CLIMATE CHANGE, CATASTROPHE, REGULATION AND THE SOCIAL COST OF CARBON

by Julian Morris

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EXECUTIVE SUMMARY

Federal agencies are required to calculate the costs and benefits of new regulations that have significant economic effects. Since a court ruling in 2008, agencies have included a measure of the cost of greenhouse gas emissions when evaluating regulations that affect such emissions. This measure is known as the "social cost of carbon" (SCC).

Initially, different agencies applied different SCCs. To address this problem, the Office of Management and Budget and Council of Economic Advisors organized an Interagency Working Group (IWG) to develop a range of estimates of the SCC for use by all agencies. However, the IWG's estimates were deeply flawed. In April 2017, President Trump issued an executive order rescinding the IWG's estimates and disbanded the IWG. The question now is what value regulatory agencies should use for the SCC—if any—when evaluating rules that affect greenhouse gas emissions.

PROBLEMS WITH CALCULATING A SOCIAL COST OF CARBON

Most analyses of the social cost of carbon, including the IWG's, have utilized "integrated assessment models" (IAMs), the basic methodology of which involves the following six steps:

1. Develop (or choose from existing) scenarios of future emissions of GHGs;
2. Use those scenarios to estimate future atmospheric concentrations of GHGs;
3. Project changes in average global temperature and/or climate resulting from these future atmospheric GHG concentrations;

4. Estimate the economic consequences of the resultant changes in temperature/climate;
5. Estimate the costs of abating specific amounts of GHG emissions;
6. Combine the estimates from steps 4 and 5 to produce an assessment of the net economic effect of different scenarios and thereby identify the optimum path of emissions.

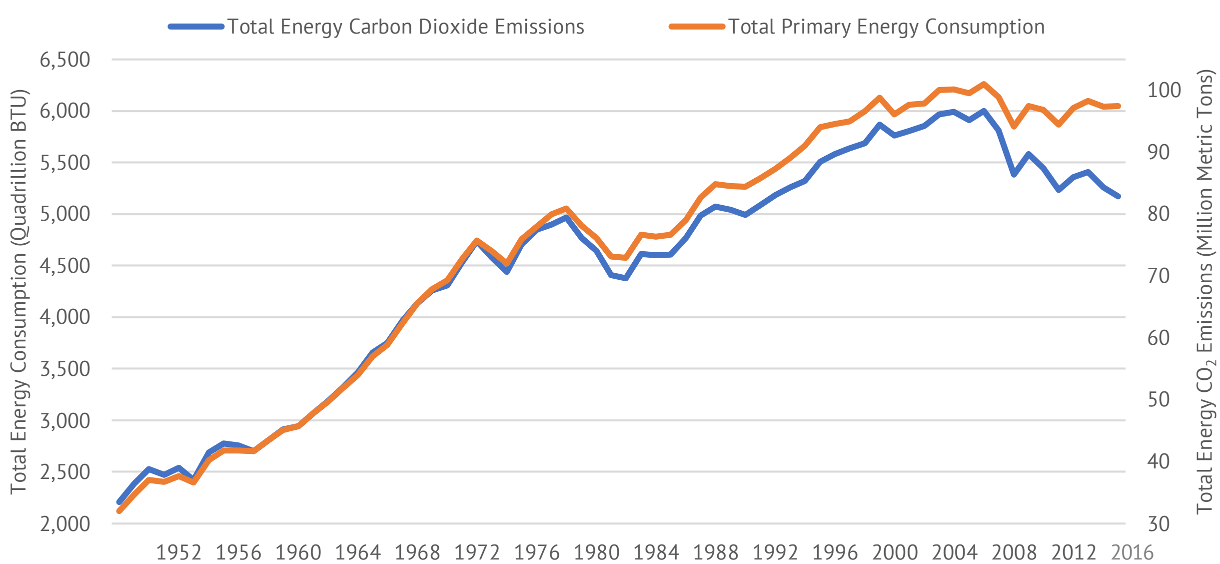
Each step in this process is fraught with difficulty:

1. Future emissions of GHGs are unknown—and unknowable—but likely lower than assumed in most IAMs.

Future human-related emissions of GHGs will depend on many factors, especially: the human population, the extent and use of technologies that result in energy consumption, the types of technology used to produce energy, and the efficiency with which technologies use energy.

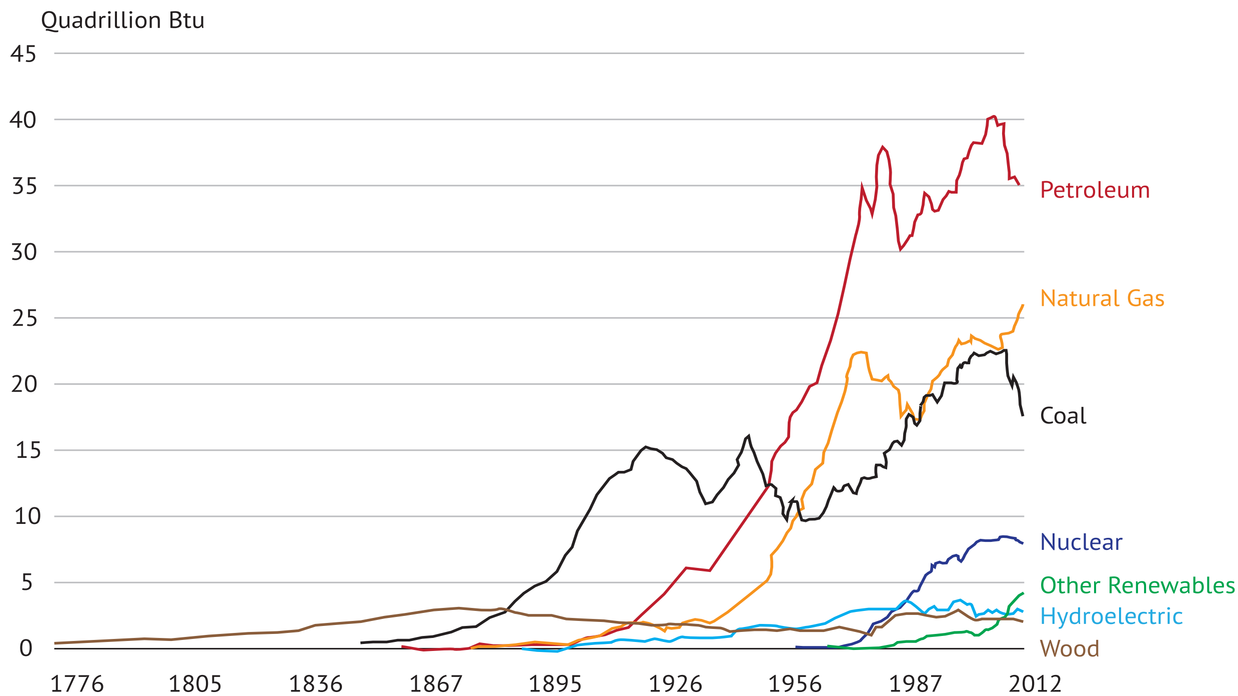
None of these factors can be forecast with any precision. Predicting future technologies is particularly challenging. However, greenhouse gas emissions from U.S. sources have declined from their peak (see Figure ES1), mainly as a result of using more energy-dense, lower carbon fuels (especially natural gas) and by using energy more efficiently (see Figure ES2).

FIGURE ES1: U.S. ENERGY CONSUMPTION AND CO_2 EMISSIONS 1949–2016



Source: Energy Information Administration. March 2017 *Monthly Energy Review*.

FIGURE ES2: SOURCES OF U.S. ENERGY 1776–2012



Source: Energy Information Administration, https://www.eia.gov/todayinenergy/detail.php?id=11951

Global emissions are rising but at a declining rate, in spite of robust economic growth. If these trends continue, future concentrations of greenhouse gases are likely to be at the low end of estimates used by the IWG when calculating the SCC.

2. The relationship between emissions and concentrations of greenhouse gases is complicated.

Calculating future atmospheric concentrations of GHGs, based on estimates of future human emissions, requires knowledge of the length of time that these GHGs will remain in the atmosphere. That in turn requires knowledge about the rate at which they will break down and/or be absorbed. This is no simple task. The rate at which GHGs such as methane and dinitrogen monoxide break down depends on such things as temperature and the amount of water vapor and other chemicals in the atmosphere with which they might react. The rate at which CO_2 is taken up by plants, soil and oceans varies considerably depending on factors such as temperature and the availability of nutrients. The dynamic and interactive nature of these effects complicates the picture further.

3. The climate is likely much less sensitive to increased emissions of GHGs than has been presumed in most IAMs, including those used by the IWG.

Early estimates of the sensitivity of the climate to increased concentrations of greenhouse gases found that a doubling of atmospheric carbon dioxide would result in a warming of between 1.5°C and 4.5°C, with a "best guess" of 3°C. But those estimates were based on poorly specified models. Tests of models using those estimates of climate sensitivity predict about twice as much warming as actually occurred. Nonetheless, the IWG used those early, inaccurate estimates. More recent estimates of climate sensitivity suggest that future emissions are likely to result in much more modest warming of the atmosphere (with a doubling of carbon dioxide concentrations resulting in a warming of 1.5°C or less).

4. The effects of climate change are unknown—but the benefits may well be greater than the costs for the foreseeable future.

If the recent lower estimates of climate sensitivity are correct and emissions follow a relatively low path, warming will likely be modest and its effects mild. Likely effects include:

- Warming will be greater in cold places (i.e. farther from the equator), seasons (winter), and times (night) than in warm places (equatorial regions), seasons (summer) and times (day).
- At higher latitudes, winters will be less extreme.
- Precipitation will increase, but not everywhere, and some places will become drier.
- Sea levels will to continue to rise slowly, as the oceans expand and land-based glaciers melt. (If current trends continue, sea level will rise by about 11 inches by 2100.)
- The incidence of extreme weather events will not change dramatically.

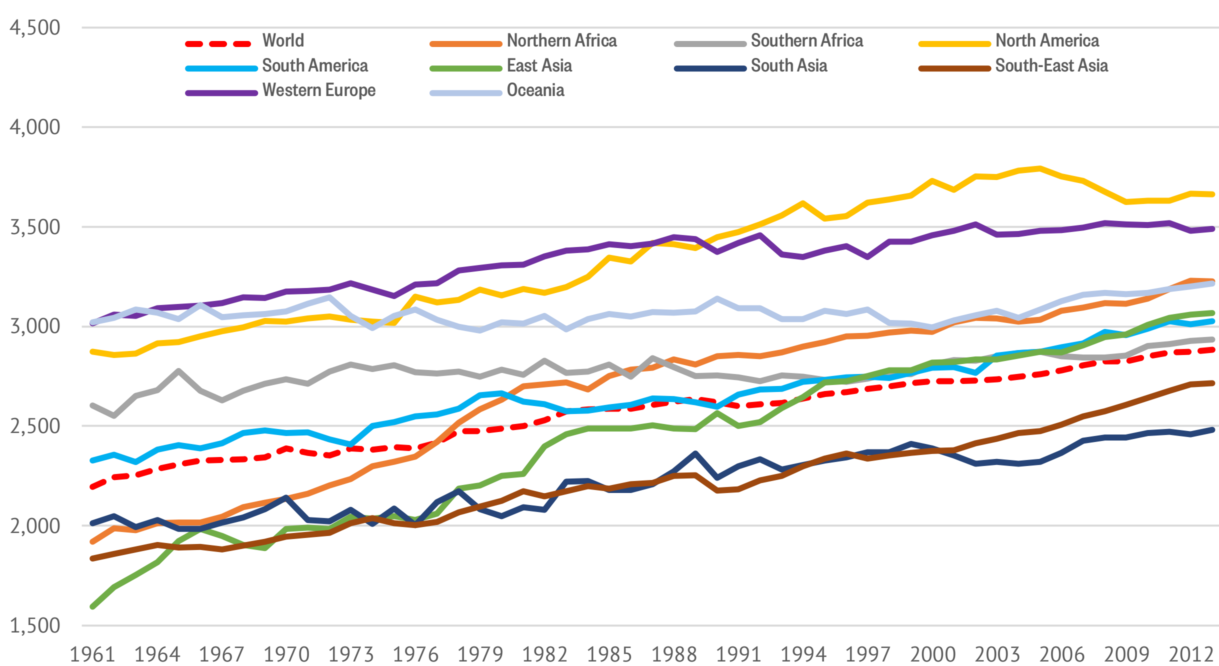
While increased temperatures in warm places and seasons may result in higher mortality among those who are less able to cope with higher temperatures, warmer winters will reduce the number of people who die from cold. Since 20 times as many people currently die from cold as die from heat, modest warming will reduce temperature-related deaths. These effects will be tempered by the use of heating and cooling technologies, but the costs of additional cooling will be more than offset by reduced expenditure on heating.

While rising temperatures have the potential to increase the incidence of some diseases, such as diarrhea, these effects are likely to be moderated by the adoption of better technologies, including piped clean water and sewerage.

Increased concentrations of carbon dioxide and higher temperatures are likely to increase agricultural output in many places. While agricultural output may fall in other places, this effect is likely to be moderated by the adoption of new crop varieties and other technologies. On net, crop production is likely to rise in the U.S. and globally.

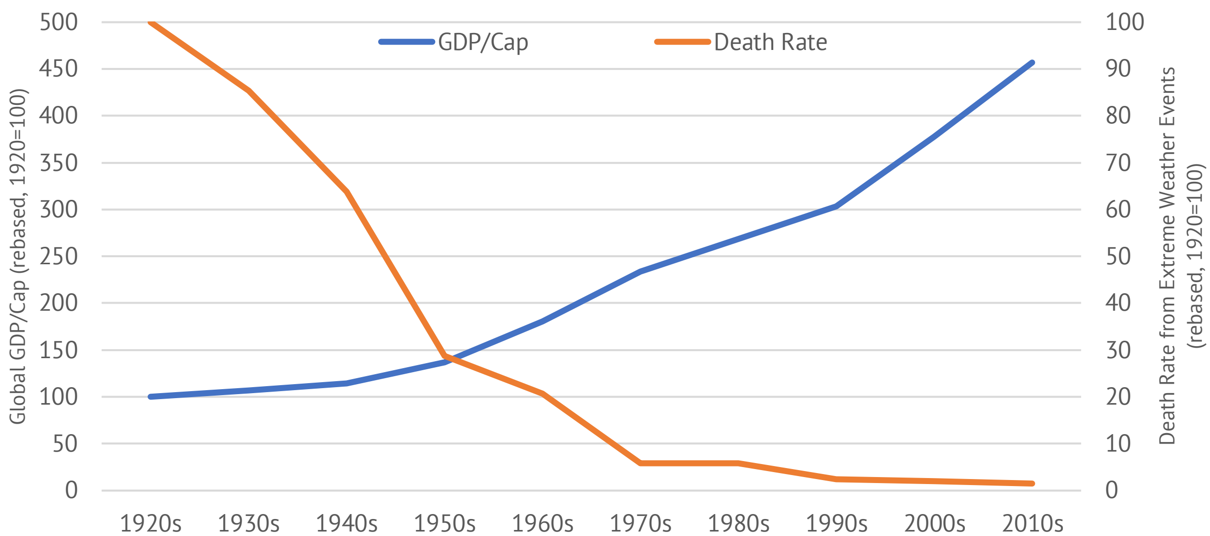
Many economic models of climate change, including two of the three IAMs used by the IWG assume very limited adaptation. Yet the history of human civilization is one of adaptation. Food availability per capita and access to clean water have risen dramatically over the past half century, reducing malnutrition and water-borne diseases and increasing life expectancy (see Figure ES3). Rising wealth and the adoption of new technologies have reduced mortality from extreme weather events by 98% in the past century (see Figure ES4). It seems highly likely that continued innovation and more widespread adoption of adaptive technologies will continue to reduce mortality, mitigating most—if not all—the adverse consequences of rising temperatures.

FIGURE ES3: FOOD AVAILABILITY PER CAPITA IN SELECT REGIONS, FOOD SUPPLY, KCAL/DAY



Source: Food and Agriculture Organization of the United Nations: FAOStat (http://www.fao.org/faostat/en/#home)

FIGURE ES4: GLOBAL MORTALITY FROM WEATHER-RELATED NATURAL DISASTERS AND PER CAPITA INCOME



Source: Author's calculations based on data from EM-DAT (the international disasters database: http://www.emdat.be/), Angus Maddison Project (http://www.ggdc.net/maddison/maddison-project/home.htm) and World Bank World Development Indicators (http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators).

5. The costs of reducing future emissions of GHGs are unknown—and will depend very much on the extent and timeframe of any reduction.

Proponents of taking action now argue that any delay would increase the total cost of emissions reductions—because baseline emissions (i.e. the emissions that would occur without any mandated reductions) would be higher and the size of any such future reduction would have to be greater. But such arguments presume both significant increases in baseline emissions and a need dramatically to reduce such emissions. If the trends in technology identified earlier do continue, growth in baseline GHG emissions will continue to slow and in the longer term may even fall without any government mandates. Indeed, it is possible that baseline emissions in the future (i.e. after 2050) will be consistent with a pathway of emissions that results in atmospheric GHG concentrations that generate net benefits.

Even if baseline emissions rise to a level that justifies intervention in the future, that does not necessarily justify reducing emissions now. Humanity currently relies predominantly on carbon-based fuels for energy generation, and the costs of alternative sources of energy are in most cases relatively high. (If alternative sources of energy were less expensive, then it would make economic sense to adopt them.) Continued innovation will almost certainly result in lower emissions per unit of output in the future, so the costs of reducing a unit of GHG emissions in the future will be lower than they are today.

6. When combining benefits and costs, the IWG used inappropriately low discount rates, giving the false impression that the benefits of reducing emissions are greater than the costs. At discount rates that reflect the opportunity cost of capital, the current costs of taking action to reduce GHG emissions now and in the near future are almost certainly greater than the benefits.

OMB guidelines state that, for the base case, "Constant-dollar benefit-cost analyses of proposed investments and regulations should report net present value and other outcomes determined using a real discount rate of 7%. This rate approximates the marginal pretax rate of return on an average investment in the private sector in recent years."

Unfortunately, when discounting the benefits and costs associated with global warming, many analysts have used discount rates that do not reflect the opportunity cost of capital. For example, the IWG provided an estimate of the SCC at a 5% discount rate, but it is the *highest* rate given. In its guidance, the IWG emphasized the SCC calculated at a 3% discount rate. Its rationale for using the lower rate is that future benefits from avoiding climate change costs relate to future consumption, rather than investment. Policies to address climate change would affect both consumption and investment, but for the purposes of evaluation what matters is the effect on investment, since it is the effect of policies on investment decisions that will determine rates of innovation and hence economic growth, the ability to adapt to climate change, and future consumption. In other words, while future consumption is of primary concern, due to its relationship to human welfare, return on investment is the key factor determining future consumption. Thus, the appropriate discount rate is the rate of return on capital.

Changing the Assumptions

Changing the assumptions made in the IWG's models can have a dramatic effect on estimates of the SCC. Anne Smith and Paul Bernstein of National Economic Research Associates ran the IAMs used by the IWG making four changes:

1. they changed the emissions scenario to reflect more realistic assumptions regarding the relationship between emissions and economic growth;
2. they changed the time horizon from 2300 to 2100;

3. they changed the discount rate from 3% to 5%;
4. they changed the scope from global to U.S. only.

When all these changes were combined, the effect was to reduce the SCC by 97%, from $43 to about $1.30.

Smith and Bernstein's analysis did not change any assumptions regarding climate sensitivity or other relevant climate parameters that might have been mis-specified in the IAMs used by the IWG. Kevin Dayaratna, Ross McKitrick and David Kreutzer assessed the effects of using more-recent empirical estimates of climate sensitivity to calculate updated SCC estimates using two of the IWG models. They found that, for one model, the average SCC fell by 30%–50% and for the other it fell by over 80%. Moreover, at a 7% discount rate, one of the models generated a negative SCC.

If all of the adjustments made by Smith and Bernstein were combined with those made by Dayaratna et al. it seems likely that the SCC would fall to well below $1. Indeed, given uncertainties in the various parameters used, it seems difficult to avoid the conclusion that for practical purposes the SCC is effectively $0.

What About Catastrophic Climate Change?

