In the Climate Casino: An Exchange

April 26, 2012

Roger W. Cohen, William Happer, and Richard Lindzen, reply by William D. Nordhaus

In response to:

Why the Global Warming Skeptics Are Wrong from the March 22, 2012 issue

To the Editors:

In the March 22, 2012, issue of The New York Review, William Nordhaus presents his opinion on why global warming skeptics in general, and the sixteen scientists and engineers who wrote two Wall Street Journal Op Eds1 in particular, are "wrong." We are three of those sixteen authors, and we respond here to Professor Nordhaus.

Professor Nordhaus's essay contains six points.

Victoria and Albert Museum, London/Art Resource

Thomas Rowlandson: The Hazard Room, 1792

The first point contorts the obvious fact that there has been no statistically significant warming for about the past fifteen years into a claim that we did not make: that there has been no warming over the past two centuries. Professor Nordhaus proceeds to confuse this with the issue of attribution, i.e., the determination of what caused the warming. Attribution is a distinctly different matter. While there is much to contest in the published temperature records, there is general acceptance that there has been a net increase in global mean temperature similar to that shown in Professor Nordhaus's first graph.

The prior two- to three-hundred-year period was much cooler and is known as the Little Ice Age, and, of course, a longer record would have shown still-earlier periods as warm or warmer than the present. The observation that the last few years include some of the warmest years on record no more implies future warming than record stock market highs imply a steadily rising future market. The fact that warming has greatly slowed does imply that, at the least, there are other processes that are currently competitive with the impact of steadily increasing greenhouse gases.

The second point concerns our observation that current computer climate models appear to exaggerate warming due to CO2. This bears on the critical issue of the climate sensitivity, the temperature rise for a doubling of atmospheric CO2. Professor Nordhaus presents two graphs from the IPCC 2007 report2 that purport to show that without anthropogenic emissions, models successfully simulate the global mean temperature until about 1970 but cannot do so thereafter. This is the basis for the IPCC's claim that it is likely that most of the warming over the past fifty years is due to man's emissions. Such a procedure absolutely requires that the model include correctly all other sources of variability. However, the failure of the models to predict the hiatus in warming over the past fifteen years is acknowledged to indicate that this condition has not been met.3 Furthermore there is the embarrassing fact that the models do not reproduce the 1910–1940 warming, which is nearly identical to the 1970–2000 warming but occurred before man's emissions became large enough to be considered important.

With respect to climate sensitivity, it should be noted that the IPCC referred to all of man's emissions rather than just CO2. The reason is that without the cooling effect of aerosols formed from certain emissions, the models significantly overpredict warming from greenhouse gases. However, each model needed a different value for the aerosol cancellation.4 This lack of consistency means that aerosols were merely an adjustment factor to bring the models into agreement with the historical record, while preserving a high climate sensitivity. Therefore, the claim that the models cannot account for post-1970 warming without including human emissions means nothing scientifically.

The third point concerns our statement that CO2 is not a pollutant, that we were perhaps using a commonsense, dictionary definition of pollutant. The Oxford English Dictionary defines pollutant as "a polluting agent; esp. a noxious or poisonous substance which pollutes the environment." Professor Nordhaus says, "The contention that CO2 is not a pollutant is a rhetorical device." Rather he takes a 5–4 Supreme Court decision to be definitive. In fact, the Supreme Court majority did not rule CO2 a pollutant; it merely found that the Clean Air Act's definition is so broad that CO2 falls under the statute, regardless of the facts of the matter. The concurrence of an economist (Richard Tol) is then taken as confirmation of the existence of specific externalities associated with CO2. We consider such references to be the real "rhetorical devices" because they obscure the key scientific issue: whether this critical component of the earth's biosphere will cause significant and destructive global warming.

