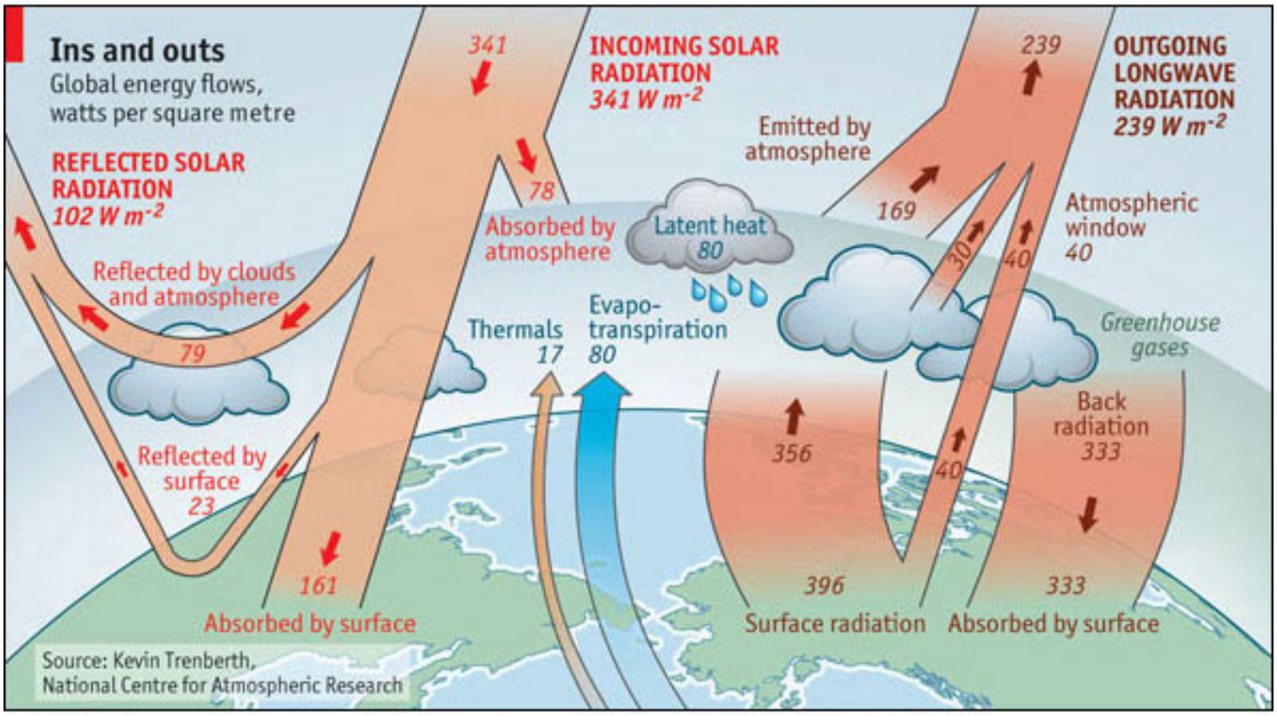
In any complex scientific picture of the world there will be gaps, misperceptions and mistakes. Whether your impression is dominated by the whole or the holes will depend on your attitude to the project at hand. You might say that some see a jigsaw where others see a house of cards. Jigsaw types have in mind an overall picture and are open to bits being taken out, moved around or abandoned should they not fit. Those who see houses of cards think that if any piece is removed, the whole lot falls down. When it comes to climate, academic scientists are jigsaw types, dissenters from their view house-of-cards-ists.

The defenders of the consensus tend to stress the general consilience of their efforts—the way that data, theory and modelling back each other up. Doubters see this as a thoroughgoing version of "confirmation bias", the tendency people have to select the evidence that agrees with their original outlook. But although there is undoubtedly some degree of that (the errors in the IPCC, such as they are, all make the problem look worse, not better) there is still genuine power to the way different arguments and datasets in climate science tend to reinforce each other.