Some economists have objected that conventional measures of the SCC fail adequately to account for the possibility of catastrophic climate change. However, such criticisms are based on assumptions concerning the probability of catastrophe that have no empirical basis. A recent attempt to estimate the SCC by surveying experts to find out what they would be willing to pay to avert catastrophe is so riddled with defects as to be of no utility.

THE SOCIAL COST OF CARBON AND REGULATORY REFORM

The IWG's SCC was developed under Executive Order 12866, which requires regulatory agencies to consider the costs and benefits of regulations they are promulgating—and alternatives—and choose the regulatory option that maximizes net benefits to society.

If the SCC is $0, mandatory reductions of GHG emissions are not justified. Thus, regulations predicated on a positive SCC should be reconsidered. While these regulations often also have purported "co-benefits" of significant magnitude (such as reduced emissions of particulates), those co-benefits could almost certainly be achieved at much lower cost through alternative means. As such, when evaluating these regulations, agencies should compare their cost to alternative regulations that specifically address the co-benefit elements.

Other alternatives to mandatory reductions in emissions of GHGs that should be considered include the reform or removal of regulatory and other restrictions on the development of lower-carbon forms of energy and the removal of barriers to adaptation.

TABLE OF CONTENTS

PART 1

INTRODUCTION

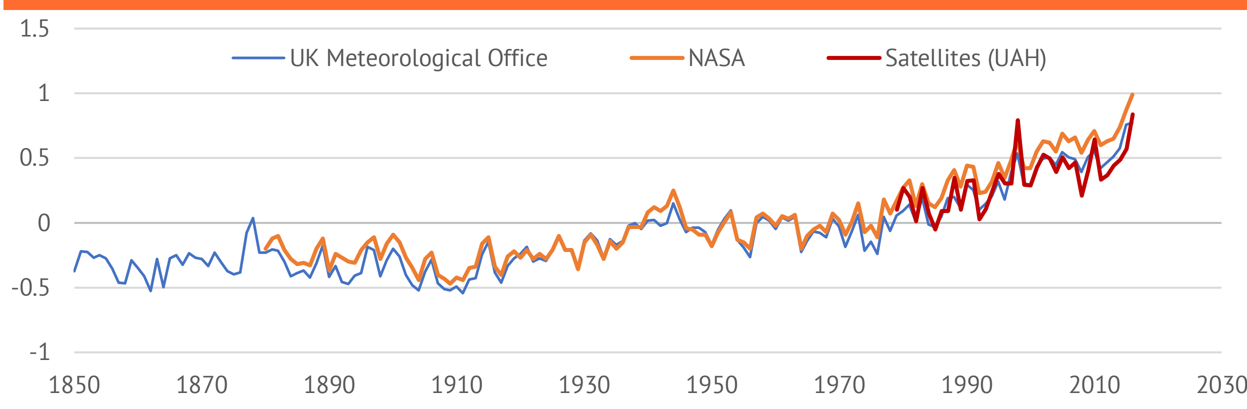
This study considers the role of federal regulation in addressing the problem of global climate change. It begins with a discussion of the nature of climate change, describes how the Social Cost of Carbon (SCC) is derived, critically evaluates the U.S. Government Interagency Working Group's estimates of the SCC and alternate approaches, including those based on assessments of catastrophic climate change, and offers an alternate, better approach to addressing climate change threats and opportunities.

PART 2

CLIMATE CHANGE AND FEDERAL REGULATION

Estimates from various sources suggest that the earth's lower atmosphere has warmed by about 1°C since the 1880s (see Figure 1). Some of that warming has likely been the result of increased radiative forcing due to higher concentrations of certain trace "greenhouse gases" (GHGs) emitted during human activities. The precise extent of human contributions to the warming is subject to much dispute (see discussion in Part 3 on climate sensitivity). The effect of current and future emissions on future climate change is even more uncertain. Nonetheless, governments around the world, including various states and the federal government in the U.S., have chosen to take action to reduce GHG emissions.

FIGURE 1: GLOBAL MEAN TEMPERATURE ANOMALIES 1850–2016 (IN DEGREES CELSIUS)



Source: NASA, the UK Meteorological Office, and the University of Alabama Huntsville[1]

1 NASA data provide annual mean temperatures for land and sea from the Godard Institute for Space Science Research (GISS). Available at: https://data.giss.nasa.gov/gistemp/graphs/. Meteorological Office data are the HadCRUT4 median temperatures for land and sea. Available at: http://www.metoffice.gov.uk/hadobs/hadcrut4/data/current/download.html. UAH data are annualized monthly average temperature data from satellite measurements produced by the University of Alabama Huntsville (UAH). Available at: https://www.nsstc.uah.edu/data/msu/v6.0beta/tlt/uahncdc_lt_6.0beta5.txt.

2.1 FEDERAL REGULATION OF GREENHOUSE GAS EMISSIONS

The effects of rising atmospheric concentrations of certain GHGs (including carbon dioxide and methane) have been a subject of interest to U.S. federal agencies since at least the 1950s, when Roger Revelle and Hans Seuss began work on the subject using funds from the Office of Naval Research.[2] But federal regulation of GHGs is a much more recent phenomenon—and is largely a result of responses to two lawsuits: *Massachusetts v. EPA* and *Center for Biological Diversity v. NHTSA*.

MASSACHUSETTS V. EPA

In 1999, the Sierra Club, Greenpeace and several other organizations petitioned the Environmental Protection Agency to regulate mobile sources of GHGs under Section 202(a)(1) of the Clean Air Act, which states:

> *The Administrator shall by regulation prescribe (and from time to time revise) ... standards applicable to the emission of any air pollutant from any class or classes of new motor vehicles or new motor vehicle engines, which in his judgment cause, or contribute to, air pollution which may reasonably be anticipated to endanger public health or welfare.*[3]

After the EPA denied the petition, the petitioners, joined by the states of Massachusetts, California and New Jersey, appealed the decision. In 2005, the D.C. Court of Appeal held that "the EPA administrator properly exercised his discretion under s. 202(a)(1) in denying the petition for rulemaking."[4] The Court noted that the EPA had relied upon a comprehensive report from the National Research Council which stated that "there is considerable uncertainty in current understanding of how the climate system varies naturally and reacts to emissions of greenhouse gases." The court also noted that "This uncertainty is compounded by the possibility for error inherent in the assumptions necessary to predict future climate change. And ... past assumptions about effects of future greenhouse gas emissions have proven to be erroneously high."

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2 Weart, Spencer. *The Discovery of Global Warming*. Cambridge, MA: Harvard University Press, 2003. 27. Supplemental information available at: http://history.aip.org/climate/Kfunds.htm.

3 Clean Air Act. Section 202 (a)(1). https://www.epa.gov/clean-air-act-overview/clean-air-act-title-ii-emission-standards-moving-sources-parts-through-c

4 415 F.3d 50, 367 U.S. App. D.C. 282 (D.C. Cir. 2005).

In 2007, the Supreme Court overturned the Court of Appeal ruling, stating that "EPA's steadfast refusal to regulate greenhouse gas emissions presents a risk of harm to Massachusetts that is both 'actual' and 'imminent'." Among other things, the Supreme Court noted:

> *The harms associated with climate change are serious and well recognized…*
>
> *While regulating motor-vehicle emissions may not by itself reverse global warming, it does not follow that the Court lacks jurisdiction to decide whether EPA has a duty to take steps to slow or reduce it…*
>
> *Because greenhouse gases fit well within the Act's capacious definition of "air pollutant," EPA has statutory authority to regulate emission of such gases from new motor vehicles.*[5]

The Court ruled that the EPA had rejected the rule-making petition based on impermissible considerations. Its action was therefore, "arbitrary, capricious, or otherwise not in accordance with law… On remand, EPA must ground its reasons for action or inaction in the statute."

Following the Supreme Court ruling, the EPA initiated a process to evaluate the threat posed by GHG emissions, which resulted in two separate but related findings issued on December 7, 2009:

> ***Endangerment Finding:*** *The Administrator finds that the current and projected concentrations of the six key well-mixed greenhouse gases—carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6)—in the atmosphere threaten the public health and welfare of current and future generations.*
>
> ***Cause or Contribute Finding:*** *The Administrator finds that the combined emissions of these well-mixed greenhouse gases from new motor vehicles and new motor vehicle engines contribute to the greenhouse gas pollution which threatens public health and welfare.*[6]

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5 U.S. Supreme Court. *Massachusetts et al v. EPA et al.* No. 05-1120. Decision April 2, 2007.

6 EPA, *Endangerment and Cause or Contribute Findings.* Washington, D.C.: U.S. Environmental Protection Agency, no date. Available at: https://www.epa.gov/ghgemissions/endangerment-and-cause-or-contribute-findings-greenhouse-gases-under-section-202a-clean

CENTER FOR BIOLOGICAL DIVERSITY V. NHTSA

The second case relates to Corporate Average Fuel Economy (CAFE) standards set by the National Highway Transportation Safety Administration (NHTSA). Between 2003 and 2006, NHTSA developed a rule for updated CAFE standards for light duty trucks with model years 2008–2011. NHTSA took this action under the auspices of the Energy Policy Conservation Act (EPCA).

Under Executive Order 12866 (discussed in more detail below), agencies are required to consider the costs and benefits of "major" rules (i.e. rules that cost at least $100 million). The amended CAFE standards developed by NHTSA constitute such a major rule, so a regulatory impact assessment was undertaken. However, that assessment did not include any assessment of the benefits or costs arising from reducing GHG emissions. Seeking to rectify this, the Center for Biological Diversity (CBD), a nonprofit organization, sued NHTSA.

In its defense, NHTSA argued that it "continues to view the value of reducing emissions of CO_2 and other greenhouse gases as too uncertain to support their explicit valuation and inclusion among the savings in environmental externalities from reducing gasoline production and use."

The 9th Circuit Court of Appeals argued that in its cost-benefit analysis "NHTSA assigned no value to the most significant benefit of more stringent CAFE standards: reduction in carbon emissions." It concluded that NHTSA's reasoning is arbitrary and capricious for several reasons:

> *First, while the record shows that there is a range of values, **the value of carbon emissions reduction is certainly not zero**. Second, NHTSA gave no reasons why it believed the range of values presented to it was "extremely wide." Third, NHTSA's reasoning is arbitrary and capricious because it has monetized other uncertain benefits, such as the reduction of criteria pollutants, crash, noise, and congestion costs. ... "and the value of increased energy security." Fourth, NHTSA's conclusion that commenters did not "reliably demonstrate" that monetizing the value of carbon reduction would have affected the stringency of the CAFE standard "runs counter to the evidence" before it. Thus, NHTSA's decision not to monetize the benefit of carbon emissions reduction was arbitrary and capricious, and **we remand to NHTSA for it to include a monetized value for this benefit in its analysis of the proper CAFE standards.*** (Emphasis added.)[7]

[7] *Center for Biological Diversity v. National Highway Traffic Safety Administration.* 538 F.3d 1172. Available at: http://static1.squarespace.com/static/549885d4e4b0ba0bff5dc695/t/5512fd17e4b0cd183ba470cf/1427307799733/CBD+v+NHTSA+%289th+Cir.+2008%29.pdf

This decision thus set the stage for NHTSA, the EPA, and other federal agencies to include a monetized value for the benefit of reducing carbon emissions.

2.2 SETTING THE SOCIAL COST OF CARBON

After the *CBD v NHTSA* ruling, federal agencies began including a measure of the optimal price of greenhouse gas emissions, known as the "social cost of carbon" (SCC), in their regulatory impact analyses in cases where regulations affected emissions of greenhouse gases. The ostensible utility of the SCC is that, applied uniformly, it should induce marginal changes in emissions of greenhouse gases that achieve the optimal level of emissions from society's perspective. However, different agencies used different numbers for the SCC.[8] In response, the Office of Management and Budget and the President's Council of Economic Advisors established an Interagency Working Group (IWG) tasked with setting a consistent SCC.[9]

The IWG issued its first estimates of the SCC in February 2010, along with a Technical Support Document explaining how it arrived at the numbers. It subsequently revised those numbers four times.[10] Numerous studies and comments criticized the IWG's estimates of the SCC, including one by this author.[11]

In an Executive Order issued on March 28, 2017, President Trump rescinded the IWG's estimates and disbanded the IWG. The order also required agencies, "when monetizing the value of changes in greenhouse gas emissions resulting from regulations" to "ensure, to the extent permitted by law, that any such estimates are consistent with the guidance contained in Office of Management and Budget (OMB) Circular A-4 of September 17, 2003."[12]

The challenge now faced by regulatory agencies, who may still feel bound by the earlier rulings that say they have authority to regulate greenhouse gas emissions and should apply a social cost of carbon, is to decide what value to use for that SCC and how best to regulate greenhouse gas emissions.

8 Pizer, William et al. "Using and improving the social cost of carbon." *Science*. Vol. 364 (6214). 1189–90. 5 December 2014. Available at: http://dukespace.lib.duke.edu/dspace/bitstream/handle/10161/10259/Science-2014-Pizer-1189-90.pdf;sequence=1

9 Ibid.

10 The most recent revision is: IWG. *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866*. Washington, D.C.: Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, August 2016. Available at: https://www.epa.gov/sites/production/files/2016-12/documents/sc_co2_tsd_august_2016.pdf

11 Morris, Julian. *Assessing the Social Costs and Benefits of Regulating Carbon Emissions*. Los Angeles: Reason Foundation, August 2015. Available at: http://reason.org/files/social_costs_of_regulating_carbon.pdf

12 The White House. *Presidential Executive Order on Promoting Energy Independence and Economic Growth*. March 28, 2017. Available at: https://www.whitehouse.gov/the-press-office/2017/03/28/presidential-executive-order-promoting-energy-independence-and-economi-1

PART 3

USING INTEGRATED ASSESSMENT MODELS TO ESTIMATE THE SCC

3.1 BASIC METHODOLOGY

Most analyses of the social cost of carbon have utilized "integrated assessment models" (IAMs), the basic methodology of which involves the following six steps:[13]

1. Develop (or choose from existing) scenarios of future emissions of GHGs
2. Use those scenarios to estimate future atmospheric concentrations of GHGs
3. Project changes in average global temperature and/or climate resulting from these future atmospheric GHG concentrations
4. Estimate the economic consequences of the resultant changes in temperature/climate
5. Estimate the costs of abating specific amounts of GHG emissions
6. Combine the estimates from steps 4 and 5 to produce an assessment of the net economic effect of different scenarios and thereby identify the optimum path of emissions

Each step in this process is fraught with difficulty.

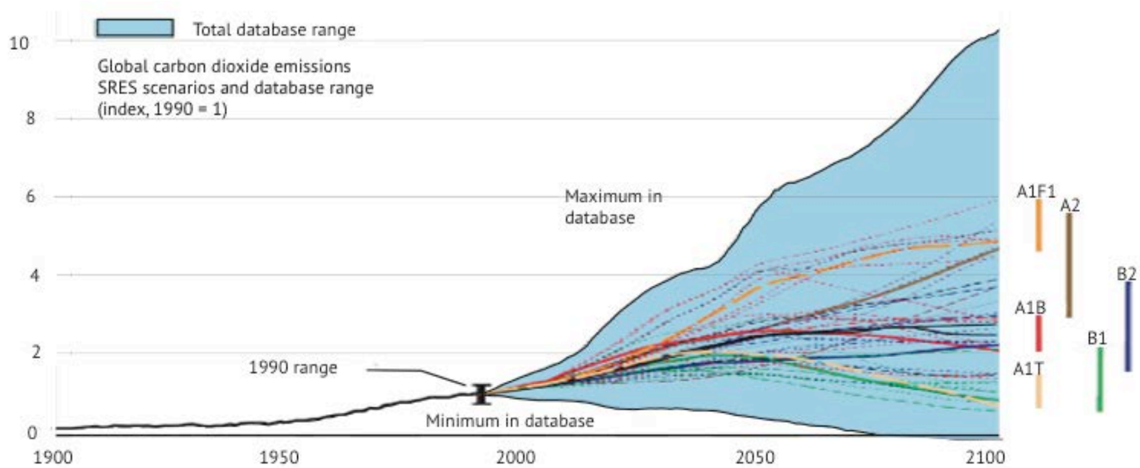
[13] These are similar to the six elements identified in Robert Pindyck, "Climate Change Policy: What do the Models Tell Us?" *Journal of Economic Literature*. 2013. 51(3). 860-872.

3.2 DIFFICULTIES INHERENT IN BASIC METHODOLOGY

FUTURE EMISSIONS OF GHGS REMAIN UNKNOWN—AND UNKNOWABLE.

Future human-related emissions of GHGs will depend on many factors, especially: the human population, the extent and use of technologies that result in energy consumption, the types of technology used to produce energy, and the efficiency with which technologies use energy.[14] While estimates of the future population of the planet can be made within reasonable bounds (the United Nations currently estimates the population rising to between 9 and 13 billion by 2100),[15] it is much more difficult to forecast what kinds of technologies are likely to exist 50 or more years from today. Indeed, when the Intergovernmental Panel on Climate Change sought to undertake such an exercise in 2000, it produced estimates that—even with no "intervention"—ranged from a significant reduction in annual emissions to a near-10-fold increase—as shown in Figure 2.[16] When it revised its emission scenarios for the Fourth Assessment Report in 2014, the IPCC retained a similar range—but simply asserted that the baseline emissions would be at the high end—as shown in Figure 3.[17]

FIGURE 2: GLOBAL CARBON DIOXIDE EMISSIONS IN THE IPCC'S 2000 SCENARIOS



Source: IPCC. *Special Report on Emission Scenarios*. 2000. 7.

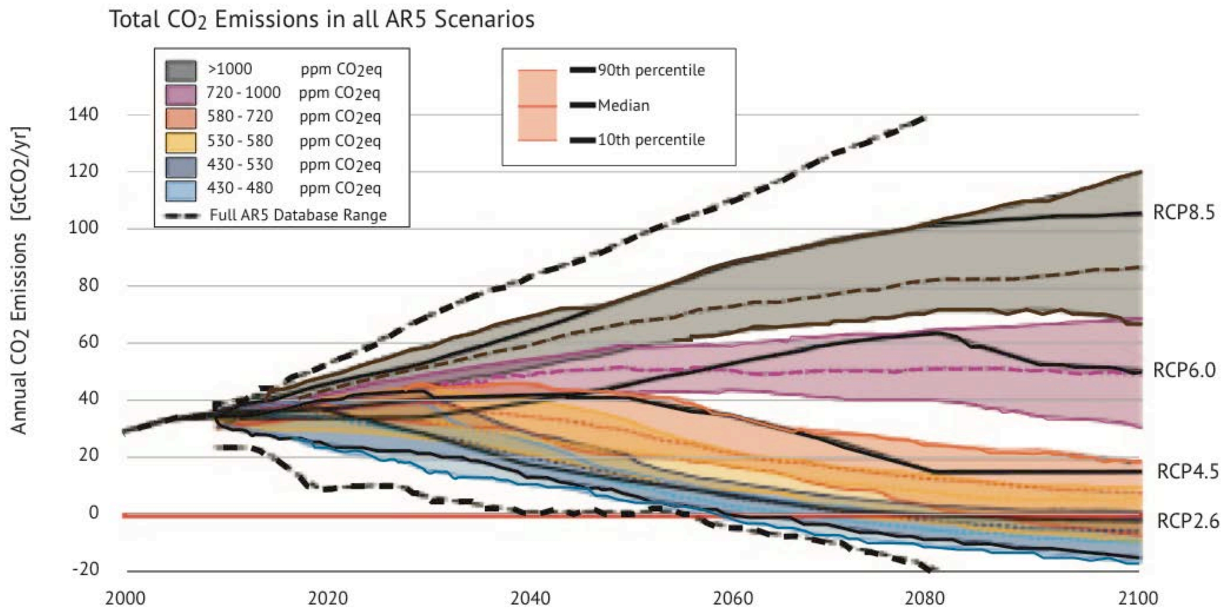
[14] These factors mainly relate to emissions of carbon dioxide and to some extent methane. Methane is also produced as a by-product of the decomposition of municipal and agricultural waste, as well as from cows, rice paddies and some other activities.

[15] United Nations Department of Economic and Social Affairs. Population Division. *World Population Prospects: The 2015 Revision*. New York: United Nations, 2015.

[16] IPCC. *Special Report on Emission Scenarios, Summary for Policymakers*. Geneva: Intergovernmental Panel on Climate Change, 2000. 7.