In another rhetorical flourish, Professor Nordhaus's fourth point misrepresents us as claiming that "skeptical climate sci-entists are living under a reign of terror about their professional and personal livelihoods." This reductio ad absurdum is inappropriate, but we observe that individuals like climate scientist James Hansen, environmental activist Robert Kennedy Jr., and economist Paul Krugman have characterized critics of climate alarm as "traitors to the planet." We noted the systematic dismissal of editors who publish peer-reviewed papers questioning climate alarm, as well as the legitimate fears of untenured faculty whose promotions depend on publications and grant support. We note here that editors like Donald Kennedy at the prestigious Science magazine have publically declared their opposition to the publication of papers finding results in opposition to climate dogma.5

The Climategate e-mails6 specifically describe these tactics, and numerous examples are given in Lindzen (2012.)7 While defense of existing paradigms is normal in science, the present situation is clearly pathological in its imposition of conformity. We cannot speak to the situation in economics, but the notion that dissident voices and new theories are encouraged in climate science is downright silly, though Professor Nordhaus is correct to view such encouragement as critical to a healthy science. Unfortunately, the current situation in climate science is far from healthy. Professor Nordhaus contributes to this when he succumbs to the introduction of the false analogy with tobacco, and his call for political leaders to "be extremely vigilant to prevent pollution [sic] of the scientific process by the merchants of doubt" is not atypical of the current situation.

Regarding Professor Nordhaus's fifth point that there is no evidence that money is at issue, we simply note that funding for climate science has expanded by a factor of 15 since the early 1990s, and that most of this funding would disappear with the absence of alarm. Climate alarmism has expanded into a hundred-billion-dollar industry far broader than just research. Economists are usually sensitive to the incentive structure, so it is curious that the overwhelming incentives to promote climate alarm are not a consideration to Professor Nordhaus. There are no remotely comparable incentives to the contrary position provided by the industries that he claims would be harmed by the policies he advocates.

In his sixth point, Professor Nordhaus says that we did not properly represent his results when we said, "Nearly the highest benefit-to-cost ratio is achieved for a policy that allows 50 more years of economic growth unimpeded by greenhouse gas controls." He objects to our reference to this ratio instead of net benefits as a metric for comparing policies: "Elementary cost- benefit and business economics teach that [benefit-to-cost ratio] is an incorrect criterion for selecting investments or policies." Yet values of calculated benefit-to-cost ratios are highlighted in the key summary Table 5-3 of his book A Question of Balance.8 Indeed, this ratio is often used for guidance in the real world of

business investment. One reason is that it can be relatively insensitive to the choice of discount rate and therefore may give more robust insights, whereas net benefits may be extremely sensitive to this choice (more on this below). Both benefit-to-cost and net benefits have their place.

But it matters little which metric one uses. The difference between Professor Nordhaus's optimal carbon tax policy and a fifty-year delay policy is insignificant economically or climatologically in view of major uncertainties in (1) future economic growth (including reductions in carbon emissions intensity); (2) the physical science (e.g., the climate sensitivity); (3) future positive and negative environmental impacts (e.g., the economic "damage function"); (4) the evaluation of long-term economic costs and benefits (e.g., the discount rate); and (5) the international political process (e.g., the impact of less than full participation).

Professor Nordhaus computes a $0.94 trillion difference between the net benefits of the two policies, just 4 percent of the computed maximum $22.55 trillion in supposed environmental damage. Results are given to three or four numerical significant figures. Yet we do not know the underlying driver for all of this, the climate sensitivity, to even one significant figure.

This relatively small difference, indeed whether it is positive or negative, depends critically on factors such as the five listed above, in particular the value of the climate sensitivity. Professor Nordhaus chooses 3.0 degrees C for doubling of CO2,9 a value that empirical evidence suggests is greatly exaggerated.10 To illustrate the point, for a climate sensitivity of 1.0 degree, a value suggested by a number of empirical studies, Professor Nordhaus's "DICE" model calculates that the optimum policy's net benefits drop from about $3 trillion to a net cost of about $1 trillion, and the benefit-to-cost ratio plunges from 2.4 to 0.5. The fifty-year-delay policy is then greatly preferred.