The doubters tend to focus on specific bits of empirical evidence, not on the whole picture. This is worthwhile—facts do need to be well grounded—but it can make the doubts seem more fundamental than they are. People often assume that data are simple, graspable and trustworthy, whereas theory is complex, recondite and slippery, and so give the former priority. In the case of climate change, as in much of science, the reverse is at least as fair a picture. Data are vexatious; theory is quite straightforward. Constructing a set of data that tells you about the temperature of the Earth over time is much harder than putting together the basic theoretical story of how the temperature should be changing, given what else is known about the universe in general.

Absorb and reflect

The most relevant part of that universal what-else is the requirement laid down by thermodynamics that, for a planet at a constant temperature, the amount of energy absorbed as sunlight and the amount emitted back to space in the longer wavelengths of the infra-red must be the same. In the case of the Earth, the amount of sunlight absorbed is 239 watts per square metre. According to the laws of thermodynamics, a simple body emitting energy at that rate should have a temperature of about −18ºC. You do not need a comprehensive set of surface-temperature data to notice that this is not the average temperature at which humanity goes about its business. The discrepancy is due to greenhouse gases in the atmosphere, which absorb and re-emit infra-red radiation, and thus keep the lower atmosphere, and the surface, warm (see the diagram below). The radiation that gets out to the cosmos comes mostly from above the bulk of the greenhouse gases, where the air temperature is indeed around –18ºC.



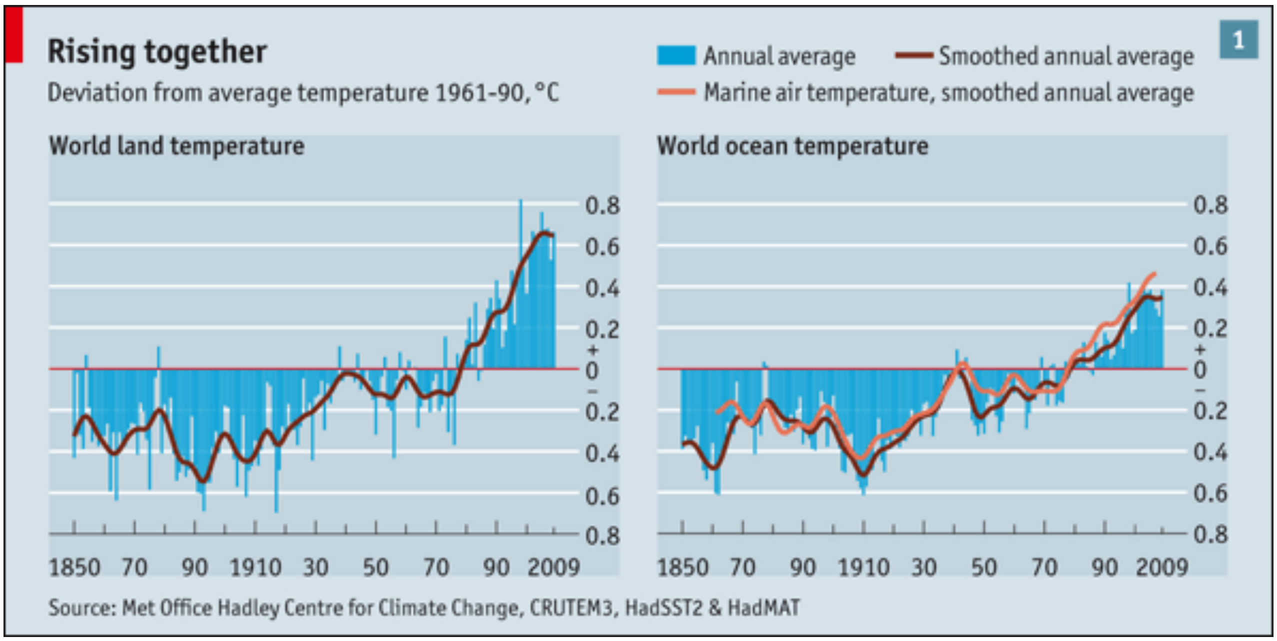
Adding to those greenhouse gases in the atmosphere makes it harder still for the energy to get out. As a result, the surface and the lower atmosphere warm up. This changes the average temperature, the way energy moves from the planet's surface to the atmosphere above it and the way that energy flows from equator to poles, thus changing the patterns of the weather.