[17] IPCC. "Chapter 6: Assessing Transformation Pathways" in *Fifth Assessment Report*. Geneva: Intergovernmental Panel on Climate Change. 2014. 432.

FIGURE 3: CARBON DIOXIDE EMISSIONS IN THE IPCC'S 2014 SCENARIOS



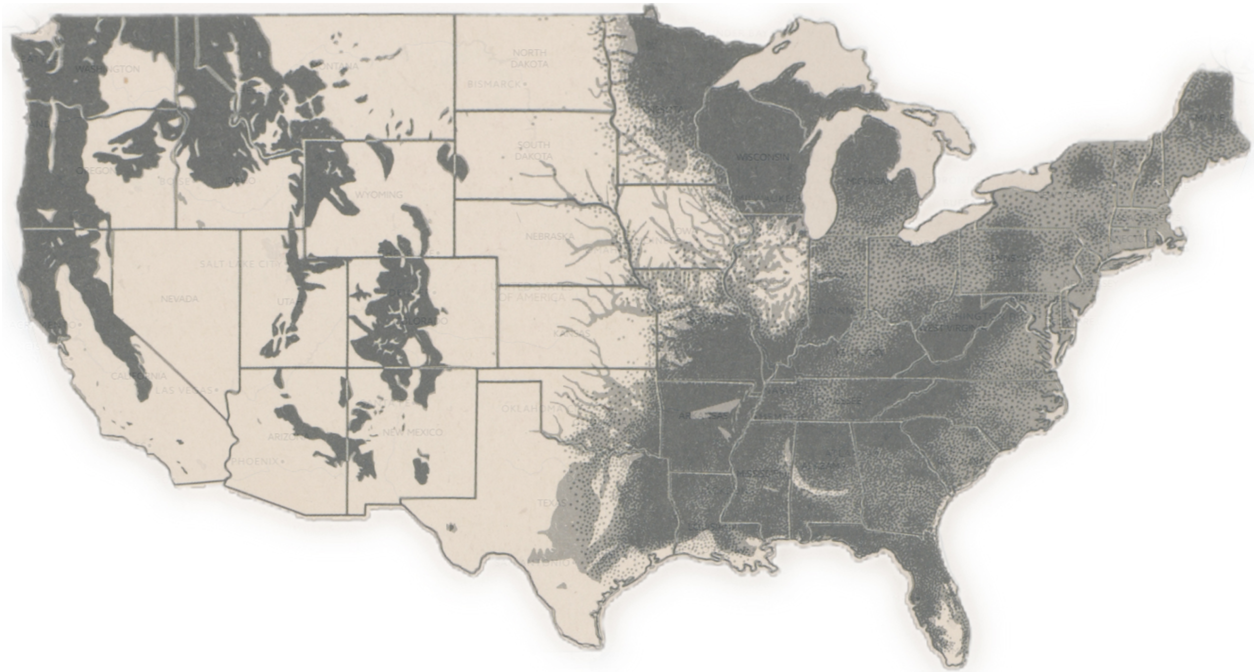
Source: IPCC. *Assessing Transformation Pathways*. 2014. 432.

Having said that, it is worth noting the effects of several trends. First, over time, innovation tends to result in technologies that are more efficient—consuming fewer resources and emitting fewer residuals, including carbon dioxide and other GHGs. This applies both to technologies that produce energy and those that consume them, as the following examples demonstrate.

Until about 200 years ago, most energy came from burning biomass—primarily wood—which has an average energy density of around 14 MJ/kg (megajoules per kilogram).[18] As demand for power increased during the Industrial Revolution, the relatively low energy density of wood—and hence large amounts required to supply significant amounts of power—led to rapid deforestation. This situation can be seen in Figures 4–6, which show how the forested area of the U.S. shrank from about 820 million acres in 1600 to 138 million acres in 1926.

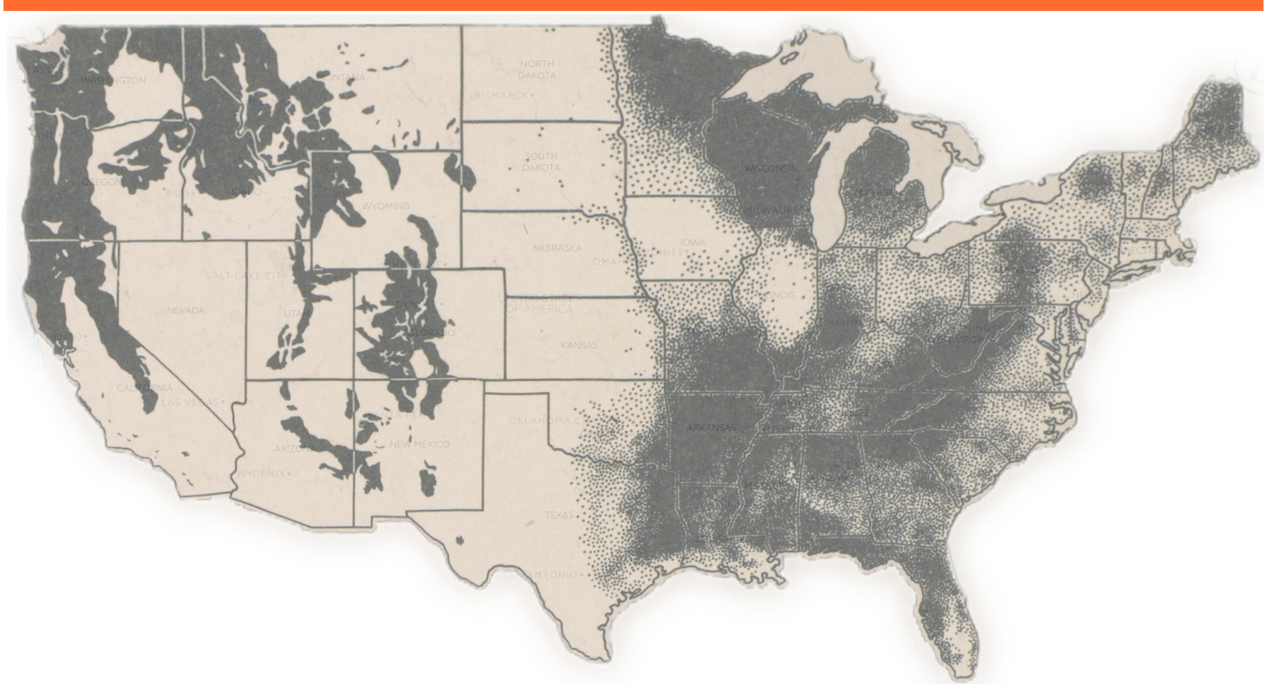
[18] FAO, *Wood Fuels Handbook*. Rome: UN Food and Agriculture Organisation, 2015. 15. http://www.fao.org/3/a-i4441e.pdf. Note that 1 MJ is equal to 239 kilocalories; 1 kg is equal to about 2.2lbs. So, 14 MJ/kg = 7378 kCal/lb.)

FIGURE 4: AREA OF VIRGIN FOREST 1620



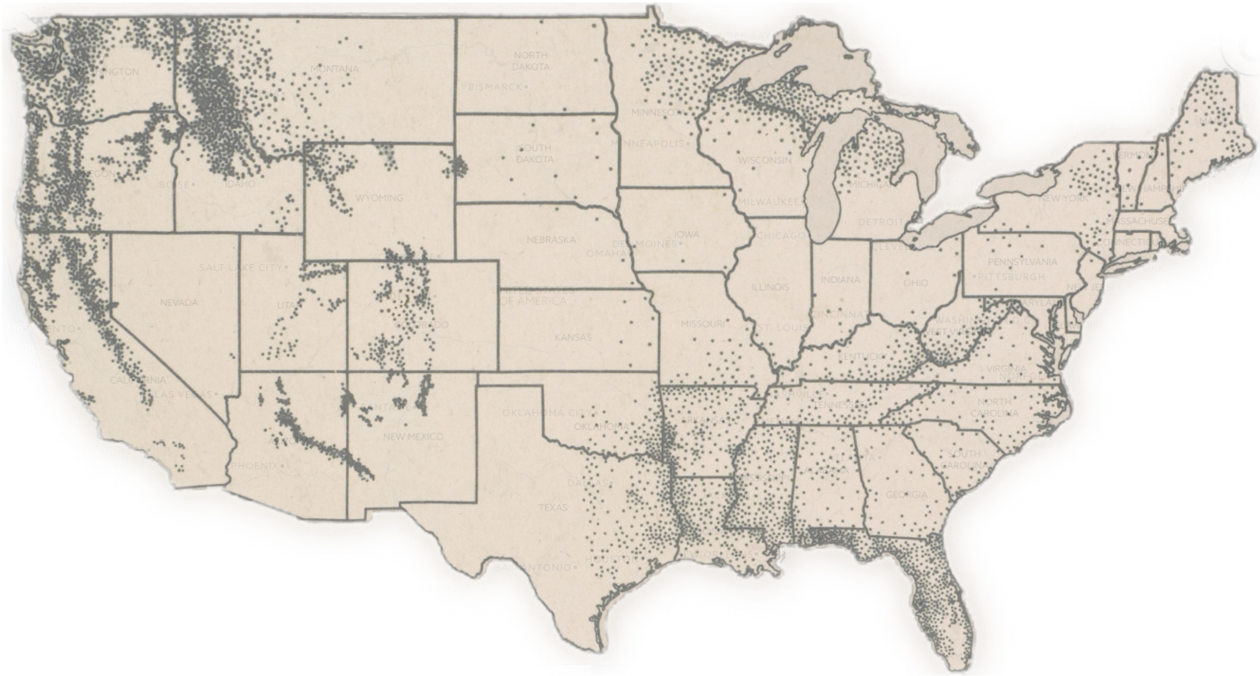
Source: Historical Atlas of the U.S.

FIGURE 5: AREA OF VIRGIN FOREST 1850



Source: Historical Atlas of the U.S.

FIGURE 6: AREA OF VIRGIN FOREST 1926



Source: Historical Atlas of the U.S.

In response to the increasing scarcity and cost of wood, alternative sources of energy were developed. During the course of the late 18th and 19th centuries, coal, which has an average energy density of around 27 MJ/kg and is present in great abundance below much of the earth's surface, gradually replaced wood as the primary source of energy.[19]

While wood had primarily been used as a source of heat for cooking and heating homes, the switch to using more-energy-dense, readily transportable, and highly abundant coal enabled the development of new technologies, most notably the steam engine, which in turn enabled much more efficient mechanization of manufacturing and transportation.

But neither wood nor coal was a very efficient source of light. Until the 19th century, the primary sources of light during the hours of darkness were tallow candles and oil lamps that burned lard. In the late 18th century, spermaceti, produced from sperm whales, began to replace tallow as the most popular type of candle.[20] Spermaceti candles burned brighter and cleaner than tallow candles. And for a while sperm whales were very abundant, making spermaceti candles cheaper too.

[19] Ibid. And see also this fact sheet from the World Nuclear Association, available at: http://www.world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx

[20] Brox, Jane. *Brilliant: The Evolution of Artificial Light*. New York: Houghton Mifflin Harcourt, 2010. 42.

The abundance of whales also led to the use of whale oil in lamps, where it was valued for the pure light that it produced. Meanwhile "The demonstrated demand for high-quality lighting spurred innovation and competition. Lard oil improved due to new refining techniques in the late 1830s, gas lighting companies operated in the five largest cities by 1840, and camphene [a mixture of alcohol and camphor] entered the lighting market in the 1830s."[21]

These and other lamps that burned camphene (a mixture of alcohol and camphor) and lard became very popular and soon outstripped candles as the main source of light during darkness in America. The popularity of these lamps led to increased demand for sperm whale oil.

By the end of the 19th century, whales were becoming scarce, reducing availability and driving up the price of spermaceti and whale oil. Fortunately, an alternative had already been discovered. In 1847, James Young developed a method for refining a light oil from petroleum that could be used in lamps. Innovations in drilling and refining gradually increased availability and reduced the price of this substitute. As the price of whale oil rose, refined petroleum became the basis for both lamps and candles.

Wider availability of low-cost petroleum, meanwhile, stimulated the development of other uses for it. Petroleum-based fuels (including gasoline and diesel) are nearly twice as energy-dense as coal—providing around 45 MJ/kg—making them well suited for powering vehicles.[22] Following the development of the internal combustion engine, gasoline-powered vehicles soon displaced heavier, less-efficient coal-powered vehicles and horse-drawn vehicles.

In the past two decades, new extraction technologies have revolutionized the production of oil and gas, especially from shale deposits. As a result, the U.S. in particular has experienced a resurgence in oil and gas production—and a commensurate fall in the price of these energy sources. With natural gas becoming plentiful and inexpensive, power generators and other heavy users of energy have shifted to the use of this fuel. Natural gas (methane) has an energy density of 55 MJ/kg (when liquefied)—about twice the density of bituminous coal.[23]

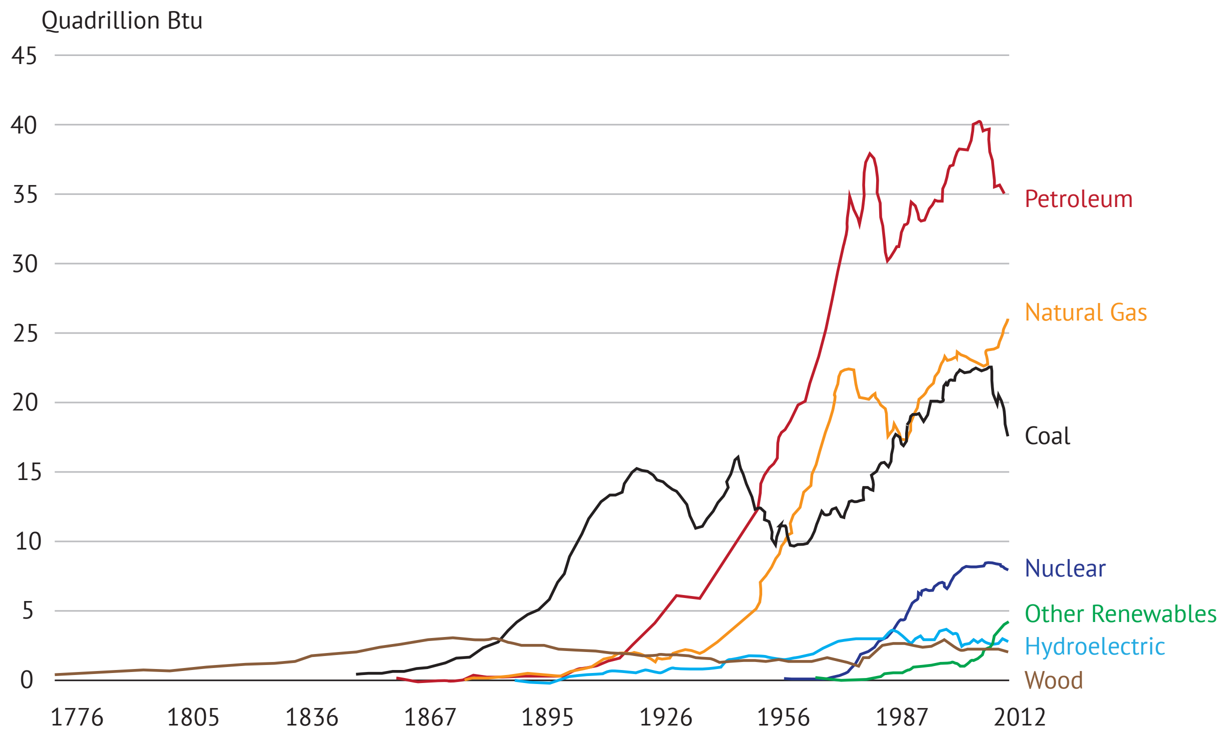
21 O'Connor, Peter A. and Cutler J. Cleveland. "U.S. Energy Transitions 1780–2010." *Energies* 2014. Vol. 7. 7955–7993.

22 World Nuclear Association estimates, based on data from the International Energy Agency and Australian Bureau for Agricultural and Resource Economics. Available at: http://www.world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx

23 Ibid.

Figure 7 shows these changes in primary energy in the U.S. over the past 240 years. An important feature of these changes is the increase in energy density of hydrocarbon fuels. A key characteristic of more-energy-dense hydrocarbons is the ratio of hydrogen to carbon: denser fuels generally have a higher hydrogen:carbon ratio, with a greater proportion of energy being released through the oxidation of hydrogen,[24] so the shift toward denser fuels has also meant a reduction in emissions of carbon per unit of energy produced, as shown in Figure 8.[25]

FIGURE 7: SOURCES OF U.S. ENERGY 1776–2012

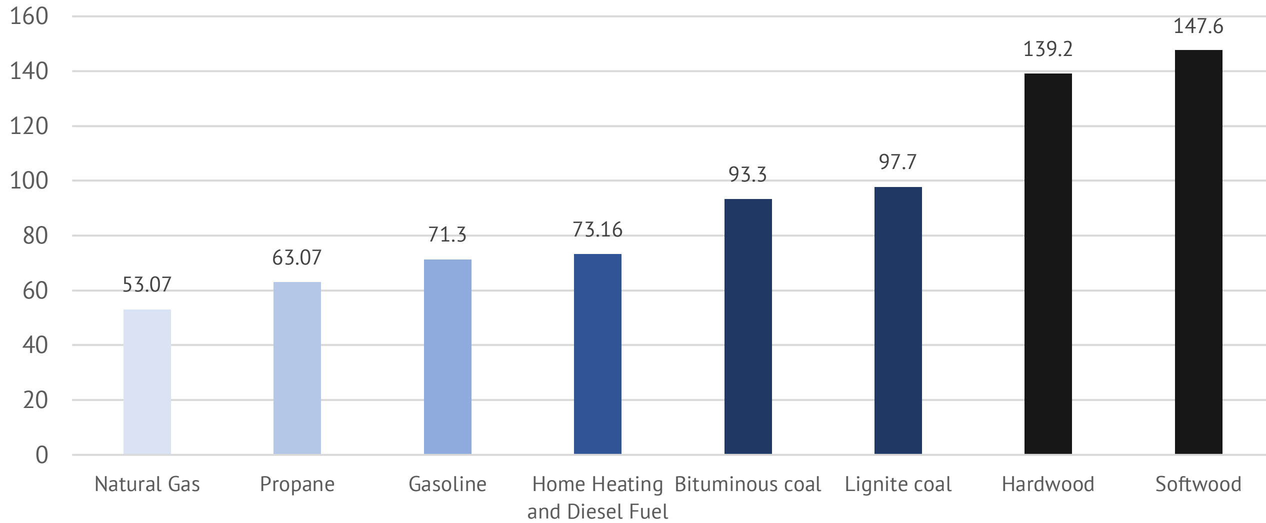


Source: Energy Information Administration, https://www.eia.gov/todayinenergy/detail.php?id=11951

[24] See e.g. West Oregon University, Energy from Fossil Fuels, no date. Available at: https://www.wou.edu/las/physci/GS361/Energy_From_Fossil_Fuels.htm

[25] The exception to the hydrogen:carbon ratio in the fuels shown is wood, which has about the same proportion of hydrogen as coal but relatively less carbon; however, its cellulosic structure and porosity make it less dense and more prone to contamination with water, which reduces its efficiency and leads to higher carbon dioxide emissions per unit of energy produced.

FIGURE 8: CO_2 EMISSIONS (KG CO_2 PER MILLION BTUS) FOR DIFFERENT HYDROCARBON FUELS



Source: Adapted by author from Energy Information Administration and Futuremetrics[26]

The transition from less-dense to more-dense forms of energy has coincided with a huge number of other innovations that have resulted in improvements in the efficiency with which energy is generated and used. As a result, the amount of energy used per real dollar of GDP has declined by 62% since 1949, from 16,000 BTU to 6,000 BTU—as can be seen in Figure 9 (red line).[27] In combination, the increase in energy density of fuels used and increasing efficiency of energy generation and use have resulted in a 70% decline in emissions of carbon dioxide per real dollar of GDP, from 1.1 kg per dollar of GDP to about 0.32 kg per dollar—also shown in Figure 9 (blue line).