We are asked to take the computed difference between the two policies seriously despite Professor Nordhaus's finding11 that the optimal policy ultimately "saves" only about 0.1 degree C in global warming relative to the fifty-year delay. Putting this in perspective, 0.1 degree is only about 10 percent of the observed warming since 1850 and is a typical year-to-year fluctuation. This tiny difference is predicted by the DICE model to occur fifty years to two centuries in the future, and yet climate models have failed the test of prediction over twenty years. Furthermore, as outlined in our Op Eds, the strong negative environmental impacts assumed in the DICE model's economic damage function are acknowledged to be extremely uncertain. There exist potential net benefits of increased atmospheric CO2, especially for a small climate sensitivity (e.g., in agricultural and timber productivity).12

We are not the first to note that Professor Nordhaus's optimal carbon tax is hardly distinguishable from a policy of delay. For example, economist Clive Hamilton said in an essay entitled "Nordhaus' Carbon Tax: An Excuse to Do Nothing?"13 written shortly after publication of Professor Nordhaus's book, "For some of those who want no action, arguing for a carbon tax has become the tactic du jour." Advocates such as Dr. Hamilton and Sir Nicholas Stern favor a discount rate far below anything familiar in a market economy, for to do otherwise means that (per Hamilton) "the interests of future generations disappear from the analysis." This, along with wildly exaggerated climate damage scenarios, is needed to justify aggressive short-term interventions such as the Al Gore or Stern proposals.14 Since calculated net benefit results for a two-hundred-year horizon are extremely sensitive to the choice of a discount rate, the debate over the discount rate is far more than technical.

Thus, when one considers the nature and magnitude of uncertainties in the climate sensitivity, the economic damage function, and the discount rate, Professor Nordhaus's defense of a difference in policies that is tiny compared to these uncertainties is difficult to understand.

The larger point here is that uncertainties in the physical science and the economic science need to be properly considered. As suggested above, a key uncertainty in the economic analysis can be treated by examining the economic impact of realistic values of the climate sensitivity. We have seen that a likely small climate sensitivity turns the optimum policy economic values sharply negative. Mother

Nature continues to tell us that the climate sensitivity is likely to be below the range considered by Professor Nordhaus.15 This is not surprising because his choices of its most likely value and its statistical "spread" were strongly influenced by a suite of climate models that have exaggerated past warming and that share common problems. These considerations make Professor Nordhaus's option of a fifty-year delay the wisest policy choice.

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William Nordhaus replies:

In reading the letter from Roger Cohen, William Happer, and Richard Lindzen (CHL), I have the sense of walking into a barroom brawl. They defend the article by sixteen scientists in The Wall Street Journal by firing a fusillade of complaints at everyone in sight, including Science editor Donald Kennedy, climate scientists with hacked e-mails, columnist Paul Krugman, biologist Paul Ehrlich, activist Robert Kennedy Jr., economist Nicholas Stern, and even former Vice President Al Gore.

However, when all the shooting has stopped and you look up from behind the table, what you see can be summarized in one central point. They argue that global warming is full of uncertainties, but its dangers are being systematically exaggerated by climate scientists. I will review the key issues in this response.

CHL begin by agreeing that global temperatures have in fact risen over the last century. So we have cleared at least one of the hurdles raised by climate-change skeptics.

They asserted in their original article that temperatures have declined over the last decade. In my article I pointed out that, because the year-to-year movements in temperature are so volatile, declines over a decade contain little information. Here is a useful way to see this point: we have a reading of average global temperature from 1880 to 2011 (shown in the figure of my article). Take the ten-year change in temperature for each of the 122 years for which we can make that calculation. Of those, forty-one show declines. In other words, if we were to pick a year at random, the chance is one in three that the ten-year change would be negative. Short-term movements in such volatile series do not provide information about long-term trends.a

As a final comment on their discussion, it has a stale quality of people repeating ancient arguments that do not reflect the current state of climate science. Climate scientists have moved way beyond global mean temperature in looking for evidence of human-caused climate change. Scientists have found several indicators that point to human-caused warming, including melting of glaciers and ice sheets, ocean heat content, rainfall patterns, atmospheric moisture, river runoff, stratospheric cooling, and the extent of Arctic sea ice. Those who look only at global temperature trends are like investigators using only eyewitness reports and ignoring fingerprints and DNA-based evidence.