No one doubts that carbon dioxide is a greenhouse gas, good at absorbing infra-red radiation. It is also well established that human activity is putting more of it into the atmosphere than natural processes can currently remove. Measurements made since the 1950s show the level of carbon dioxide rising year on year, from 316 parts per million (ppm) in 1959 to 387ppm in 2009. Less direct records show that the rise began about 1750, and that the level was stable at around 280ppm for about 10,000 years before that. This fits with human history: in the middle of the 18th century people started to burn fossil fuels in order to power industrial machinery. Analysis of carbon isotopes, among other things, shows that the carbon dioxide from industry accounts for most of the build-up in the atmosphere.

The serious disagreements start when discussion turns to the level of warming associated with that rise in carbon dioxide. For various reasons, scientists would not expect temperatures simply to rise in step with the carbon dioxide (and other greenhouse gases). The climate is a noisy thing, with ups and downs of its own that can make trends hard to detect. What's more, the oceans can absorb a great deal of heat—and there is evidence that they have done so—and in storing heat away, they add inertia to the system. This means that the atmosphere will warm more slowly than a given level of greenhouse gas would lead you to expect.

There are three records of land-surface temperature put together from thermometer readings in common use by climatologists, one of which is compiled at the Climatic Research Unit of e-mail infamy. They all show warming, and, within academia, their reliability is widely accepted. Various industrious bloggers are not so convinced. They think that adjustments made to the raw data introduce a warming bias. They also think the effects of urbanisation have confused the data because towns, which are sources of heat, have grown up near weather stations. Anthony Watts, a retired weather forecaster who blogs on climate, has set up a site, surfacestations.org, where volunteers can help record the actual sites of weather instruments used to provide climate data, showing whether they are situated close to asphalt or affected by sources of bias.

Those who compile the data are aware of this urban heat-island effect, and try in various ways to compensate for it. Their efforts may be insufficient, but various lines of evidence suggest that any errors it is inserting are not too bad. The heat-island effect is likely to be strongest on still nights, for example, yet trends from data recorded on still nights are not that different from those from windy ones. And the temperature of waters at the surface of the seas shows similar trends to that on land over the past century, as does the record of air temperature over the oceans as measured at night (see chart 1).



A recent analysis by Matthew Menne and his colleagues at America's National Oceanic and Atmospheric Administration, published in the *Journal of Geophysical Research*, argued that trends calculated from climate stations that surfacestation.org found to be poorly sited and from those it found well sited were more or less indistinguishable. Mr Watts has problems with that analysis, and promises a thorough study of the project's findings later.

There is undoubtedly room for improvement in the surface-temperature record—not least because, at the moment, it provides only monthly mean temperatures, and there are other things people would like to know about. (When worrying about future heatwaves, for example, hot days and nights, not hot months, are the figures of most interest.) In February Britain's Met (ie, meteorological) Office called for the creation of a new set of temperature databases compiled in rigorously transparent ways and open to analysis and interpretation by all and sundry. Such an initiative would serve science well, help restore the credibility of land-surface records, and demonstrate an openness on the part of climate science which has not always been evident in the past.

Simplify and amplify

For many, the facts that an increase in carbon dioxide should produce warming, and that warming is observed in a number of different indicators and measurements, add up to a *primafacie* case for accepting that greenhouse gases are warming the Earth and that the higher levels of greenhouse gases that business as usual would bring over the course of this century would warm it a lot further.