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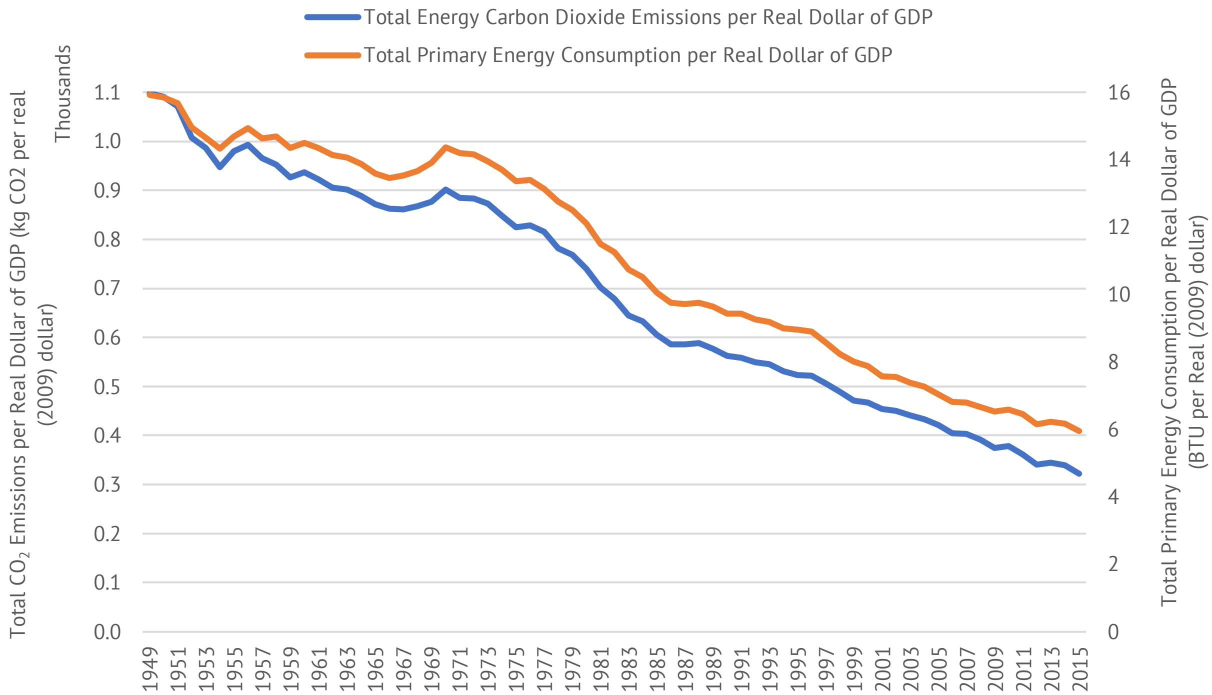
26 Figures for all except wood from Energy Information Administration: Carbon dioxide emissions coefficients (https://www.eia.gov/environment/emissions/co2_vol_mass.cfm); wood based on analysis by Futuremetrics http://futuremetrics.info/wp-content/uploads/2013/07/CO2-from-Wood-and-Coal-Combustion.pdf adjusted by assuming 20% moisture content.

27 Data from U.S. Energy Information Administration.

FIGURE 9: U.S. ENERGY CONSUMPTION AND CO_2 EMISSIONS PER UNIT OF GDP



Source: U.S. Energy Information Administration. March 2017 *Monthly Energy Review*.

Moreover, innumerable innovations have resulted in consumer products that more efficiently use resources and result in fewer emissions, including of greenhouse gases. Many, perhaps most, of these innovations have been motivated by a desire on the part of entrepreneurs and investors to profit by providing consumers with better products that use fewer inputs. (This is not to say that regulations have played no role: restrictions on emissions of certain pollutants and regulations mandating energy efficiency have certainly had an effect. But the point is that profit-seeking among competing producers has in many cases been the main driver of innovations that have reduced the use of energy and other resources, and thereby reduced associated emissions.)

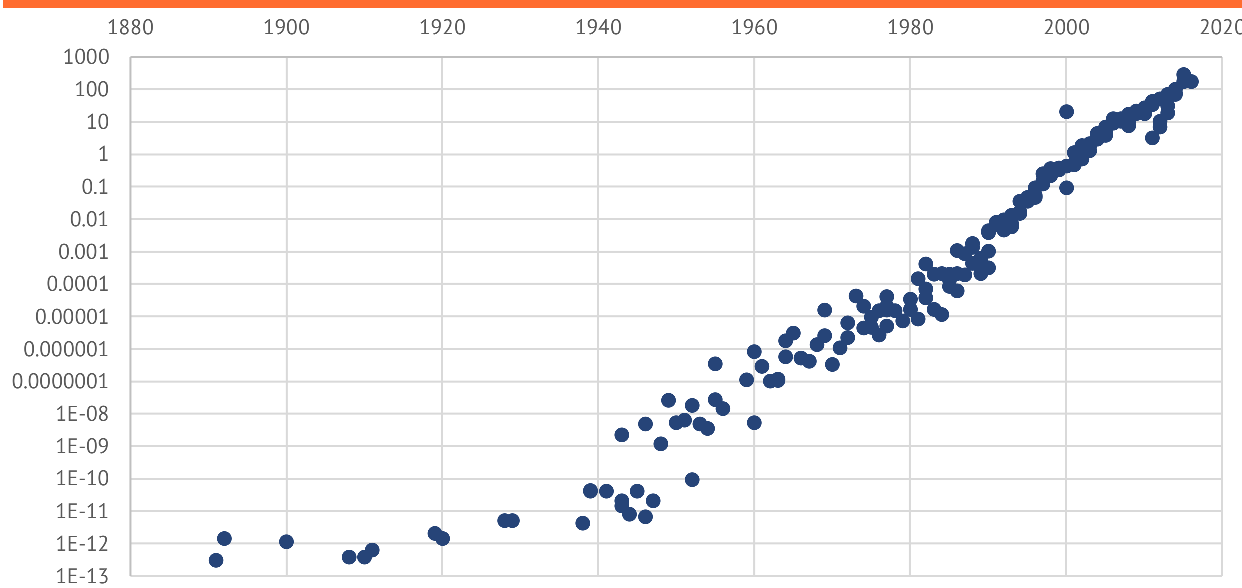
Computers are probably the most astounding example of this trend. Early computers were vast, heavy, expensive and slow. The ENIAC, for example, occupied about 1800 square feet, weighed 30 tons, consumed 160 kilowatts of energy, cost $600,000 (in 1997 dollars), and was capable of processing only about 300 instructions per second.[28] Today it is possible to

[28] See e.g.: Bellis, Mary. The History of the ENIAC Computer. ThoughtCo. Updated 7/31/2017. Available at: https://www.thoughtco.com/history-of-the-eniac-computer-1991601 and Moravec, Hans. *Robot: Mere Machine to Transcend Mind*. New York: Oxford University Press, 1998. Available at https://www.frc.ri.cmu.edu/~hpm/book97/ch3/processor.list.txt

purchase a fully functioning computer (the Raspberry Pi Zero W) that processes about 870 million instructions per second,[29] consumes less than one watt of power,[30] has built-in wifi, can fit in the palm of one's hand, and costs only $10.

Much of the advance in computing power and reductions in size and cost has come from developments associated with the microprocessor. In 1965, Gordon Moore, co-founder of chip maker Intel, observed that the density of microprocessors had doubled every year since 1958 and predicted that such an exponential increase in density would continue.[31] This relationship became known as Moore's law—and it has held more or less consistently since Moore made it. Indeed, the relationship holds further back, as can be seen in Figure 10.

FIGURE 10: PROCESSING POWER OF COMPUTING MACHINES (MILLION INSTRUCTIONS PER SECOND) PER DOLLAR



Source: Hans Moravec (https://www.frc.ri.cmu.edu/~hpm/book97/ch3/processor.list.txt) and Roy Longbottom (http://www.roylongbottom.org.uk/Raspberry%20Pi%20Benchmarks.htm)

There is little dispute that innovations in many other fields are resulting in more-efficient use of resources. Lighting is a good example. A typical modern candle burns at a rate of

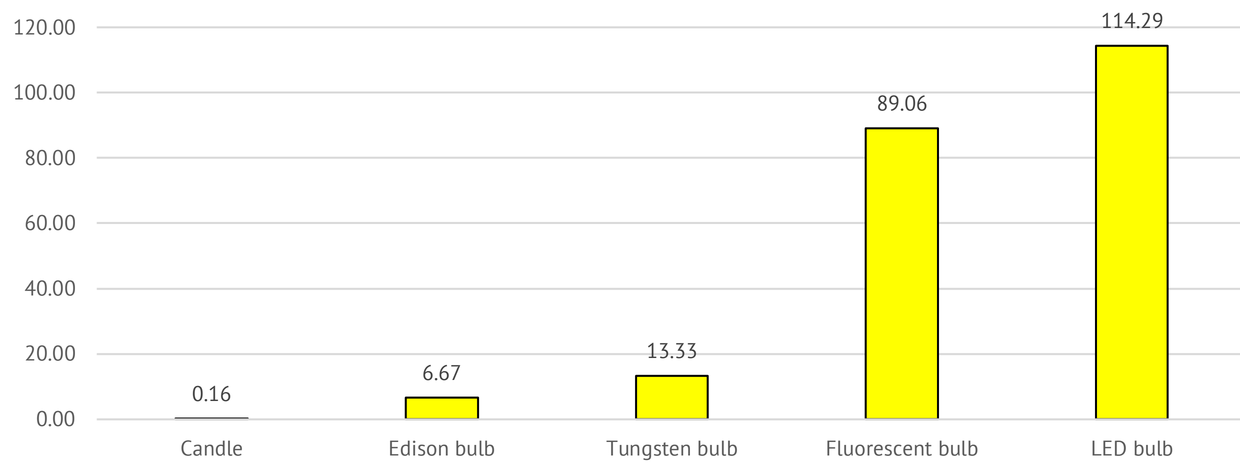
29 Heath, Nick. "Raspberry Pi Zero W: Hands-on with the $10 board." *Techrepublic.com.*, 2/28/2017. Available at: http://www.techrepublic.com/article/raspberry-pi-zero-wireless-hands-on/

30 Ibid. and http://raspi.tv/2017/how-much-power-does-pi-zero-w-use; (0.18 amps at 5.19 volts = 0.93 watts).

31 Li, Michael (Siyang). "Keeping Up with Moore's Law." *Dartmouth Undergraduate Journal of Science.* 5/29/2013. Available at: http://dujs.dartmouth.edu/2013/05/keeping-up-with-moores-law/#.WSh8j2jyvb0

about 80 watts and produces about 13 lumens.[32] An incandescent lightbulb with a carbon filament (of the kind developed by Thomas Edison) rated at 60W produces about 400 lumens.[33] A typical 60W incandescent lightbulb with a tungsten filament produces about 800 lumens.[34] A typical 40W fluorescent bulb produces about 2850 lumens.[35] And a 14W LED lightbulb produces about 1600 lumens.[36] In other words, over the past 150 years the efficiency of light sources has increased nearly 1,000 fold—as can be seen in Figure 11.

FIGURE 11: EFFICIENCY OF LIGHT SOURCES (LUMENS PER WATT)



Sources: Author's calculations based on sources in footnotes 32, 33, 35 and 36 of this study.

This trend toward "dematerialization" is true in many fields, not just electronics. Innovations in processing and packaging, for example, have increased the proportion of food that is utilized, lengthened the shelf life of perishable foods and beverages, and reduced waste. Orange juice provides an opposite example, as Harry Teasley, former President of Coca Cola Foods and Emeritus Chairman of Reason Foundation has noted:[37]

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32 Hamins, Anthony, Matthew Bundy and Scott E. Dillon. "Characterization of Candle Flames." *Journal of Fire Protection Engineering.* 15 (277). 265–285. November 2005. Available at: http://fire.nist.gov/bfrlpubs/fire05/PDF/f05141.pdf; https://en.wikipedia.org/wiki/Candle

33 Data from 1000bulbs.com website. Available at: https://blog.1000bulbs.com/home/edison-bulbs-brightness

34 Ibid.

35 Hovey, Jimmy. *T8 Lighting: What Is The Actual Lumen Output For T8 Fluorescent Bulbs?* Hoveyelectric.com. 5/23/2013. Available at: http://www.hoveyelectric.com/hovey-electric-power-blog/bid/97456/T8-Lighting-What-Is-The-Actual-Lumen-Output-For-T8-Fluorescent-Bulbs

36 Data for the Maxlite LED Omnidirectional A-Lamp. Available at: http://www.maxlite.com/item/datasheet?=9A19ND27

37 Teasley, Harry E. "The role of markets and economics for thinking about how to deal with environmental issues and concerns." Speech to Agnes Scott College. October 7, 2010. (On file with the author.)

Industrial juice processors squeeze oranges more efficiently than consumers' because of the equipment they use to perform the task. A consumer will, at a minimum, require about 20 percent more oranges than an industrial juice processor to yield the same amount of juice.

So, home squeezing of fresh oranges is less efficient of oranges and, therefore, less efficient of agricultural land, fertilizers, pesticides, herbicides, water resources, agricultural capital, and agricultural labor than packaged orange juice.

Fresh oranges generate almost 9 times more corrugated waste at retail than does the 12-oz. frozen concentrate alternative. And, at the consumer level, fresh oranges generate over 60 times the poundage of waste as the 12-oz. frozen concentrate alternative. The consumer waste is, of course, wet peels versus the small composite can.

When a consumer squeezes oranges, the wet peels are disposed of through the solid waste collection and disposal system, while a juice processor converts the peel to animal feed and also recovers orange oil and d'limonene, which are used for other products and processes.

The fresh orange alternative also weighs about 7.5 times as much as the 12-oz. frozen concentrate alternative, and requires about 6.5 times as many trucks to distribute equal quantities of orange juice to the consumer. So, in addition to agricultural efficiencies, the 12-oz. frozen concentrated orange juice produced is more efficient of trucks, diesel fuel, and road systems.

Well, the bottom line to that little story is that squeezing oranges industrially, and packaging either concentrate or ready-to-serve juice, is very efficient from a waste-produced standpoint, very efficient economically, and very efficient environmentally.

But innovations have also reduced resource use and emissions related to packaging and distribution. In 1965, nearly all beverage cans were made from steel and, when empty, a 12-ounce can weighed about 0.66 ounces. By 1994, the vast majority of beverage cans were made from aluminum and weighed 0.48 ounces.[38] Similar improvements have occurred in many areas of packaging.[39] The reduction in packaging weight has reduced

[38] Hosford, William F. and John L. Duncan. "The Aluminum Beverage Can." *Scientific American*. September 1994. 48–53. Available at: http://www.chymist.com/Aluminum%20can.pdf

[39] See e.g.: Flexible Packaging Association, "Lightweight Advances in Flexible Packaging: FPA Member Case Stories." No Date. Available at: https://www.flexpack.org/assets/1/6/FPA_Lightweighting_Case_Stories.pdf

energy and resource use in the production of packaging, as well as lowered transportation costs and associated emissions per item shipped.

While this process has been going on for decades, if not centuries, recent developments may be speeding it up. The ability to transfer data over the Internet has reduced the use of physical resources that previously delivered all manner of products, from books, magazines and newspapers to music and movies. Estimates suggest that delivery of audio and video content via the Internet has significantly reduced energy consumption and associated emissions.[40]

To be sure, many people continue to read books and newspapers made from paper—and some people still buy CDs, DVDs, Blu Ray discs and even LPs. But the trend toward dematerialization seems inexorable as the quality of virtual products available improves and cost declines.

Ray Kurzweil has extended Moore's law back to the 19th century, to show that it applies to previous generations of information processing devices. And Kurzweil, somewhat speculatively, has extended the concept to other areas of technological development, making the case that innovation is accelerating.[41]

Regardless of whether Kurzweil is correct, it is clear that increasing efficiency of production and more-efficient consumer products has meant that, even with rising population and economic activity, total energy consumption in the U.S. has fallen over the past 10 years. Meanwhile, the shift to more energy-dense fuels has meant that CO_2 emissions have fallen even faster—as can be seen in Figure 12.

In the future, these effects could be magnified by developments in virtual reality, which have the potential to reduce the need for people to travel in order to participate in meetings.[42]

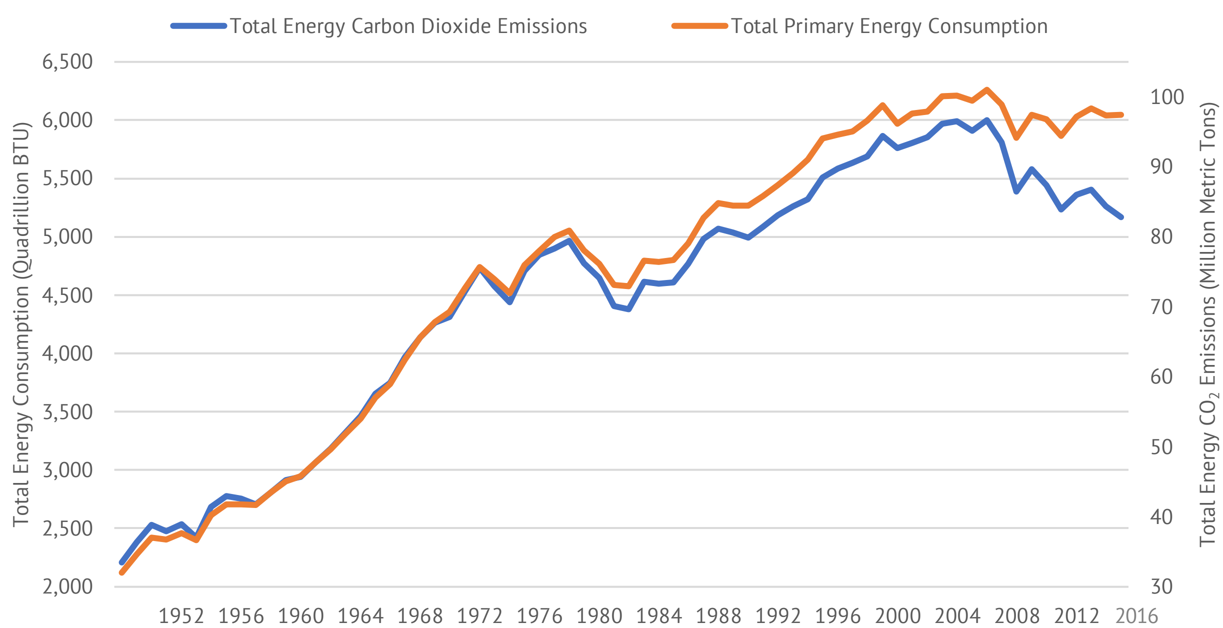
40 Weber, Christopher L., Jonathan G. Koomey and H. Scott Matthews. "The Energy and Climate Change Implications of Different Music Delivery Methods." *Journal of Industrial Ecology*. Volume 14, Number 5, 2010, 754-769; Arman Shehabi, Ben Walker and Eric Masanet. "The energy and greenhouse-gas implications of internet video streaming in the United States. *Environmental Research Letters*. Volume 9, Number 5, 2014.

41 Kurzweil, Ray. *The Law of Accelerating Returns*. March 7, 2001. Available at: http://www.kurzweilai.net/the-law-of-accelerating-returns

42 Lemley, Mark and Eugene Volokh. *Law, Virtual Reality, and Augmented Reality*. Stanford Public Law Working Paper No. 2933867. UCLA School of Law. Public Law Research Paper No. 17-13. 14 Apr 2017. Available at: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2933867##

Meanwhile, advancements in technology are likely to enable dramatic changes in the way people travel, with a shift toward less car ownership—and a smaller total number of vehicles—as fleets of autonomous vehicles ply the streets.[43]

FIGURE 12: U.S. ENERGY CONSUMPTION AND CO_2 EMISSIONS 1949–2016



Source: U.S. Energy Information Administration. March 2017 Monthly Energy Review.

At the same time, it is almost certain that new energy production technologies will be developed that use resources more efficiently and produce fewer emissions. Among other possibilities is the use of carbonate fuel cells to capture carbon dioxide and generate additional energy.[44]

These trends in and the relationship between technological innovation, economic growth and GHG emissions suggest that emissions are very unlikely to follow the higher path—and more likely to follow a low path.