The second point in CHL's response involves climate modeling. I noted that the climate models reviewed by the UN's Intergovernmental Panel on Climate Change (IPCC) showed that temperature

trends in the last century could not be explained on the basis of natural forces (such as volcanic eruptions) alone. The IPCC indicated that the long-term rise in global temperatures over the last century could be explained when the influence of CO2 and other human factors were introduced into the models.

CHL do not dispute the point that model simulations excluding human influences cannot capture global temperature trends. Rather, they contend that the models overstate the sensitivity of climate to atmospheric CO2 concentration.b This subject has been intensively studied over more than three decades. Different climate models show different climate sensitivities, and the differences among them have not been resolved. The actual number might be smaller than the consensus, or it might be larger, but CHL have no special insight or results to demonstrate that they are right and others are wrong. I return to the issue of the uncertainties in the last point below.c

The next three points are argumentative and have little scientific significance. Surprisingly, the statement by the sixteen scientists that "CO2 is not a pollutant" is defended by reference to a common dictionary rather than to a scientific source.d But in the end they agree that the real issue is whether this "component" will "cause significant and destructive global warming." This simply returns the discussion back to the major question under discussion.

I also criticized their suggestion that climate-change skeptics are suffering under a reign of terror similar to that of Soviet geneticists in the Lysenko era; they dismiss my criticism as a "rhetorical flourish." If they did not mean to imply a parallel of the situations of Soviet geneticists and Western climate skeptics, why did they use the example? Their approach is like the campaigner who smiles benignly and says, "I would never call my opponent a Communist."

As a fifth point, they defend their argument that standard climate science is corrupted by the need to exaggerate warming to obtain research funds. They elaborate this argument by stating, "There are no remotely comparable incentives to the contrary position provided by the industries that he claims would be harmed by the policies he advocates."

This is a ludicrous comparison. To get some facts on the ground, I will compare two specific cases: that of my university and that of Dr. Cohen's former employer, ExxonMobil. Federal climate-related research grants to Yale University, for which I work, averaged $1.4 million per year over the last decade. This represents 0.5 percent of last year's total revenues.

By contrast, the sales of ExxonMobil, for which Dr. Cohen worked as manager of strategic planning and programs, were $467 billion last year. ExxonMobil produces and sells primarily fossil fuels, which lead to large quantities of CO2 emissions. A substantial charge for emitting CO2 would raise the prices and reduce the sales of its oil, gas, and coal products. ExxonMobil has, according to several reports, pursued its economic self-interest by working to undermine mainstream climate science. A report of the Union of Concerned Scientists stated that ExxonMobil "has funneled about $16 million between 1998 and 2005 to a network of ideological and advocacy organizations that manufacture uncertainty" on global warming.e So ExxonMobil has spent more covertly undermining climate-change science than all of Yale University's federal climate-related grants in this area.

The final part of the response of CHL comes back to the economics of climate change and public policy. They make two major points: that the difference between acting now and doing nothing for fifty years is "insignificant economically or climatologically," and that the policy questions are dominated by major uncertainties.

Is the difference between acting now and waiting fifty years indeed "insignificant economically"? Given the importance attached to this question, I recalculated this figure using the latest published model. When put in 2012 prices, the loss is calculated as $3.5 trillion, and the spreadsheet is available on the Web for those who would like to check the calculations themselves.f If, indeed, the climate

skeptics think this is an insignificant number, they should not object to spending much smaller sums for slowing climate change starting now.

But the larger point is that climate-change economics and policies are haunted by vast uncertainties. They mention five: economic growth, physical science, the impacts of climate change, politics, and discounting.