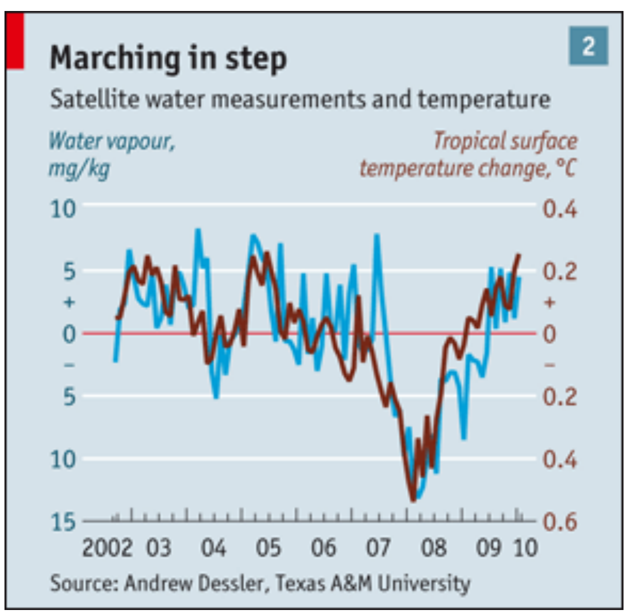
The warming caused by a given increase in carbon dioxide can be calculated on the basis of laboratory measurements which show how much infra-red radiation at which specific wavelengths carbon dioxide molecules absorb. This sort of work shows that if you double the carbon dioxide level you get about 1ºC of warming. So the shift from the pre-industrial 280ppm to 560ppm, a level which on current trends might be reached around 2070, makes the world a degree warmer. If the level were to double again, to 1,100ppm, which seems unlikely, you would get another degree.

The amount of warming expected for a doubling of carbon dioxide has become known as the "climate sensitivity"—and a climate sensitivity of one degree would be small enough to end most climate-related worries. But carbon dioxide's direct effect is not the only thing to worry about. Several types of feedback can amplify its effect. The most important involve water vapour, which is now quite well understood, and clouds, which are not. It is on these areas that academic doubters tend to focus.

As carbon dioxide warms the air it also moistens it, and because water vapour is a powerful greenhouse gas, that will provide further warming. Other things people do—such as clearing land for farms, and irrigating them—also change water vapour levels, and these can be significant on a regional level. But the effects are not as large.

Climate doubters raise various questions about water vapour, some trivial, some serious. A trivial one is to argue that because water vapour is such a powerful greenhouse gas, carbon dioxide is unimportant. But this ignores the fact that the level of water vapour depends on temperature. A higher level of carbon dioxide, by contrast, governs temperature, and can endure for centuries.

A more serious doubting point has to do with the manner of the moistening. In the 1990s Richard Lindzen, a professor of meteorology at the Massachusetts Institute of Technology, pointed out that there were ways in which moistening might not greatly enhance warming. The subsequent two decades have seen much observational and theoretical work aimed at this problem. New satellites can now track water vapour in the atmosphere far better than before (see chart 2). As a result preliminary estimates based on simplifications have been shown to be reasonably robust, with water-vapour feedbacks increasing the warming to be expected from a doubling of carbon dioxide from 1ºC without water vapour to about 1.7ºC. Dr Lindzen agrees that for parts of the atmosphere without clouds this is probably about right.



This moistening offers a helpful way to see what sort of climate change is going on. When water vapour condenses into cloud droplets it gives up energy and warms the surrounding air. This means that in a world where greenhouse warming is wetting the atmosphere, the lower parts of the atmosphere should warm at a greater rate than the surface, most notably in the tropics. At the same time, in an effect that does not depend on water vapour, an increase in carbon dioxide will cause the upper stratosphere to cool. This pattern of warming down below and cooling up on top is expected from greenhouse warming, but would not be expected if something other than the greenhouse effect was warming the world: a hotter sun would heat the stratosphere more, not less.

During the 1990s this was a point on which doubters laid considerable weight, because satellite measurements did not show the warming in the lower atmosphere that theory would predict. Over the past ten years, though, this picture has changed. To begin with, only one team was turning data from the relevant instruments that have flown on weather satellites since the 1970s into a temperature record resolved by altitude. Now others have joined them, and identified errors in the way that the calculations (which are complex and depend on a number of finicky details) were carried out. Though different teams still get different amounts and rates of warming in the lower atmosphere, there is no longer any denying that warming is seen. Stratospheric cooling is complicated by the effects of ozone depletion, but those do not seem large enough to account for the degree of cooling that has been seen there, further strengthening the case for warming by the greenhouse effect and not some other form of climate perturbation.