[43] Shaheen, Susan A. "Reducing Greenhouse Emissions And Fuel Consumption: Sustainable Approaches For Surface Transportation." *IATSS Research.* 31 (1. 6–20. 2007. Available at: http://www.sciencedirect.com/science/article/pii/S0386111214601795 ; Gonder, Jeff, Yuche Chen, Mike Lammert, Eric Wood. "Assessing the Energy Impact of Connected and Automated Vehicle (CAV) Technologies." Paper presented at the SAE 2016 Government/Industry Meeting. January 21, 2016. Available at: http://www.nrel.gov/docs/fy16osti/65743.pdf

[44] Fuel Cell Energy and Exxon Mobil are working on just such a technology. See Thomas Overton. "Fuel Cells Could Be a 'Game-Changer' for Carbon Capture." *powermag.com.* 05/11/2016. Available at: http://www.powermag.com/fuel-cells-could-be-a-game-changer-for-carbon-capture/

ESTABLISHING FUTURE CONCENTRATIONS OF GHGS, EVEN IF FUTURE EMISSIONS PATHWAYS WERE KNOWN, WOULD NOT BE SIMPLE.

Worldwide, concentrations of several greenhouse gases, particularly carbon dioxide, methane and dinitrogen monoxide, have undoubtedly been increasing. In combination with estimates of natural and human emissions of these GHGs, it is possible to estimate the historic relationship between emissions and concentrations. But that relationship is not necessarily stable.

Calculating future atmospheric concentrations of GHGs, based on estimates of future emissions, requires knowledge of the length of time that these GHGs will remain in the atmosphere. That in turn requires knowledge about the rate at which they will break down and/or be absorbed. This is no simple task. The rate at which GHGs such as methane and dinitrogen monoxide break down depends on such things as temperature (reactions occur more quickly at higher temperatures) and the amount of water vapor and other chemicals in the atmosphere with which they might react. The rate at which CO_2 is taken up by plants, soil and oceans varies considerably depending on factors such as temperature and the availability of nutrients. The dynamic and interactive nature of these complicates the picture further.[45]

THE SENSITIVITY OF THE CLIMATE TO INCREASED EMISSIONS OF GHGS IS STILL NOT WELL ESTABLISHED—THOUGH CURRENT ESTIMATES SUGGEST THAT THE CLIMATE IS SIGNIFICANTLY LESS SENSITIVE THAN HAS BEEN PRESUMED IN MOST IAMS, INCLUDING THOSE USED BY THE IWG.

While the basic physics of the greenhouse effect is well established, the precise relationship between atmospheric concentrations of GHGs and temperature remains contentious. Climate scientists have developed a standard measure for evaluating the impact of increasing the concentrations of greenhouse gases: "equilibrium climate sensitivity" (ECS), which is the change in global mean surface temperature over the very long term—more than a century—in response to doubling the atmospheric concentration of CO_2. (The effect of increasing CO_2 concentrations is logarithmic, which means that each time concentrations double, the temperature rises by the same amount. So, if a doubling of CO_2 led to a 2°C rise in temperature, a quadrupling of concentrations would lead to a 4°C rise in temperature, all else being equal.) In addition, for shorter-term effects, a measure known as the transient climate response (TCR) is used to estimate the rise in global mean

45 IPCC. "Carbon and Other Biogeochemical Cycles." *Chapter 6 of Working Group 1, Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva: Intergovernmental Panel on Climate Change, 2013. Available at: http://www.ipcc.ch/report/ar5/wg1/

temperature in response to a continual increase in CO_2 concentrations of 1% per year for 70 years (by the 70^{th} year, CO_2 concentrations will have doubled).[46]

The range of ECS estimates used in most climate models—and integrated assessment models—can be traced to a 1979 National Academy of Sciences panel chaired by Jule Charney, who asked James Hansen of NASA and Syukuru Manabe of Princeton to give estimates of ECS. Veteran *Science* correspondent Richard Kerr describes the result:

> *On the first day of deliberations, Manabe told the committee that his model warmed 2°C when CO_2 was doubled. The next day Hansen said his model had recently gotten 4°C for a doubling. According to Manabe, Charney chose 0.5°C as a not-unreasonable margin of error, subtracted it from Manabe's number, and added it to Hansen's. Thus was born the 1.5°C-to-4.5°C range of likely climate sensitivity that has appeared in every greenhouse assessment since, including the three by the Intergovernmental Panel on Climate Change (IPCC). More than one researcher at the workshop called Charney's now-enshrined range and its attached best estimate of 3°C so much hand waving.*[47]

To reiterate: the ECS range of 1.5°C–4.5°C was not based on empirical data; it was based on assumptions built into two models from the 1970s. While those models fit past temperatures, they had not been evaluated on the basis of their ability to forecast future temperatures. In the past few years, many of the models used in IPCC reports have been evaluated by comparing simulations with actual changes in temperature.[48] The results cast serious doubt on the predictive ability of the models—and hence on the underlying assumptions of those models, especially climate sensitivity.

In its most recent report (in 2013), the IPCC evaluated the performance of its own models. First, the authors fit their models to temperature data for the period 1986–2005 (using four datasets[49]), then they ran simulations going forward, allowing a comparison with estimated temperatures for 2005–2012 (from the same datasets). As Figure 13 shows, the vast majority of model simulations over-predicted the temperature for 2005–2012. Actual temperatures were at the very bottom of the forecast range.

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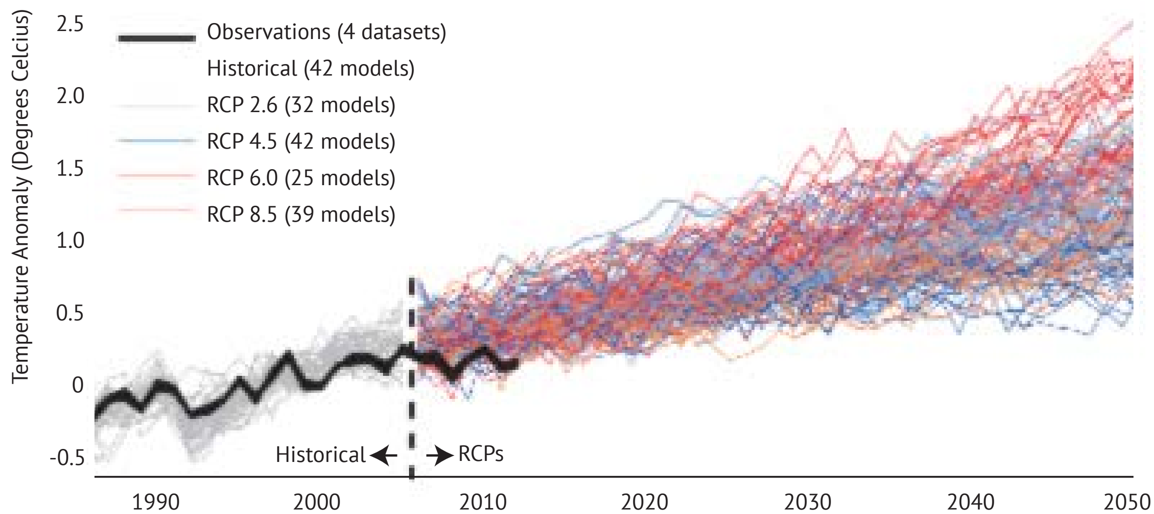
46 $1.01^{70}=2.0067$

47 Kerr, Richard A. "Three Degrees of Consensus." *Science* 13. August 2004. 305 no. 5686. 932–934, available at: http://science.sciencemag.org/content/305/5686/932.

48 These simulations were parameterized using temperature data up to a certain point (e.g. 1979 or 1993) and then run forward.

49 The four datasets were: Hadley's HADCRUT4, the European Center for Medium-Range Weather Forecasting's ERA-interim, NASA's GISTEMP, and NOAA's.

FIGURE 13: GLOBAL MEAN TEMPERATURE NEAR-TERM PROJECTIONS RELATIVE TO 1986–2005



Source: IPCC Fifth Assessment Report. Working Group 1. 2013. Chapter 11. Figure 11.25. 1011.[50]

A 2013 study published in *Nature Climate Change* by John Fyfe and Nathan Gillett of the Canadian Centre for Climate Modelling and Analysis and Francis Zwiers of the Pacific Climate Impacts Consortium similarly compared actual global mean temperature to a set of 117 simulations using 37 of the models used by the IPCC and found that over the period 1993–2012 the change in observed temperatures (from the UK Hadley Center's HadCRUT4 dataset) was less than half that of the simulations.[51] Moreover, they observe that "The inconsistency between observed and simulated global warming is even more striking for temperature trends computed over the past fifteen years (1998–2012). For this period, the observed trend of 0.05 ± 0.08 °C per decade is more than four times smaller than the average simulated trend of 0.21 ± 0.03 °C per decade."[52]

Meanwhile, Professor John Christy of the University of Alabama Huntsville, one of the world's foremost experts on temperature data, has compared temperatures in the tropical troposphere—a part of the climate that is assumed to be particularly susceptible to warming from greenhouse gases—with simulations from 102 runs of 24 IPCC models over the period

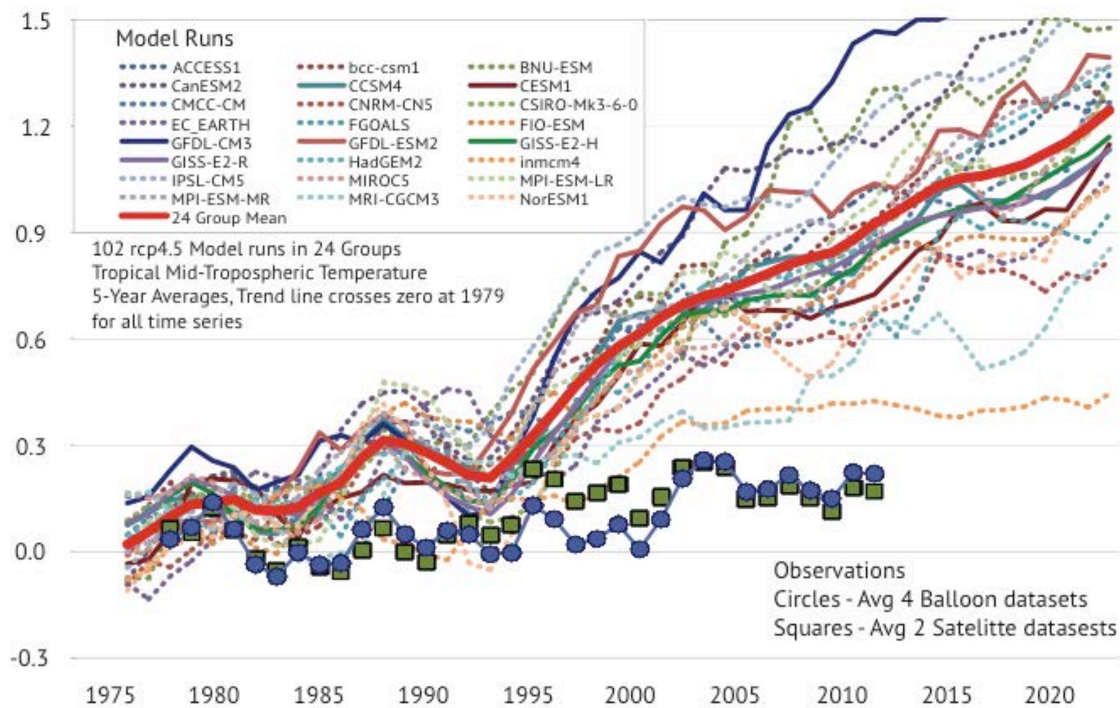
[50] Available at: https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter11_FINAL.pdf

[51] Fyfe, John C., Nathan P. Gillett and Francis W. Zwiers. "Overestimated global warming over the past 20 years." Nature Climate Change. 3, September 2013. 767-769.

[52] Ibid. 767.

1979–2013.[53] Figure 14, taken from Christy's December 2013 testimony to the House Committee on Science, Space and Technology, shows that the models wildly overestimate warming in the tropical troposphere: After the year 2000, observations are below the lowest model run; by 2013, the models on average over-predict warming by a factor of three.

FIGURE 14: CHRISTY'S COMPARISON OF ACTUAL TEMPERATURE AT THE TROPICAL TROPOSPHERE WITH IPCC MODELS



Source: Christy, John. Testimony to the House Committee on Science, Space and Technology. 2013. (Model output: KNMI Climate Explorer.)

In a paper published in *Geophysical Research Letters* in 2013, Professor Kyle Swanson of the University of Wisconsin compared both older generation IPCC model ensembles and more recent IPCC ensembles with observed trends at various latitudes for the period 2002 to 2011.[54] Swanson concludes that while the earlier generation of models had sufficient internal variability to account for the changes that occurred, the narrower variability of the new models highlights an apparent upward bias.

53 "A Factual Look at the Relationship Between Climate and Weather." Subcommittee on Environment, House Committee on Science, Space and Technology. 11 December 2013. Testimony of... John R. Christy, University of Alabama in Huntsville. Available online at http://nsstc.uah.edu/users/john.christy/docs/ChristyJR_Written_131211_01.pdf

54 Swanson, Kyle. "Emerging Selection Bias in Large Scale Climate Change Simulations." *Geophysical Research Letters* 40 (12). 2013. 3184–3188. Abstract available here: http://onlinelibrary.wiley.com/doi/10.1002/grl.50562/abstract.

The reason that climate model simulations—as opposed to analyses based on evaluation of empirical data alone—were used as a basis for early ECS estimates is that global mean temperature varies considerably from day to day, month to month and year to year. In other words, the temperature "signal" suffers from noise.

One main contributor to noise in the temperature signal is aerosols, which reflect incoming solar radiation and may also make clouds brighter and/or longer lived and thereby cool the climate.[55] One source of such aerosols is the sulphur dioxide that is emitted during the combustion of coal and other fossil fuels: these emissions are converted into sulfuric acid, which condenses to form aerosols. Aerosols also result from intentional and unintentional burning of trees and other biomass, as well as from other natural sources, such as volcanoes. But the scale and effects of these emissions are very difficult to estimate.[56]

In a 2014 study published in *Climate Dynamics*, Nicholas Lewis and Judith Curry address these problems by using periods relatively unaffected by volcanic activity and well-matched in terms of noise. Using this methodology and the estimated ranges for the cooling or warming forces of, among other things, aerosols and greenhouse gases given in the IPCC AR5 WG1 report, they report a median estimate for ECS of 1.64°C.[57]

But the ECS may be even lower. As explained, a main reason for the wide range of estimates of the ECS and TCR historically has been uncertainty regarding the impact of aerosols. But a paper by Bjorn Stevens of the Max Planck Institute for Meteorology published in the *Journal of Climate*, seems to narrow the bounds considerably. Specifically, Stevens finds that the maximum reduction in temperature caused by aerosols is considerably less than was assumed by the IPCC—and hence by Lewis and Curry. Armed with Stevens' new estimates of the impact of aerosols, Nicholas Lewis re-ran his analysis of ECS and TCR and found that the best estimate for ECS is 1.45°C. [58] Moreover, Lewis gives a 95% confidence interval of 1.05°C to 2.2°C.

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[55] See e.g.: NASA. Aerosols and Incoming Sunlight (Direct Effects). NASA website. Available at: https://earthobservatory.nasa.gov/Features/Aerosols/page3.php

[56] See e.g. Ghan, Steven, et al. "Challenges in constraining anthropogenic aerosol effects on cloud radiative forcing using present-day spatiotemporal variability." *Proceedings of the National Academy of Sciences* 113 (21). May 24, 2016. Available at: http://www.pnas.org/content/113/21/5804.full.pdf

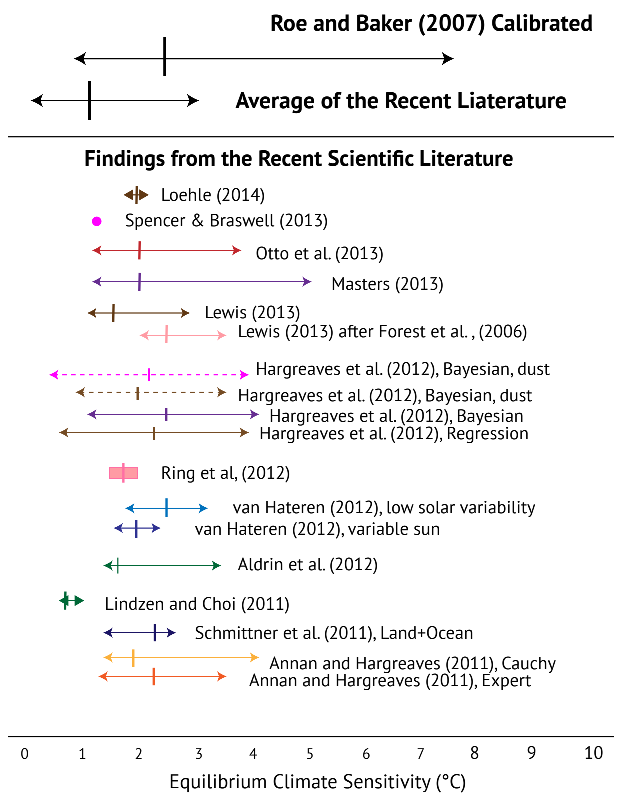
[57] Lewis, Nicholas and Judith Curry. "The implications for climate sensitivity of AR5 forcing and heat uptake estimates." *Climate Dynamics*. September 2014 (http://link.springer.com/article/10.1007/s00382-014-2342-y); a pre-print version is here: https://niclewis.files.wordpress.com/2014/09/lewiscurry_ar5-energy-budget-climate-sensitivity_clim-dyn2014_accepted-reformatted-edited.pdf.

[58] Lewis, Nic. "The implications for climate sensitivity of Bjorn Stevens' new aerosol forcing paper." ClimateAudit, 3/19/2015. Available at: http://climateaudit.org/2015/03/19/the-implications-for-climate-sensitivity-of-bjorn-stevens-new-aerosol-forcing-paper/

Several other recent studies have also found that the range of likely ECS is considerably lower than was initially assumed by the National Academy of Sciences—and used in IPCC models. These new, lower estimates of ECS (and TCR), shown in Figure 15 below, are consistent with the finding that the IPCC model simulations predict significantly more warming than has occurred.

By contrast, in all of its GHG emissions impact estimates (including those undertaken after these new ECS estimates became available—and after criticisms of the IWG's use of inappropriately high ECS and TCR estimates by Kevin Dayaratna and David Kreutzer,[59] Patrick Michaels and Paul Knappenberger,[60] and others, including this author), the IWG used a range of estimates of ECS drawn from the "Roe-Baker distribution," which is shown at the top of Figure 15. Roe-Baker is a probability density function, which means that each estimate of climate sensitivity (specifically, each temperature interval) is assumed to have a certain probability of occurrence. While the median estimate under Roe-Baker is approximately 3°C (5.4°F), the range is wide and skewed toward higher temperatures. That is no coincidence: the Roe-Baker distribution used by the IWG is not an empirically based estimate of the ECS but rather it is a distribution selected and calibrated by the IWG to meet its criteria, which specifically included the likelihood of an ECS greater than 4.5°C.

FIGURE 15: EQUILIBRIUM CLIMATE SENSITIVITY



Source: Michaels, Patrick J. and Paul C. Knappenberger (footnote 60 of this study)

[59] Dayaratna, Kevin and David Kreutzer. "Unfounded FUND: Yet Another EPA Model Not Ready for the Big Game." Washington, D.C.: Heritage Foundation, April 2014.

[60] Michaels, Patrick J. and Paul C. Knappenberger. "Comment on the Office of Management and Budget's Request for Comments on the Technical Support Document entitled Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866." Submitted February 26, 2014. https://object.cato.org/sites/cato.org/files/pubs/pdf/omb_scc_comment_part2_michaels_knappenberger.pdf

THE EFFECTS OF CLIMATE CHANGE ARE UNKNOWN—BUT THE BENEFITS MAY WELL BE GREATER THAN THE COSTS FOR THE FORESEEABLE FUTURE.