Economists have made major efforts to include these uncertainties in their models. However, other uncertainties have proven much more resistant. The first is a set of threats from climate change to the "world's cultural and natural treasures" (to cite the words of the UNESCO World Heritage Convention), among them major glaciers, marine and terrestrial biodiversity, archaeological sites, and historical cities and settlements. For example, with respect to sea-level rise, there are major threats to the cities of London and Venice and to several low-lying coastal ecosystems.g Ecologists and economists have been unable to find reliable ways of incorporating these threats into economic models.

A second and even more dangerous uncertainty is caused by "tipping points" in the earth system. Among the global-scale tipping points identified by earth scientists are the collapse of large ice sheets in Greenland and Antarctica, changes in ocean circulation, feedback processes by which warming triggers more warming, and the acidification of the ocean.h

The thrust of CHL's argument is that the uncertainties are likely to resolve in favor of inaction rather than strong action to slow climate change policies, and in any case, they argue, policies are unimportant given the size of the uncertainties.

Are the uncertainties likely to be resolved in favor of inaction? Of course, if we knew the answer, we would not be uncertain. However, the economic models have attempted to reflect the state of scientific knowledge and uncertainty as it is reflected in the best unbiased assessments. In the one area that has been around long enough to judge—the impact on climate of rising concentrations of CO2—the interesting finding is that assessments of the uncertainties have changed little since the first major review in 1979.

However, the major problem with the conclusions of CHL is that they ignore the perils of the climate-change uncertainties. To illustrate, think of the issues as if we are playing roulette in a Climate Casino. Each time the roulette wheel stops, we resolve one of the uncertainties. Our best guess is that CO2 doubling will increase temperatures by 3°C, but if the ball lands on black it will be 2°C while a ball on red will produce 4°C. Similarly, a ball in a black pocket will lead to minimal damages from a certain amount of warming, while a ball in a red pocket will lead to much larger warming than we anticipate. On the next spin, a ball in the black will produce low growth and slow growth in emissions, while a ball in the red will produce rapid growth in CO2 emissions. And so forth.

But, in the Climate Casino, the ball also might land on zero or double-zero. If it lands on zero, we find significant loss of species, ecosystems, and cultural landmarks like Venice. If it lands on double-zero, we find an unanticipated shift in the earth's climate system, such as a rapid disintegration of the West Antarctic Ice Sheet.

CHL suggest in effect that the ball will always land in the black pocket. We might hope that all the balls land to our advantage on black, but the odds of that outcome on five spins of the wheel are only 1 in 50.i Moreover, when the different uncertainties interact, the outcomes are likely to be even more costly because of nonlinearities in the physical system. For example, assume that the climate uncertainties are larger than we thought and that the impacts were much more damaging than we projected. This would lead to disproportionately larger damages than in the "best-guess" case.

The point is that CHL have the impact of uncertainty exactly backward. A sensible policy would pay a premium to avoid the roulette wheel in a Climate Casino. This means that the economic model

estimates of the cost of doing nothing for fifty years are understated because they cannot incorporate all the uncertainties—not just the obvious ones such as climate sensitivity but also the zero and double-zero uncertainties such as tipping points, including ones that are yet undiscovered.

The arguments of the sixteen scientists in The Wall Street Journal, their response here, and others who continue to attack climate science and economics are sometimes serious and sometimes foolish. We sometimes hear that we cannot act because scientists are not really 100 percent sure that global warming will occur. But a good scientist is never 100 percent sure of any empirical phenomenon. This point was captured by the following comment on scientific uncertainty by the distinguished physicist Richard Feynman:

Some years ago I had a conversation with a layman about flying saucers…. I said, "I don't think there are flying saucers." So my antagonist said, "Is it impossible that there are flying saucers? Can you prove that it's impossible?"