On top of the effect of water vapour, though, the clouds that form from it provide a further and greater source of uncertainty. On the one hand, the droplets of water of which these are made also have a strong greenhouse effect. On the other, water vapour is transparent, whereas clouds reflect light. In particular, they reflect sunlight back into space, stopping it from being absorbed by the Earth. Clouds can thus have a marked cooling effect and also a marked warming effect. Which will grow more in a greenhouse world?

Model maze

It is at this point that detailed computer models of the climate need to be called into play. These models slice the atmosphere and oceans into stacks of three-dimensional cells. The state of the air (temperature, pressure, etc) within each cell is continuously updated on the basis of what its state used to be, what is going on in adjacent cells and the greenhousing and other properties of its contents.

These models are phenomenally complex. They are also gross oversimplifications. The size of the cells stops them from explicitly capturing processes that take place at scales smaller than a hundred kilometres or so, which includes the processes that create clouds.

Despite their limitations, climate models do capture various aspects of the real world’s climate: seasons, trade winds, monsoons and the like. They also put clouds in the places where they are seen. When used to explore the effect of an increase in atmospheric greenhouse gases on the climate these models, which have been developed by different teams, all predict more warming than greenhouse gases and water-vapour feedback can supply unaided. The models assessed for the IPCC’s fourth report had sensitivities ranging from 2.1ºC to 4.4ºC. The IPCC estimated that if clouds were not included, the range would be more like 1.7ºC to 2.1ºC. So in all the models clouds amplify warming, and in some the amplification is large.

However, there are so far no compelling data on how clouds are affecting warming in fact, as opposed to in models. Ray Pierrehumbert, a climate scientist at the University of Chicago who generally has a strong way with sceptics, is happy to agree that there might be processes by which clouds rein in, rather than exaggerate, greenhouse-warming effects, but adds that, so far, few have been suggested in any way that makes sense.

Dr Lindzen and a colleague suggested a plausible mechanism in 2001. They proposed that tropical clouds in an atmosphere with more greenhouse gas might dry out neighbouring parts of the sky, making them more transparent to outgoing infra-red. The evidence Dr Lindzen brought to bear in support of this was criticised in ways convincing enough to discourage other scientists from taking the idea further. A subsequent paper by Dr Lindzen on observations that would be compatible with his ideas about low sensitivity has also suffered significant criticisms, and he accepts many of them. But having taken them on board has not, he thinks, invalidated his line of research.

Arguments based on past climates also suggest that sensitivity is unlikely to be low. Much of the cooling during the ice ages was maintained by the presence of a large northern hemisphere ice cap reflecting away a lot of sunlight, but carbon dioxide levels were lower, too. To account for all of the cooling, especially in the southern hemisphere, is most easily done with a sensitivity of temperature to carbon dioxide higher than Dr Lindzen would have it.

Before the ice age, the Earth had a little more carbon dioxide and was a good bit warmer than today—which suggests a fairly high sensitivity. More recently, the dip in global temperatures after the eruption of Mt Pinatubo in the Philippines in 1991, which inserted a layer of sunlight-diffusing sulphur particles into the stratosphere, also bolsters the case for a sensitivity near the centre of the model range—although sensitivity to a transient event and the warming that follows a slow doubling of carbon dioxide are not exactly the same sort of thing.

Logs and blogs

Moving into data from the past, though, brings the argument to one of the areas that blog-based doubters have chosen as a preferred battleground: the temperature record of the past millennium, as construed from natural records that are both sensitive to temperature and capable of precise dating. Tree rings are the obvious, and most controversial, example. Their best known use has been in a reconstruction of temperatures over the past millennium published in *Nature* in 1998 and widely known as the hockey stick, because it was mostly flat but had a blade sticking up at the 20th-century end. Stephen McIntyre, a retired Canadian mining consultant, was struck by the very clear message of this graph and delved into the science behind it, a process that left him and followers of his blog, *Climate Audit*, intensely sceptical about its value.