If the recent lower estimates of ECS are correct, warming from continued human emissions of GHGs will likely be modest and its effects mild. Warming will be greater in cold places (i.e. farther from the equator), seasons (winter), and times (night) than in warm places (equatorial regions), seasons (summer) and times (day).[61] At higher latitudes, winters will likely be less extreme.[62] Precipitation will likely increase, but not everywhere, and some places will probably become drier.[63] Sea levels will to continue to rise slowly, as the oceans expand and land-based glaciers melt.[64] Unfortunately, in spite of the confident pronouncements of the IPCC, more-precise forecasts simply are not possible. Nonetheless, some generalizations concerning the likely consequences of these changes may plausibly be made:

Effects on temperature-related morbidity, mortality, and expenditures on heating and cooling

Warming will have differing health effects at different times of year and locations. Warmer summers will likely cause some additional morbidity and mortality among those who are less able to cope with higher temperatures, while warmer winters will likely reduce mortality and morbidity from cold. A team led by Antonio Gasparini of the London School of Hygiene and Tropical Medicine analyzed the cause of over 74 million deaths over the period 1985–2012 in 384 locations in Australia, Brazil, Canada, China, Italy, Japan, South Korea, Spain, Sweden, Taiwan, Thailand, UK and USA. They found that cold weather caused nearly 20 times more deaths than hot weather. [65]

[61] Arndt, Deke. "Climate change rule of thumb: cold 'things' warming faster than warm 'things.'" Washington, DC: National Oceanographic and Atmospheric Administration. Available at: https://www.climate.gov/news-features/blogs/beyond-data/climate-change-rule-thumb-cold-things-warming-faster-warm-things

[62] Research led by Tapio Schneider of ETH Zurich and published in the *Journal of Climate* in 2015, finds that climate change does not lead to more extreme winters (as some have claimed)—rather the opposite. The research is summarized here: http://phys.org/news/2015-03-climate-extreme-winters.html.

[63] Research by Kate Marvel and Celine Bonfils of Lawrence Livermore National Laboratory provides some tentative evidence of changes in precipitation. See: Marvel, Kate and Celine Bonfils. "Identifying External Influences on Global Precipitation." *Proceedings of the National Academy of Sciences* 110 (48). 19301–19306. Abstract available here: http://www.pnas.org/content/110/48/19301,accessed 4/1/2016.

[64] Since the early 1990s, average sea level has risen by about 3.3mm/yr (see e.g. the research by the University of Colorado Sea Level Research group, here: http://sealevel.colorado.edu/content/2016rel1-global-mean-sea-level-time-series-seasonal-signals-retained). If that trend continues—which seems likely under modest warming—by 2100, global average sea level would rise by 27cm (about 11 inches). A recent paper claimed that sea level might rise much faster—but that presumes much more rapid warming; see the observations by Pat Michaels and Chip Knappenberger here: http://wattsupwiththat.com/2016/03/31/deconto-and-pollard-an-antarctic-science-fiction-disaster-2/.

[65] See: Gasparini, Antonio et al. "Mortality associated with high and low ambient temperature: a multicountry observational study." *The Lancet* 386 (9991). 369–375. July 2015. Available at: http://www.thelancet.com/journals/lancet/article/PIIS0140-6736(14)62114-0/fulltext.

Warming will also have differing economic effects at different times of year and locations. Warmer summers will likely result in additional expenditure on cooling. But warmer winters will reduce heating costs. Using data for 157 countries over three decades, Sebastian Petrick and Katrin Rehdanz of Kiel Institute for the World Economy and Richard S. J. Tol of the Economic and Social Research Institute in Dublin found that net energy use decreases with rising temperatures (albeit at a declining rate).[66]

On net, then, a warmer climate is likely to result in fewer deaths and lower expenditures on heating and cooling.

How does one reconcile these mostly beneficial effects with claims that global warming is already causing disease and death? For example, "Climate Change Kills 400,000 a Year, New Report Reveals" roared a *Daily Beast* headline on September 27, 2012.[67] The "new report" in question came from DARA International, a Geneva-based NGO.[68] Meanwhile, the Health and Environment Linkages Initiative (HELI) of the World Health Organization and the United Nations Environment Program claims that climate change is responsible for 150,000 deaths per year.[69] A quick look at the numbers, however, suggests that these claims are not grounded in empirical reality.

Of the 400,000 deaths DARA alleges are caused by climate change, 85,000 were caused by diarrhea.[70] In the HELI analysis, diarrhea accounted for a larger proportion but smaller number, 47,000, of the 150,000 alleged total deaths. Is either estimate realistic? Almost all of these deaths are assumed to be occurring in low- and middle-income countries. The most authoritative and comprehensive evaluation of incidence and change in incidence of diarrhea in low- and middle-income countries yet undertaken is a study by Dr. Christa L. Fischer Walker and fellow public health and biostatistics researchers at Johns Hopkins University and the World Health Organization, funded by the Bill and Melinda Gates Foundation. That study found that the incidence of diarrhea "declined from 3.4

66 Petrick, Sebastian, Katrin Rehdanz and Richard S. J. Tol. *The Impact of Temperature Changes on Residential Energy Consumption*. Kiel Working Paper No. 1618. April 2010.

67 "Climate Change Kills 400,000 A Year, New Report Reveals." *The Daily Beast*. 9/27/2012. Available at http://www.thedailybeast.com/articles/2012/09/27/climate-change-kills-400-000-a-year-new-report-reveals.html.

68 DARA. *Climate Vulnerability Monitor*. 2nd Edition. Geneva: DARA International. Full report available at http://www.daraint.org/wp-content/uploads/2012/10/CVM2-Low.pdf.

69 The WHO claims that 150,000 deaths per year are currently caused by climate change: Health and Environment Linkages Initiative, World Health Organization/United Nations Environment Program, Available at: http://www.who.int/heli/risks/climate/climatechange/en/.

70 Ibid.

episodes/child year in 1990 to 2.9 episodes/child year in 2010."[71] Over the same period (1990 to 2010), the global mean temperature is estimated to have increased by 0.25 C (with a range of 0.08°C to 0.43°C).[72] So, an increase in temperature has not been associated with an increase in incidence of diarrhea.

Looking at the alleged effects in more granular detail reinforces this point. About half (40,000) of the alleged total climate-related deaths from diarrhea in the DARA report occurred in India.[73] Between 1990 and 2009, mean temperatures in India reportedly rose by about 0.5°C.[74] Applying the methodology used by DARA, diarrhea incidence should have risen by 2.5% during that period.[75] Yet, Fischer Walker et al.'s data indicate that the unweighted average number of annual diarrheal infections per Indian child under five *fell* by about 20% between 1990 and 2010.[76] Over the same period, mortality of children under five in India has fallen by half, from approximately 12% to approximately 6%.[77]

It is true that in places where diarrhea is already a serious problem, higher temperatures *might* cause more widespread outbreaks.[78] But adaptations—especially better access to clean water and better sanitation—are likely to reduce the incidence of diarrhea, thereby more than offsetting any potential effect from a warming climate.

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71 Fischer Walker, Christa L., Jamie Perin, Martin J. Aryee, Cynthia Boschi-Pinto and Robert E. Black. "Diarrhea incidence in low- and middle-income countries in 1990 and 2010: a systematic review." *BMC Public Health* 12 (2012). Available at: http://www.biomedcentral.com/1471-2458/12/220.

72 The range and mean change are based on the 95% confidence intervals of the HADCRUTV4 data set. The two other main data sets, NASA's GISS and NOAA's NCDC both find a mean warming over the period of 0.27 C and 0.26 C respectively. See: http://www.metoffice.gov.uk/research/monitoring/climate/surface-temperature

73 See India country profile: http://daraint.org/climate-vulnerability-monitor/climate-vulnerability-monitor-2012/country-profile/?country=India, accessed 7/14/2013.

74 Attri, S. D. and Ajit Tyagi. (2010) *Climate of India*, New Delhi, India: Government of India Ministry of Earth Sciences, India Meteorological Department, Met Monograph No. Environment Meteorology-01/2010, at Figure 4. Available at: http://www.indiaenvironmentportal.org.in/files/climate_profile.pdf.

75 In its technical paper on "methodology," DARA explains that it starts with a set of "climate impact factors" (CIF) for each disease and then calculates the "climate effect"—i.e. the number of deaths from each disease that it attributes to climate change—"by multiplying the variable (disease burden) with the CIF." It then shows how it does this, using the example of hunger: "CE_Hunger2010 = (CIF_Hunger2010, country x Disease burden 2008, country)/Population 2010, country x."

So, for example, to calculate the number of diarrhea-related deaths in India caused by climate change in 2010 one would multiply the climate impact factor for diarrhea for India (in 2010) by the disease burden for India (in 2008) and divide that by the population of India (in 2010). In this way, DARA calculated that, in 2010, 40,000 people in India died of diarrhea as a result of climate change.

76 Fischer Walker et al. "Diarrhea incidence in low- and middle-income countries in 1990 and 2010." Additional file 2: Diarrhea Incidence Rates for Included Countries.

77 http://www.childmortality.org/index.php?r=site/graph#ID=IND_India

78 For example, a study published in 2013 found that in Botswana an increase in the length and intensity of the dry season might, all other things being equal, result in an increase in diarrheal diseases. See: Alexander, Kathleen, Marcos Carzolio, Douglas Goodin and Eric Vance. "Climate Change is Likely to Worsen the Public Health Threat of Diarrheal Disease in Botswana." *International Journal of Environmental Research and Public Health*. 2013.. 10. 1202–1230. Available at: http://www.mdpi.com/1660-4601/10/4/1202, accessed 4/1/2016.

Concerns have also been raised about the potential for vector-borne diseases, such as malaria, to increase in response to rising temperatures. DARA attributes 20,000 of the 400,000 alleged deaths from climate change to malaria and other vector-borne diseases.[79] But these diseases are far more dependent on the level of development than on temperatures. Many of today's affluent countries once experienced levels of such diseases similar to those now experienced by poor countries. Although now often considered a "tropical" disease, malaria was once prevalent throughout Europe and the U.S. In England it was known as the Ague—which Shakespeare buffs might recognize—and was a major killer even during the Little Ice Age, especially around the marshes of Kent and Essex.[80] Giancarlo Majori, the director of the Laboratory of Parasitology at the Instituto Superiori di Santi in Rome, notes that at the end of the 19th century in Italy alone each year, malaria is estimated to have infected about two million people and caused 15,000 to 20,000 deaths.[81] But its range extended far, far from the tropics, as Professor Paul Reiter of the Pasteur Institute in Paris, one of the world's leading experts on mosquito-borne diseases, notes:

> *In fact, the most catastrophic epidemic on record anywhere in the world occurred in the Soviet Union in the 1920s, with a peak incidence of 13 million cases per year, and 600,000 deaths. Transmission was high in many parts of Siberia, and there were 30,000 cases and 10,000 deaths due to falciparum infection (the most deadly malaria parasite) in Archangel, close to the Arctic circle.*[82]

By the late 20th century, malaria and most other vector-borne diseases had disappeared from wealthy countries. As a result, global deaths from malaria are estimated to have fallen by 97% between 1900 and 2015, from 194 per 100,000 to 6 per 100,000.[83] The main causes of this dramatic improvement in human well-being seem to have been: environmental interventions (such as the use of pesticides and mechanized agriculture), improved water

[79] http://daraint.org/wp-content/uploads/2012/09/CVM2ndEd-Climate-Malaria-and-Vector-Borne.pdf

[80] Reiter, Paul. "From Shakespeare to Defoe: Malaria in England in the Little Ice Age." *Emerging Infectious Diseases* 6 (1). 2000. Available at: http://wwwnc.cdc.gov/eid/article/6/1/00-0101_article.htm

[81] Majori, Giancarlo. "A Short History of Malaria and Its Eradication in Italy With Short Notes on the Fight Against the Infection in the Mediterranean Basin." *Mediterranean Journal of Hematology and Infectious Diseases* 4(1). March 2012. Available at: http://www.mjhid.org/article/view/9990

[82] Reiter, Paul. *Memorandum by Professor Paul Reiter, Institut Pasteur, Paris to House of Lords Economic Affairs Select Committee Report on the Economics of Climate Change*. London: Hansard, 2005. Available at: http://www.publications.parliament.uk/pa/ld200506/ldselect/ldeconaf/12/12we21.htm

[83] World Health Organisation. "Rolling Back Malaria" in *World Health Report 1999*. 51, available at http://www.who.int/whr/1999/en/whr99_ch4_en.pdf, and "World Health Organisation Malaria Fact Sheet," available at: http://www.who.int/mediacentre/factsheets/fs094/en.

and sewerage systems, improved nutrition, improved human living conditions (including the use of air conditioning), and the development and use of vaccines and medicines.[84]

However, vector-borne diseases, especially malaria, remain a significant public health problem in Sub-Saharan Africa and in poorer parts of Asia and Latin America. The WHO estimates that in 2015 there were approximately 212 million cases of malaria worldwide,[85] causing 429,000 deaths.[86] This appalling toll is mainly restricted to the tropics; indeed, about 90% of malaria incidence and 92% of deaths occurred in Sub-Saharan Africa.[87] But there is simply no evidence that any of these cases of malaria were caused by climate change.

Paul Reiter outlines no fewer than nine behavioral and ecological factors (birth rate, forest clearance, agricultural practices, movement of people, urbanization, insecticide resistance, drug resistance, degradation of the health infrastructure, and war and civil strife) and three climatic factors (temperature, humidity and rainfall) which affect the transmission of malaria to human beings.[88] He concludes that the complex interaction of these factors makes it difficult to predict the likely impact of long-term climate change on the transmission of malaria.

Similar problems plague attempts to assess the impact of climate change on other vector-borne diseases, such as yellow fever, dengue, Chikungunya, West Nile Virus, and tick-born encephalitis (TBE). Regarding TBE, Reiter says:

> *The factors that influence transmission are so complex that they present an outstanding example of how intuitive thinking from a starting point of changing climate can offer an explanation that is simple, persuasive, and wrong.*[89]

Reiter roundly refutes the claim that vector-borne diseases have been increasing primarily as a result of climate change:

> *The ecology and natural history of disease transmission, particularly transmission by arthropods, involves the interplay of a multitude of interacting factors that defy simplistic*

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84 Smith, David L. et al. “A sticky situation: the unexpected stability of malaria elimination.” *Philosophical Transactions of the Royal Society B.* 2013. 368 (1623). Available at: http://rstb.royalsocietypublishing.org/content/368/1623/20120145.long

85 WHO International. Malaria fact sheet. Updated April 2017. http://www.who.int/mediacentre/factsheets/fs094/en/, accessed 3/4/2017.

86 Ibid.

87 Ibid.

88 Reiter, Paul. *Human Ecology and Human Behavior: Climate change and health in perspective.* London: International Policy Network. 2007.

89 Ibid. 22.

analysis. The rapid increase in the incidence of many diseases worldwide is a major cause for concern, but the principal determinants are politics, economics, human ecology and human behaviour.[90]

Effects on agriculture and forestry

Warmer summers will extend the growing season at high latitudes (i.e. much of North America, Europe, Russia, China, South Africa, Australia, New Zealand, Argentina and Chile)—indeed there is evidence that this is already occurring.[91] And longer growing seasons, other things being equal, are likely to result in higher crop output. However, it is also possible that in some places warmer summers will cause unfavorable growing conditions for the crops currently being grown.[92] But that effect can be offset by changing the crops that are grown and irrigation practices.[93]

Increased precipitation in some areas may improve productivity of existing crops.[94] In the U.S., increased precipitation over the course of the past 100 years has reduced the incidence of drought.[95] However, it could also increase the potential for flooding in some places, with adverse consequences, including for crop production.[96]

Reduced precipitation in other areas could reduce crop productivity. However, as a 2013 study published in *Nature* shows, at higher carbon dioxide levels, plants tend to use water more efficiently (by reducing the size of stomata), which may at least partly offset any reduction in precipitation.[97]

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90 Ibid. 23.

91 Lindsey, Rebecca. "High-latitude growing season getting longer." www.climate.gov. 12/5/2012. Washington, DC: National Oceanographic and Atmospheric Administration. https://www.climate.gov/news-features/featured-images/high-latitude-growing-season-getting-longer

92 For a recent analysis see: Hatfield, Jerry and John Prueger. "Temperature Extremes: Effect on Plant Growth and Development." *Weather and Climate Extremes*. 2015. 10 (A). 4-10, available at: http://www.sciencedirect.com/science/article/pii/S2212094715300116, accessed 4/10/2016

93 Zhang, Tianyi. Xiaomao Lin and Gretchen F. Sassenrath. "Current Irrigation Practices in the Central United States Reduce Drought and Extreme Heat Impacts for Maize and Soybean, but Not for Wheat." *Science of the Total Environment* 508. 331–342. 2014.

94 Kang, Yinhong, Shahbaz Khan and Xiaoyi Ma. "Climate change impacts on crop yield, crop water productivity and food security—A review." *Progress in Natural Science* 19. 1665–1674. 2009.

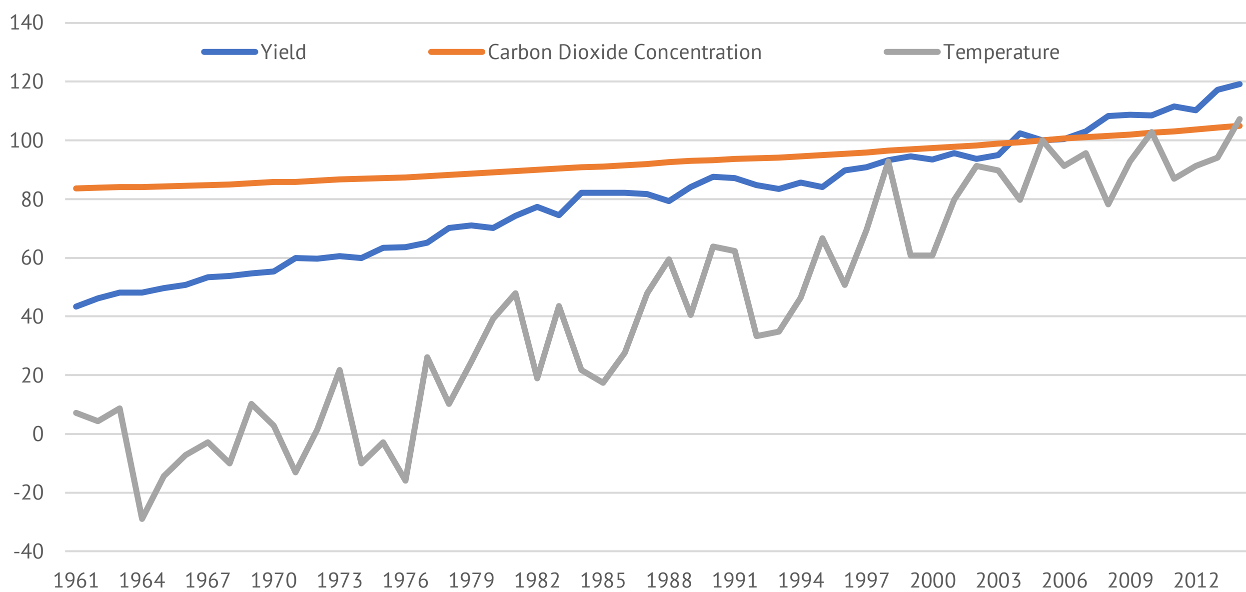
95 McCabe, G.J., D.M. Wolock and S.H. Austin. "Variability of runoff-based drought conditions in the conterminous United States." *International Journal of Climatology* **37**. 1014–1021. 2017.

96 Held, Isaac and Brian Soden. "Robust Responses of the Hydrological Cycle to Global Warming." *Journal of Climate*. 19. 5686–5702. 2006. Available at: http://journals.ametsoc.org/doi/pdf/10.1175/JCLI3990.1, accessed 4/4/2016.

97 Keenan et al. "Increase in forest water-use efficiency as atmospheric carbon dioxide concentrations rise." *Nature* 499. 2013. 324–327.

Additional atmospheric carbon dioxide will also directly increase yields of most crops. Indeed, this is already happening.[98] Moreover, evidence suggests that a considerable part of the increase in crop output over the past 50 years has been a result of increases in carbon dioxide concentrations. The simple relationship between carbon dioxide and crop yields is shown in Figure 16.[99] Since other factors, such as improved cultivars and pesticides, as well as increased fertilizer use, also contributed to higher yields, a more sophisticated analysis is necessary to determine the actual effect of carbon dioxide. Just such an analysis was undertaken by a group of researchers from the National Institute for Agro-Environmental Sciences in Japan. In a 2014 study published in *Scientific Reports*, they found that between 1980 and 2002–2006, average yields of soybeans in the U.S., Brazil and China had increased by between 4.34% and 7.37% due to carbon dioxide fertilization effects.[100]

FIGURE 16: CROP PRODUCTIVITY, TEMPERATURE AND CO_2 LEVELS (INDEXED, 2005 = 100)



Data sources: NOAA Mauna Loa observations (carbon dioxide); NASA GISS (temperature anomalies); UN FAO (crop yields).