"No," I said, "I can't prove it's impossible. It's just very unlikely." At that he said, "You are very unscientific. If you can't prove it impossible, then how can you say that it's unlikely?" But that is the way that is scientific. It is scientific only to say what is more likely and what less likely, and not to be proving all the time the possible and impossible.j

This story is a reminder about how good science proceeds. It is possible that the world will not warm over the coming years. It is possible that the impacts will be small. It is possible that a miraculous technology will be invented that can suck CO2 out of the atmosphere at low cost. But in view of the evidence we now have, it would be foolish to bet on these outcomes just because they are possible.

In the end, this barroom brawl is just an entertaining diversion from the main issue. Scientists, economists, and politicians have serious challenges beyond dodging distractions. We must continue to improve our scientific understanding, particularly of the impacts of climate change; we must implement policies such as raising the market price of carbon to provide incentives to households to alter their consumption so that they will have a low- carbon diet; we must also raise carbon prices to send a signal to firms like ExxonMobil that their future lies in research, development, and production of low-carbon fuels; and we must devise mechanisms so that countries will join in a global effort rather than one limited to northwest Europe. All these efforts need to start now, not in fifty years.

1
Claude Allegre et al., " No Need to Panic About Global Warming," The Wall Street Journal , January 27, 2012; Claude Allegre et al., " Concerned Scientists Reply on Global Warming ," The Wall Street

Journal online, February 21, 2012. ↩

2
Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change , edited by S. Solomon and

others (Cambridge University Press, 2007), p. 687. ↩

3
D.M. Smith, S. Cusack, A.W. Colman, C.K. Folland, G.R. Harris, J.M. Murphy, " Improved Surface Temperature Prediction for the Coming Decade from a Global Climate Model," Science , Vol. 317

(2007); N.S. Keenlyside, M. Latif, J. Jungclaus, L. Kornblueh, and E. Roeckner, " Advancing Decadal-Scale Climate Prediction in the North Atlantic Sector," Nature , Vol. 453 (2008). ↩

4
J.T. Kiehl, "Twentieth-Century Climate Model Response and Climate Sensitivity," Geophysical Research Letters. , Vol. 34 (2007). ↩

5
D. Kennedy, "Science, Policy, and the Media," Bulletin of the American Academy of Arts & Sciences , Vol. 61 (2008). ↩

6
The complete Climategate documents can readily be found on the Web. A short summary is available at http://www.climateau dit.info/pdf/mcintyre-heartland_2010.pdf. ↩

7
R.S. Lindzen, " Climate Science: Is It Currently Designed to Answer Questions?" Euresis Journal (in press). An earlier version is available online at http://arxiv.org/abs/0809.3762. ↩

8
William D. Nordhaus, A Question of Balance: Weighing the Options on Global Warming Policies (Yale University Press, 2008). ↩

9
Nordhaus, A Question of Balance , p. 45. ↩

10

Evidence for a small climate sensitivity can be found in the peer-reviewed literature, as well as online sources. It includes results from a variety of different empirical approaches, including (1) time series analyses of the published temperature record; (2) examination of the response of the earth's outgoing radiation response to transient climate events; (3) calorimetric studies of the ocean-atmosphere system; (4) mechanisms for secular climate change arising from ocean circulation systems and astronomical influences; and (4) radiative and convective heat transfer in the oceans and atmosphere.

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11

Nordhaus, A Question of Balance , Table 5–8. ↩

12
The Impact of Climate Change on the United States Economy, edited by Robert Mendelsohn and James Neumann (Cambridge University Press, 1999); Robert Mendelsohn, The Greening of Global

Warming (AEI Press, 1999). ↩

13
Clive Hamilton, "Nordhaus' Carbon Tax: An Excuse to Do Nothing?," May 4, 2009, available at

http://www.clivehamilton.net .au/cms/media/critique_of_nordhaus.pdf. ↩

14

Nordhaus, A Question of Balance , p. 18. ↩

15

Nordhaus, A Question of Balance , p.127. ↩

a
This can be seen more generally as follows. Assume, based on the historical data, that temperature is following an upward trend with an average increase of 0.006°C per year and a random variability