In 2006 a review by America's National Research Council endorsed points Mr McIntyre and his colleagues made on some methods used to make the hockey stick, and on doubts over a specific set of tree rings. Despite this it sided with the hockey stick's overall conclusion, which did little to stem the criticism. The fact that tree-ring records do not capture recent warming adds to the scepticism about the value of such records.

For many of Mr McIntyre's fans (though it is not, he says, his central concern) the important thing about this work is that the hockey stick seemed to abolish the "medieval warm period". This is a time when temperatures are held to have been as high as or higher than today's—a warmth associated with the Norse settlement of Greenland and vineyards in England. Many climate scientists suspect this phenomenon was given undue prominence by climatologists of earlier generations with an unduly Eurocentric view of the world. There is evidence for cooling at the time in parts of the Pacific.

Doubters for the most part are big fans of the medieval warm period, and see in the climate scientists' arguments an attempt to rewrite history so as to maximise the drama of today's warming and minimise the possibility that natural variation might explain the 20th-century record. The possibility of more climatic variability, though, does not, in itself, mean that greenhouse warming is not happening too. And if the medieval warmth were due to some external factor, such as a slightly brighter sun, that would suggest that the climate was indeed quite sensitive.

Looking at the more recent record, logged as it has been by thermometers, you might hope it could shed light on which of the climate models is closest to being right, and thus what the sensitivity actually is. Unfortunately, other confounding factors make this difficult. Greenhouse gases are not the only climatically active ingredients that industry, farming and land clearance add to the atmosphere. There are also aerosols—particles of pollution floating in the wind. Some aerosols cool the atmosphere. Other, sootier, ones warm it. The aggregate effect, globally, is thought to be a cooling, possibly a quite strong one. But the overall history of aerosols, which are mostly short-lived, is nothing like as well known as that of greenhouse gases, and it is unlikely that any of the models are properly capturing their chemistry or their effects on clouds.

Taking aerosols into account, climate models do a pretty good job of emulating the climate trends of the 20th century. This seems odd, since the models have different sensitivities. In practice, it appears that the way the aerosols are dealt with in the models and the sensitivity of those models tend to go hand in hand; sensitive models also have strong cooling aerosol effects.

Reto Knutti of ETH Zurich, an expert on climate sensitivity, sees this as evidence that, consciously or unconsciously, aerosols are used as counterweights to sensitivity to ensure that the trends look right. This is not evidence of dishonesty, and it is not necessarily a bad thing. Since the models need to be able to capture the 20th century, putting them together in such a way that they end up doing so makes sense. But it does mean that looking at how well various models match the 20th century does not give a good indication of the climate's actual sensitivity to greenhouse gas.

Adding the uncertainties about sensitivity to uncertainties about how much greenhouse gas will be emitted, the IPCC expects the temperature to have increased by 1.1ºC to 6.4ºC over the course of the 21st century. That low figure would sit fairly well with the sort of picture that doubters think science is ignoring or covering up. In this account, the climate has natural fluctuations larger in scale and longer in duration (such as that of the medieval warm period) than climate science normally allows, and the Earth's recent warming is caused mostly by such a fluctuation, the effects of which have been exaggerated by a contaminated surface-temperature record. Greenhouse warming has been comparatively minor, this argument would continue, because the Earth's sensitivity to increased levels of carbon dioxide is lower than that seen in models, which have an inbuilt bias towards high sensitivities. As a result subsequent warming, even if emissions continue full bore, will be muted too.

It seems unlikely that the errors, misprisions and sloppiness in a number of different types of climate science might all favour such a minimised effect. That said, the doubters tend to assume that climate scientists are not acting in good faith, and so are happy to believe exactly that. Climategate and the IPCC's problems have reinforced this position.

Using the IPCC's assessment of probabilities, the sensitivity to a doubling of carbon dioxide of less than 1.5ºC in such a scenario has perhaps one chance in ten of being correct. But if the IPCC were underestimating things by a factor of five or so, that would still leave only a 50:50 chance of such a desirable outcome. The fact that the uncertainties allow you to construct a relatively benign future does not allow you to ignore futures in which climate change is large, and in some of which it is very dangerous indeed. The doubters are right that uncertainties are rife in climate science. They are wrong when they present that as a reason for inaction.