98 Donahue, Randall J., Michael L. Roderick, Tim R. McVicar and Graham D. Farquhar. "Impact of CO_2 fertilization on maximum foliage cover across the globe's warm, arid environments." *Geophysical Research Letters.* 40 (12). 3031–3035. 2013. See also: Allen, L. Hartwell, Jr., Jeff T. Baker and Ken J. Boote. *The CO_2 fertilization effect: higher carbohydrate production and retention as biomass and seed yield.* Rome: Food and Agriculture Organization of the United Nations. Available at: http://www.fao.org/docrep/w5183e/w5183e06.htm, accessed 4/4/2016

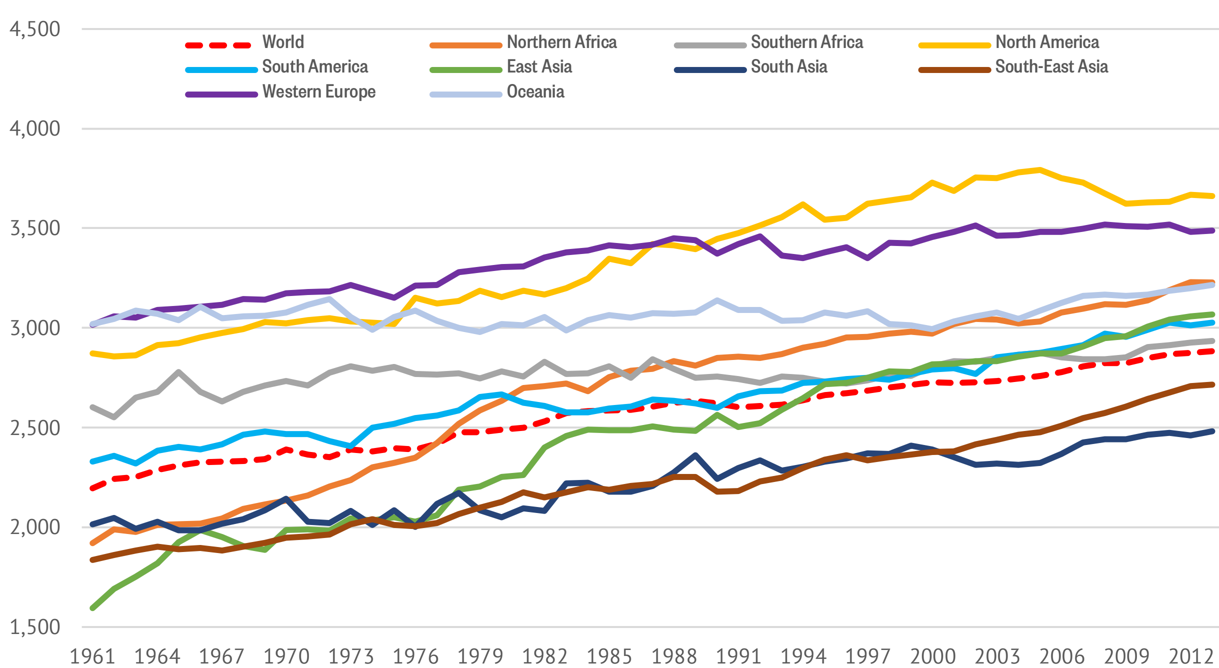
99 A regression analysis shows that changes in yields are highly correlated with CO_2 concentrations but not correlated with temperature.

100 Sakurai, Gen, Toshichika Iizumi, Motoki Nishimori & Masayuki Yokozawa. "How much has the increase in atmospheric CO2 directly affected past soybean production?" *Scientific Reports* 4, Article number: 4978. Available at: http://www.nature.com/srep/2014/140515/srep04978/full/srep04978.html. Among other things, the study took into account factors such as improvements in yield due to improved cultivars and pesticides, which also played a role in increasing yields. See the supplemental information available here: https://images.nature.com/original/nature-assets/srep/2014/140515/srep04978/extref/srep04978-s1.pdf

Rising carbon dioxide levels have not only increased food crop production but also growth of trees and other plants. Warming has also contributed to this wider increase in growth of flora. The phenomenon has rightly been called "global greening." An extensive analysis by an international team of 25 researchers of "leaf area images" (LAIs) produced by earth-orbiting satellites found that over the period 1982–2009, there was "persistent and widespread increase of growing season integrated LAI (greening) over 25% to 50% of the global vegetated area, whereas less than 4% of the globe shows decreasing LAI (browning)."[101] Moreover, the researchers found that "CO_2 fertilization effects explain 70% of the observed greening trend, followed by nitrogen deposition (9%), climate change (8%) and land cover change (LCC) (4%)."

Increases in crop production over the past half century have resulted in increased food availability per capita—as shown in Figure 17. This has resulted in a significant decline in the proportion of undernourished people even in the least developed countries—as shown in Figure 18. Clearly increased food availability, no matter the cause, increases nourishment.

FIGURE 17: FOOD AVAILABILITY PER CAPITA IN SELECT REGIONS, FOOD SUPPLY, KCAL/DAY

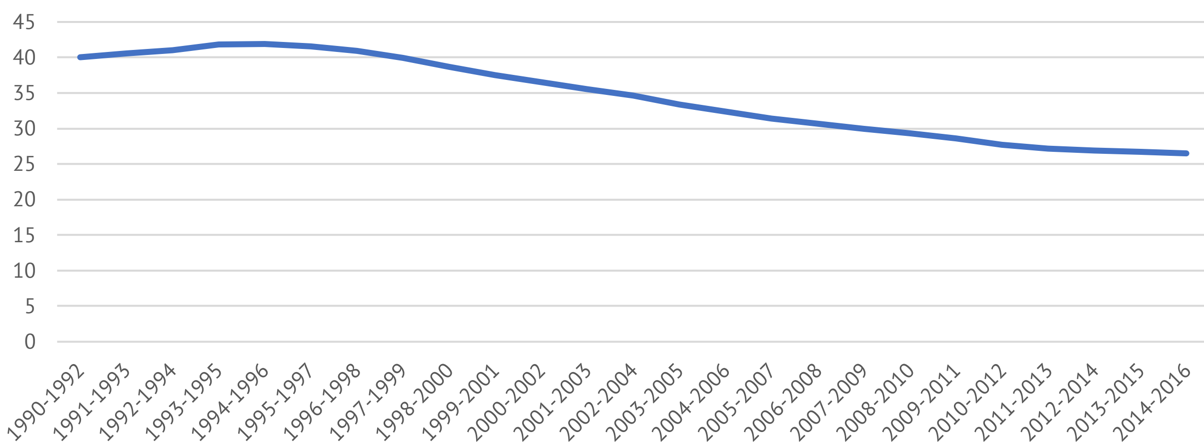


Source: Food and Agriculture Organization of the United Nations: FAOStat (http://www.fao.org/faostat/en/#home)

[101] Zhu, Zaichun et al. "Greening of the Earth and its drivers." *Nature Climate Change* 6. 791–795. 2016. Available at: http://www.nature.com/nclimate/journal/v6/n8/full/nclimate3004.html

On net, increased concentrations of carbon dioxide and associated increases in temperature are likely to increase agricultural output, especially in more temperate regions such as the U.S. A 2010 study by researchers at Rothamstead Research in the U.K. concluded that a 60 ppm increase in CO_2 concentrations (to 550ppm) by 2050 would increase yields of most crops by 13% on average.[102] And these increases are likely to continue to reduce hunger, malnutrition, and associated diseases.

FIGURE 18: PROPORTION OF UNDERNOURISHED PEOPLE IN LEAST DEVELOPED COUNTRIES (%)



Source: World Bank World Development Indicators (http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators).

Yet, alarmists claim that global warming is leading to hunger and death. DARA attributes 225,000 of its alleged 400,000 climate-related deaths in 2010 to hunger. Of those, nearly half, 100,000, were said to have occurred in India. In support of this claim, DARA asserts that "Rising heat, increasing variability, overabundance, or absence of rainfall, flooding, drought, disease and insect infestations are real threats to agricultural communities around the world."[103]

The International Food Policy Research Index produces a Global Hunger Index, which provides factors and outcomes relating to hunger, including the "proportion of undernourished in the population," "prevalence of wasting in children under five years,"

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[102] Jaggard, Keith W., Aiming Qi and Eric S. Ober. "Possible changes to arable crop yields by 2050." *Philosophical Transactions of the Royal Society B* 365. 2835–2851. 2010. Available at: http://rstb.royalsocietypublishing.org/content/royptb/365/1554/2835.full.pdf

[103] See: http://daraint.org/wp-content/uploads/2012/09/CVM2ndEd-Climate-Hunger.pdf

"prevalence of stunting in children under five years," and the "under-five mortality rate." Between 1991–1993 and 2014–2016, the unweighted average of all these factors and outcomes fell. The proportion of undernourished halved, from 25% to 12.6%. The prevalence of wasting in children under five fell from 7.4% to 6%.[104] The prevalence of stunting in children under five fell from 33% to 22%. And the under-five mortality rate fell by more than half, from 9.2% to 4.1%.

Looking specifically at India, the proportion of undernourished in the population fell from 22.2% in 1991–1993 to 17.2% in 2007–2009—and continued falling to 15.2% in 2014–2016. The prevalence of wasting was 20%, in both 1991–1993 and 2007–2009, but fell to 15.1% in 2014–2016. The prevalence of stunting in children under five fell from 61.9% in 1991–1993 to 47.9% in 2007–2009 and fell again, to 38.7% in 2014–2016. Finally, the under-five mortality rate fell from 11.9% in 1992 to 6.6% in 2009—and then fell further to 4.8% in 2015.

Contributing to the decline in malnutrition has been an increase in food production in India. For example, production of cereal crops rose from 193 million tons in 1990 to 263 million tons in 2010. Meanwhile, the area of land used for cereal production fell over same period by about 3%, implying an increase in yields of around 40%.[105] (Production has continued to rise, reaching 295 million tons in 2014, while the area cultivated has continued to fall.)

These increases in agricultural production and productivity, and declines in the proportion of those suffering from malnutrition, have occurred in spite of India's average temperature rising by about 0.5°C between 1990 and 2010.[106] As such, it is difficult to understand how warming might be resulting in 100,000 deaths per year from hunger in India.

A recent paper by a team of economists from the London School of Economics, Stanford University, the University of California Santa Barbara, and the University of Chicago, found that while death rates in urban India did not increase in proportion to the number of hot days during growing, corresponding rates for rural India were considerably higher, mainly

[104] Wasting is an acute loss of muscle and fat tissues as a result of malnutrition and/or disease.

[105] UN Food and Agriculture Organization, Country Indicators for India, Available at: http://www.fao.org/faostat/en/#country/100

[106] Attri, S. D. and Ajit Tyagi. 2010. *Climate of India*. New Delhi, India: Government of India Ministry of Earth Sciences. India Meteorological Department. Met Monograph No. Environment Meteorology-01/2010, at Figure 4. Available at: http://www.indiaenvironmentportal.org.in/files/climate_profile.pdf

due to the effects on agricultural output and wages.[107] The authors worried that in the future, warming might lead to "considerable reductions" in the life expectancy of rural Indians due to impacts on crop production. However, the analysis, which was cited in a *Wall Street Journal* article, suffers a number of defects:

First, the paper assumes as its baseline the highest emission scenario developed for the IPCC's 2000 report (known as A1FI) combined with the Hadley Center's HadCM3 model. Under A1FI (FI stands for "fuel intensive"), atmospheric CO_2 concentrations would rise to 925 ppm by 2100, nearly four times the pre-industrial level of 280 ppm.[108] Meanwhile, under HadCM3, at 925 ppm CO_2 land temperatures would rise on average by nearly 8°C by 2100, with higher levels immediately north and south of the equator (i.e. in India and other similar locations).[109] This effectively represents a "catastrophe" scenario—and is highly unlikely, as has been argued earlier.

Second, the paper's historical analysis is based on responses to short-term weather patterns, so it does not take into account the potential for rural Indians to adopt different crops and other adaptive strategies in response to changing climatic conditions over time. The authors acknowledge this, noting "our procedure draws on estimates of the impact of year-to-year weather fluctuations to gauge the potential impact of climate change, a slower, more permanent and more forecastable weather shock. Individuals can adapt to worsening climatic conditions for example by shifting away from climate exposed occupations and regions, by using more heat resistant agricultural technologies or by adopting protective technologies such as fans and air conditioning."[110] Unfortunately, one of the most promising innovations that would enable such adaptation, genetically engineered varietals of food crops, has largely been prohibited by India's government and courts.[111] If rural Indians are permitted to adopt new food crop varieties and other technologies, the impact of an increase in hot days is likely to be much reduced.

107 Burgess, Robin, Olivier Deschenes, Dave Donaldson and Michael Greenstone. *Weather, Climate Change and Death in India.* Working Paper: London School of Economics. April 20, 2017. Available at: http://www.lse.ac.uk/economics/people/facultyPersonalPages/facultyFiles/RobinBurgess/WeatherClimateChangeAndDeathInIndia.pdf

108 Johns, T.C., J.M. Gregory, W.J. Ingram, C.E. Johnson, A. Jones, J.A. Lowe, J.F.B. Mitchell, D.L. Roberts, D.M.H. Sexton, D.S. Stevenson, S.F.B. Tett and M.J. Woodage. "Anthropogenic climate change for 1860 to 2100 simulated with the HadCM3 model under updated emissions scenarios." *Climate Dynamics* 20. 583–612, 2003.

109 Ibid.

110 Burgess et al. *Weather, Climate Change and Death in India.* 2017. at p. 37.

111 Kumar, Sanjay. "India's First GM Food Crop Held Up by Lawsuit." *Nature.* 1/18/2017. Available at: https://www.nature.com/news/india-s-first-gm-food-crop-held-up-by-lawsuit-1.21303

Third, the paper assumes that the proportion of Indians living in rural areas is likely to remain high. This is based on migration patterns from 1960 to 2000, during which the proportion of people living in rural India fell from 82% to 72%—a decline of 2.5% per decade. The authors conclude from this that "the at-risk population will continue to comprise a large share of the total population over the coming century."[112] Yet, between 2001 and 2011, the rural population declined from 72% to 69%—a decline of 3% per decade. If that trend continues until 2100, the proportion of people living in rural India will fall to 42%. Quite plausibly, the trend could increase, as it appears already to have done—and as it did in most countries that have developed (e.g. the U.S. went from 72% rural in 1880 to 26% rural in 1970[113]). Two factors are likely to accelerate the rate of urbanization in India: first, increasing disparity between rural and urban wages as the economy continues to develop; second, the removal of existing restrictions on land holdings by rural Indians. The latter would also increase agricultural efficiency and enable more-effective rural adaptation to climate change.[114]

In sum, claims that rising levels of greenhouse gases are reducing agricultural output and food availability, and thereby increasing mortality, are based on highly dubious assumptions that are largely contradicted by the evidence. Increases in carbon dioxide concentration have contributed to increased crop production globally—and can be expected to continue to do so. While rising temperatures certainly have the potential negatively to affect food production and life expectancy in some locations, the presumption that they *will* do so ignores adaptations that will likely take place.

Effects of extreme weather

The incidence of extreme weather events (droughts, floods, tornadoes, hurricanes and other storms) has not increased in the U.S. over the course of the past 60–100 years.[115] Globally, the picture is murkier due to the lack of reliable data in many locations; it is possible that the incidence of some extreme weather events has increased over the past century, however mortality from such events has declined by 98%.[116] The reasons for this decline

112 Burgess et al. *Weather, Climate Change and Death in India.* 2017. 3. Footnote 2.

113 U.S. Census Bureau. Available at: https://www.census.gov/population/censusdata/table-4.pdf

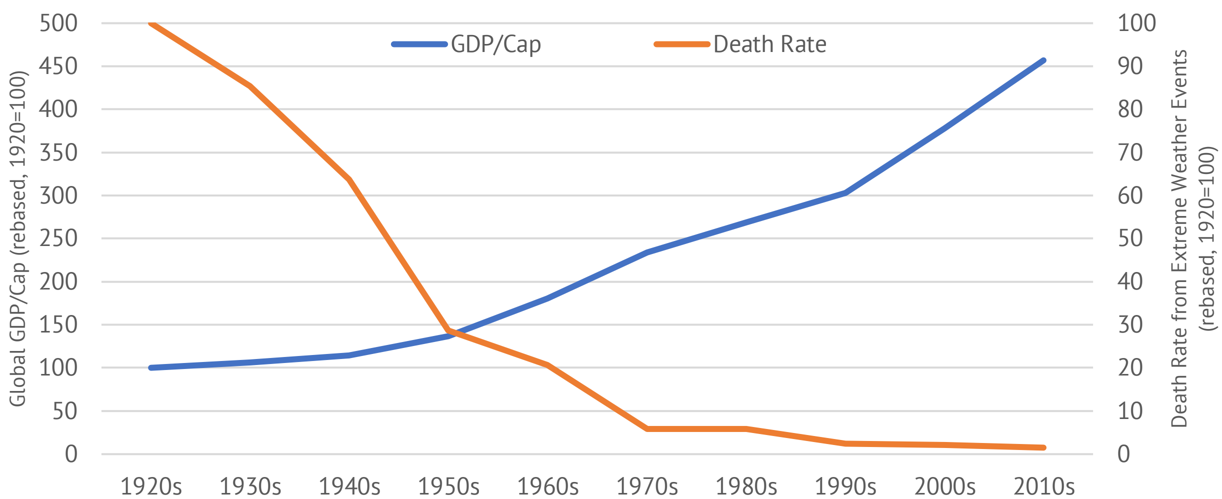
114 See e.g. Deininger, Klaus, Jin Songqing and Hari K. Nagarajan. "Equity and efficiency impacts of rural land rental restrictions: Evidence from India." Selected Paper prepared for presentation at the American Agricultural Economics Association Annual Meeting. Long Beach, California. July 23–26, 2006. Available at: http://ageconsearch.tind.io//bitstream/21305/1/sp06de06.pdf

115 See the collection of data at: https://wattsupwiththat.com/reference-pages/climatic-phenomena-pages/extreme-weather-page/

116 Goklany, Indur M., *Wealth and Safety: The Amazing Decline in Deaths from Extreme Weather in an Era of Global Warming, 1900*–2010. Los Angeles: Reason Foundation. Available at: http://reason.org/news/show/decline-deaths-extreme-weather

are manifold, but of great importance have been: improved technologies for food production, housing and transportation; increased openness to trade—which enables people to access food and medical supplies more readily when an extreme event occurs—and greater income, wealth and access to financial services, which enable people better to save for and insure against disasters. As Figure 19 shows, the decline in mortality is almost perfectly inversely correlated with the increases in per capita income.

FIGURE 19: GLOBAL MORTALITY FROM WEATHER-RELATED NATURAL DISASTERS AND PER CAPITA INCOME



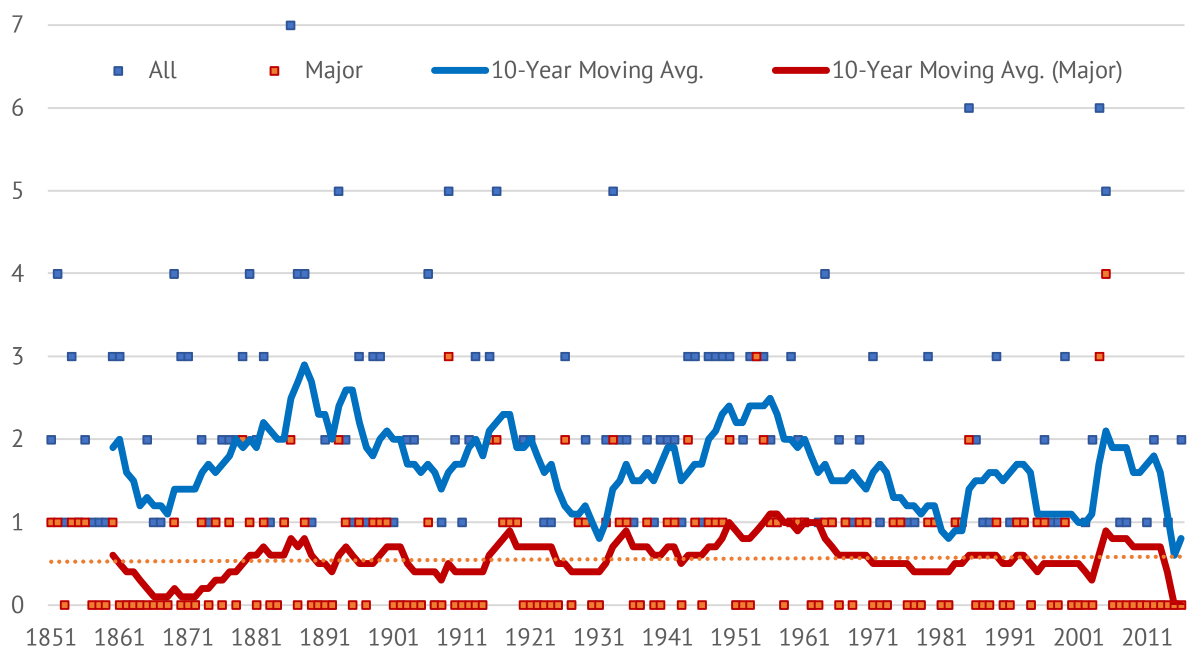
Source: Author's calculations based on data from EM-DAT (the international disasters database: http://www.emdat.be/), Angus Maddison Project (http://www.ggdc.net/maddison/maddison-project/home.htm) and World Bank World Development Indicators (http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators).