(standard deviation for a normal error) of 0.133°C per year. Elementary statistics will show that this process will have decadal declines in temperature in 44 percent of the years. ↩

b
More precisely, CHL argue that the standard estimates of the sensitivity of climate to increases in CO2 and other greenhouse gases are overstated. The technical term for this is the "equilibrium climate sensitivity," which is the equilibrium or long-run global average surface warming following a doubling of atmospheric CO2 concentration. ↩

c
CHL further argue that the inputs into the models for the simulations of historical climate models are reverse-engineered to produce the results, that is, that modelers have selected the inputs of radiative forcings for their models to match historical temperature changes. "Radiative forcing" is a technical term denoting the impact of the different gases and climate-affecting factors on the earth' s energy balance. Forcings are measured as watts per meter squared in the lower atmosphere, but I simply call these "warming units." Some impacts, such as those caused by CO2 concentrations in the atmosphere, are well determined. However, others are very difficult to measure. CHL correctly point to the large uncertainties here. The largest uncertainty is the forcing due to "aerosols," which are basically particles caused by sources such as power plants, agriculture, and clearing of forests. (For this discussion, I rely on the authoritative discussion in the IPCC Fourth Assessment Report, Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by S. Solomon and others (Cambridge University Press, 2007.)
To give a sense of the magnitudes here, the IPCC estimated the change in forcings from 1750 to 2005 from CO2 alone to be 1.7 units of warming, while the total including all other factors was estimated to be 1.6 units. However, there is great uncertainty about the impact of the other forcings, particularly aerosols. The IPCC estimates that the uncertainty range for total warming was between 0.6 and 2.4 units of warming (p. 4). This range is the (5, 95) percentile confidence interval and reflects the authors' expert judgment that there is at least a 9 in 10 chance that the actual number is within the cited range.
Climate scientists have recognized this uncertainty for many years and are working to reduce it, but model-building is not simply a curve-fitting exercise. A recent model comparison shows clearly the importance of aerosols for simulating historical climates. The model ensemble with aerosols alone is estimated to reduce global mean temperature by about 0.5°C over the last century. Simulations that include all forcings except aerosols lead to an overprediction of approximately the same amount (see Olivier Boucher et al., "Climate Response to Aerosol Forcings in CMIP5," CLIVAR Exchanges , No. 56, Vol. 16, No. 2, May 2011). The ultimate answer to the uncertainty is not to dismiss our climate models but to improve our measurements, particularly of the effects of aerosols. ↩

d
For example, a leading textbook on air pollution cites the following definition from the US Environmental Protection Agency as a good place to start thinking: "Air pollution: The presence of contaminants or pollutant substances in the air that interfere with human health or welfare, or produce

other harmful environmental effects." Daniel A. Vallero, Fundamentals of Air Pollution , fourth

edition (Academic Press, 2008), p. 3. ↩

e
"Smoke, Mirrors, and Hot Air," available at www.ucsusa.org/assets

documents/global_warming/exxon_report.pdf. ↩

f
For those who would like to see the Excel spreadsheet model on which these calculations were made to check them, or try other experiments, it is available at www.econ.yale.edu/~nordhaus/homepage/NYRB_RICE.htm. Download the Excel program, go to the sheet named "50yeardelay" and follow the instructions there. You will be able to verify the number in

the text and do other experiments as well. ↩

g
The case studies can be found in Augustin Colette et al., Case Studies on Climate Change and World Heritage (Paris: UNESCO World Heritage Centre, 2007), available at

unesdoc.unesco.org/images/0015/001506/150600 e.pdf. ↩

h
A major source here is Timothy M. Lenton et al., "Tipping Elements in the Earth's Climate System,"

Nature , Vol. 105, No. 6 (February 12, 2008). ↩

i
More exactly, it is (16/38) 5 = 0.0238. Moreover, on five rolls of the wheel, there is a 24 percent chance that a zero or double-zero catastrophic event will occur. These probabilities are only

illustrative to show how multiple uncertainties interact. ↩

j

Richard Feynman, The Character of Physical Law (MIT Press, 1970). ↩