Some alarmists have claimed that climate-change-induced extreme weather events are causing more death and economic harm. To date, however, the evidence suggests that the increase in the number of people affected and economic damage from weather-related natural disasters is almost entirely a consequence of increasing populations and the fact that more buildings of greater value have been located in areas affected by extreme weather events.[117]

[117] Bauer, Laurens. "Have Disaster Losses Increased due to Anthropogenic Climate Change?" *Bulletin of the American Meteorological Society*. January 2011. 39–46. Available at: http://journals.ametsoc.org/doi/abs/10.1175/2010BAMS3092.1; Visser, Hans, Arthur C. Petersen and Willem Ligtvoet. "On the relation between weather-related disaster impacts, vulnerability and climate change," *Climatic Change* 125. 461–477. 2014.

The number of hurricanes making landfall in the U.S. has not increased in response to increasing temperatures. Indeed, as can be seen in Figure 20, the 10-year moving average of both total hurricanes and significant hurricanes (category 3 or greater) has declined over the past 100 years. Modelling suggests that tropical cyclones (hurricanes and typhoons) might increase in intensity (by up to 11% by 2100, at higher levels of warming) but decrease in number.[118] Combined with higher sea levels, these cyclones have the potential to do more damage. However, continued improvements in prediction, combined with the development and adoption of better technologies, ranging from flood defenses to housing, are likely able to mitigate these adverse effects.

FIGURE 20: HURRICANES MAKING LANDFALL IN THE U.S. (1851–2016)



Source: Author's calculations based on: National Oceanographic and Atmospheric Administration Hurricane Research Division: Complete List of Continental U.S. Landfalling Hurricanes (http://www.aoml.noaa.gov/hrd/tcfaq/E23.html).

On net, the effects of any increase in extreme weather due to climate change are likely to be modest—and will likely be mitigated by continued improvements in technology and wealth.

118 Knutson, Thomas et al. "Tropical cyclones and climate change." *Nature Geoscience*. Published online: 21 February 2010. Available at: http://www.aoml.noaa.gov/hrd/Landsea/knutson-et-al-nat-geo.pdf. Accessed 4/4/2016.

EVALUATING THE ECONOMIC CONSEQUENCES OF CLIMATE CHANGE'S EFFECTS IS EQUALLY FRAUGHT WITH DIFFICULTY.

Not only is the future state of the climate unknown, but future technologies are unknown and unknowable. As Professor William Nordhaus, inventor of the IAM, said in 1990, "If climate change itself is *terra infirma*, the social and economic impacts of such change are *terra incognita*."[119] Nonetheless, Nordhaus and others have made heroic attempts to undertake such evaluations.

In a 2009 study commissioned by the UK Commission for Economic Growth and funded by various government aid agencies along with the Hewlett Foundation and the World Bank,[120] Yale University economist Robert Mendelsohn concluded that "These impacts are simply not large enough to affect economic growth this century."[121] In the same year, Richard Tol, probably the world's leading climate economist, concluded that warming of up to 3°C compared to pre-industrial levels (i.e. about 2°C warmer than today) is likely to have net benefits for humanity.[122] (This conclusion was reaffirmed in a working paper by Tol published in 2015.[123])

An important feature of both Tol's and Mendelsohn's analyses is that humans will develop and disseminate new technologies that enable us to adapt more effectively to changes in climate. In other words, our "adaptive capacity" will increase.

While the costs and benefits are unlikely to be distributed evenly, even these distributional effects are unknown (and unknowable). People in poor countries might be expected to suffer more for various reasons. First, many poor countries are in locations closer to the equator that will not experience much benefit from longer growing seasons or shorter winters but will suffer from hotter summers. Second, many poor countries—including Bangladesh and many small island states—are low-lying and thus more likely to be adversely impacted by sea-level rise. Third, poor countries are poor because they lack the conditions necessary for economic development: the institutions and culture that foster

[119] Nordhaus, William D. "Greenhouse Economics: Count Before You Leap." *The Economist.* July 7, 1990.

[120] The Australian Agency for International Development (AusAID), the Dutch Ministry of Foreign Affairs, the Swedish International Development Cooperation Agency (SIDA), the U.K. Department of International Development (DFID), The William and Flora Hewlett Foundation, and The World Bank Group.

[121] Mendelsohn, Robert. *Climate Change and Economic Growth.* London/Washington, D.C.: Commission on Growth and Development. Available at: https://environment.yale.edu/files/biblio/YaleFES-00000397.pdf.

[122] Tol, Richard S. J. "The Economic Effects of Climate Change." *Journal of Economic Perspectives* 23(2): 29–51. 2009.

[123] Tol, Richard S. J. *Economic Impacts of Climate Change*. University of Sussex Working Paper No. 75-2015. 2015. Available at: https://ideas.repec.org/p/sus/susewp/7515.html.

trade and innovation. As such, people in countries *that remain poor* might on net suffer as a result of climate change.

But it is likely that many places that are currently poor will not be poor in 50 or 100 years' time. In 1972, the year the UN held its Stockholm conference on environment and development, annual average income per capita in India and China was $130 and both were in the poorest 15% of the world's countries.[124] Forty-five years later, India's annual per capita income has risen to $1600, a 12-fold increase, while China's had risen to $7930, a 60-fold increase (both figures are in "real" terms—i.e. discounting for inflation).[125] Many other countries have experienced rapid growth and about three quarters grew at least five-fold. On average, real per capita income in the 96 countries for which the World Bank has complete data for that period grew about 10-fold. Only three of those 96 countries experienced a less than doubling in real per capita income: Congo (which experienced a decline in average income), Liberia and Zimbabwe. The delinquent performance of those countries is largely due to persistent civil wars and other violent internal struggles that have inhibited economic activity.

Ironically, the scenarios used by the IPCC to forecast future emissions presume that economic conditions will improve. And they will improve most in the scenarios associated with the largest emissions of greenhouse gases. This is because those scenarios are associated with the largest increases in economic activity and the most rapid convergence in rates of economic activity between rich and poor countries. So, in the very scenarios in which climate change is presumed to have the greatest impact, that impact will be distributed most evenly and the harms will be most readily mitigated by adaptive responses.[126]

[124] World Bank. World Development Indicators (http://data.worldbank.org/data-catalog/world-development-indicators), using GNI Per Capita Atlas Method.

[125] Ibid.

[126] However, while the scenarios presume that conditions will change, they offer no account as to how this will occur. As Lee Lane and David Montgomery point out in a paper in the same special issue of the journal *Climatic Change* in which the IPCC scenarios are described, the scenarios provide no account of the requisite changes in culture and institutions that would underpin changes in rates of economic development, or indeed other changes that are presumed in several scenarios (such as shifts in societal values). See: Lane, Lee and W. David Montgomery. "An Institutional Critique of New Climate Scenarios." *Climatic Change*. Special Issue on "A Framework for the Development of New Socio-economic Scenarios for Climate Change Research" edited by Nebojsa Nakicenovic, Robert Lempert and Anthony Janetos. 2013. Available at: https://ncar.ucar.edu/sites/default/files/isp/l-lane-an-institutional-critique.pdf

THE COSTS OF REDUCING FUTURE EMISSIONS OF GHGS WILL DEPEND VERY MUCH ON THE EXTENT AND TIMEFRAME OF ANY REDUCTION.

Proponents of taking action now argue that any delay would increase the total cost of emissions reductions—because baseline emissions (i.e. the emissions that would occur without any mandated reductions) would be higher and the size of any such future reduction would have to be greater. But such arguments presume both significant increases in baseline emissions and a need dramatically to reduce such emissions.[127]

If the trends in technology identified earlier do continue, growth in baseline GHG emissions will continue to slow and in the longer term may even fall without any government mandates. Indeed, it is possible that baseline emissions in the future (i.e. after 2050) will be consistent with a pathway of emissions that results in atmospheric GHG concentrations that generate net benefits.

Even if baseline emissions rise in the future to a level that results in net costs for humanity, it is unlikely that mandating emissions reductions now or in the next couple of decades would generate net benefits when taking into account the costs of reducing emissions. Future innovations will almost certainly result in lower emissions per unit of output, so the costs of reducing a unit of GHG emissions in the future will be lower than it is today.

The costs of attempting to reduce GHG emissions more rapidly than would occur in the absence of government intervention could well be very high, especially if those emissions reductions are mandated now or in the near future. The reason is that humanity currently relies predominantly on carbon-based fuels for energy generation and the costs of alternative sources of energy are in most cases relatively high. If alternative sources of energy were less expensive, then it would make economic sense to adopt them.

However, there are regulatory and other government-created barriers that inhibit adoption of some lower carbon sources of energy. There are also regulatory barriers that inhibit innovations that would likely result in more efficient use of energy. The removal of these barriers would result in lower GHG emissions, while at the same time reducing costs and increasing rates of economic growth.

[127] See e.g. Kriegler, Emily et al. "What does the 2°C target imply for a global climate agreement in 2020? The LIMITS study on Durban Platform scenarios." *LIMITS Special Issue on Durban Platform scenarios*. Available at: http://www.feem-project.net/limits/docs/02.%20cce%20limits%20special%20issue_paper1_rev.pdf

EVALUATING COSTS DEPENDS ON REASONABLE DISCOUNT RATES.

When combining benefits and costs, IAMs have sometimes used inappropriately low discount rates, giving the false impression that the benefits of reducing emissions are greater than the costs. At discount rates that reflect the opportunity cost of capital, the current costs of taking action to reduce GHG emissions now and in the near future are likely greater than the benefits.

With suitable investments in the development and adoption of new technologies, many of the costs that would otherwise be associated with rising temperatures can be avoided. Such investments thus represent the primary alternative to reducing greenhouse gas emissions as a means of addressing climate change.

Since investments either in adaptation or in greenhouse gas emission reduction must compete with other investments, it is necessary for them to generate a competitive rate of return. In other words, the future benefits of such investments should be discounted at a rate that reflects the opportunity cost of capital.

The opportunity cost of capital varies according to the degree of risk associated with any particular investment: higher risk investments generally require a higher rate of return, due to the lower likelihood that the investment will pay off.

Many investments in technologies that enhance adaptation are relatively low risk. Take, for example, investments in new agricultural technologies. Monsanto has a large portfolio of agricultural technologies, many of which enable farmers to increase their productivity, in no small measure by ensuring their crops and crop protection technologies are suitable to their agro-environmental circumstances.[128] New technologies being developed by Monsanto are among those likely to be useful for farmers facing a changing climate.[129] Monsanto invests about $1.5 billion annually in research and development on new crops and crop protection products, which it funds (in part at least) by issuing bonds. On July 1, 2014, it issued $750 million in 50-year corporate bonds with a coupon of 4.7%;[130] on the

[128] Monsanto Annual Report 2016. Available at: http://www.monsanto.com/investors/publishingimages/annual%20report%202016/2016_monsanto_annual_report.pdf

[129] Fraley, Robb. *R&D Update*. Monsanto.com. 2017. Available at: http://www.monsanto.com/investors/documents/2017/2017.01.05_q1f17_mon_pipeline_update.pdf

[130] Morningstar: http://quicktake.morningstar.com/StockNet/Bondsquote.aspx?cid=0C000008H1&bid=177ac458609ccccf3dcf33df80bd5535&bname=Monsanto+Co+New+4.7%25+%7c+Maturity%3a2064&ticker=MON&country=USA&clientid=dotcom

same day, it issued $750 million in 10-year corporate bonds with a coupon of 3.375%.[131] The difference in the coupon reflects the higher risk associated with longer-dated bonds, which in turn reflects concerns about the potential for Monsanto (or any purchaser of its stock) to default on the bonds in the future.

By contrast, many investments in "low-carbon" technologies are far riskier. For example, in 2013, Solar Star Funding issued $1 billion in bonds in order to support the construction of its solar photovoltaic electricity project in California. In spite of several government schemes that result in solar power companies receiving a premium for the electricity they generate (in Solar Star's case, this includes an agreement with Southern California Edison to purchase electricity at a fixed rate for 20 years), the coupon on Solar Star's bonds, which pays out for 20 years starting in 2016, was 5.75%.[132] The higher coupon offered by Solar Star Funding compared with Monsanto reflects the greater riskiness perceived by investors, in part as a result of the high failure rate of solar power companies.[133] And in the case of Solar Star Funding, that perception has been at least partly borne out by reality: in July 2016, Fitch downgraded the rating on its bonds to BBB after several power outages at its facilities.[134]

OMB guidelines state that for the base case, "Constant-dollar benefit-cost analyses of proposed investments and regulations should report net present value and other outcomes determined using a real discount rate of 7 percent. This rate approximates the marginal pretax rate of return on an average investment in the private sector in recent years."[135] William Nordhaus also favors the use of market interest rates and notes that in his empirical work, "based on returns from many studies, I generally use a benchmark real return on capital of around 6 percent per year."[136]

131 Morningstar: http://quicktake.morningstar.com/StockNet/Bondsquote.aspx?cid=0C000008H1&bid=177ac458609ccccf62bef145369fc10d&bname=Monsanto+Co+New+3.375%25+%7c+Maturity%3a2024&ticker=MON&country=USA&clientid=dotcom

132 "Solar Star Funding. LLC Announces Completion of $1 Billion Notes Offering for Solar Star Projects." *Businesswire.com*. 6/27/2013. Available at: http://www.businesswire.com/news/home/20130627006610/en/Solar-Star-Funding-LLC-Announces-Completion-1

133 For example, in 2011, Solyndra, a large start-up solar company, backed by over $500m in federal loan guarantees, filed for bankruptcy (see: Hals, Tom. "U.S. solar firm Solyndra files for bankruptcy." Reuters, 9/6/2011. Available at: http://www.reuters.com/article/us-solyndra-idUSTRE77U5K420110906); in 2016, Spanish solar power company Abengoa, which operates several plants in the U.S., was granted bankruptcy protection in the U.S. (see: Fitzgerald, Patrick. "Spain's Abengoa Wins U.S. Bankruptcy Court Protection." *The Wall Street Journal*. 4/27/2016. Available at: https://www.wsj.com/articles/spains-abengoa-wins-u-s-bankruptcy-court-protection-1461783532).

134 "Fitch Places Solar Star Funding, LLC's 'BBB' Senior Notes on Rating Watch Negative." Available at: http://www.businesswire.com/news/home/20160721006432/en/Fitch-Places-Solar-Star-Funding-LLCs-BBB-

135 Circular A-94 Guidelines and discount rates for benefit-cost analysis of federal programs. Washington, DC: Office of Management and Budget. 9. Available at: https://www.whitehouse.gov/sites/default/files/omb/assets/a94/a094.pdf

136 Nordhaus, William D. "A Review of the Stern Review on the Economics of Climate Change." *Journal of Economic Literature*. XLV (September 2007). 690. Available at: http://www.econ.yale.edu/~nordhaus/homepage/documents/Nordhaus_stern_jel.pdf

Unfortunately, when discounting the benefits and costs associated with global warming, many analysts have used discount rates that do not reflect the opportunity cost of capital. For example, the IWG provided an estimate of the SCC at a 5% discount rate, but it is the *highest* rate given.[137] In its guidance, the IWG emphasized the SCC calculated at a 3% discount rate.[138] Its rationale for using the lower rate is that future benefits from avoiding climate change costs relate to future consumption, rather than investment. Policies to address climate change would affect both consumption and investment but for the purposes of evaluation what matters is the effect on investment, since it is the effect of policies on investment decisions that will determine rates of innovation and hence economic growth, the ability to adapt to climate change, and future consumption. In other words, while future consumption is of primary concern due to its relationship to human welfare, return on investment is the key factor determining future consumption. Thus, the appropriate discount rate is the average real rate of return on capital.

Returns on capital vary and, generally speaking, investors are willing to accept lower returns on investments with lower risk—and vice versa. Using a discount rate lower than the average real return on capital would be acceptable if the risk of investments in GHG reductions were low (and increases in consumption expenditure thus more certain). But in the case of investments in reducing GHG emissions, the risk is unknowable—it could be lower, it could be higher—so it is unclear why lower rates have been used.

U.S. POLICY DEPENDS ON CALCULATING COSTS AND BENEFITS TO THE U.S.

Most IAMs are designed to assess the global costs and benefits of climate change. That would be appropriate for setting global policy. But the U.S. government is not responsible for setting global policy, it is responsible for setting U.S. policy, and for that the appropriate geographical boundary is the territory of the United States. But the geographical reach of the benefits component of the analysis by the IWG is global. Even if the benefits could be calculated with precision, which they cannot (even within an order of magnitude), the analysis is distorted. In a paper for the Brookings Institution, Ted Gayer and Kip Viscusi calculate that if the IWG had limited its analysis to the U.S., even using the other dubious

[137] IWG. *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866*. Washington, D.C.: Interagency Working Group on Social Cost of Greenhouse Gases. United States Government. August 2016. Available at: https://www.epa.gov/sites/production/files/2016-12/documents/sc_co2_tsd_august_2016.pdf

[138] EPA. “EPA Fact Sheet: Social Cost of Carbon.” Washington, D.C.: Environmental Protection Agency, 2016. Available at: https://www.epa.gov/sites/production/files/2016-12/documents/social_cost_of_carbon_fact_sheet.pdf

modelling techniques adopted, the benefits would be only 7% to 10% of the global benefits.[139]

CLIMATE CHANGE COST/BENEFIT ANALYSIS SHOULD ACCOUNT FOR CURRENT AND FUTURE WEALTH.

The time horizon of the IWG's assessment of the SCC is 2300. And under the IWG's preferred 3% discount rate, 47% of all damages occur after 2100.[140] But as noted above, forecasts of emissions and temperature response become increasingly uncertain the further one attempts to peer into the future. Meanwhile, even under the most pessimistic growth scenario used by the IWG (the MERGE scenario), run on an IAM that allows for limited improvements in adaptive capacity (Nordhaus's DICE model), real average global per capita consumption triples by 2100 and multiplies about seven-fold by 2300.[141] So, the question arises: should people today be forced to pay for highly speculative investments in low carbon technologies that might increase the wealth of people in 2100 who will be three times richer than them even without the investment, let alone those in 2300 who will be seven times richer than them?

3.3 CHANGING THE ASSUMPTIONS IN INTEGRATED ASSESSMENT MODELS

Changing the assumptions made in the IWG's models can have a dramatic effect on the estimate of the SCC. Anne Smith and Paul Bernstein of National Economic Research Associates ran the IAMs used by the IWG making four changes, each of which individually reduced the SCC. First, they changed the emissions scenario to reflect more realistic assumptions regarding the relationship between emissions and economic growth. This change alone reduced the SCC in 2020 from $43/ton to around $32/ton. Second, they changed the time horizon from 2300 to 2100, which alone reduced the SCC from $43/ton to about $25/ton. Third, they changed the discount rate from 3% to 5%, which alone reduced the SCC from $43 to $12/ton. Fourth, they changed the scope from global to U.S.

139 Gayer, Ted and W. Kip Viscusi. *Determining the Proper Scope of Climate Change Benefits*. Washington, DC: Brookings Institution. 2014. Available at: https://www.brookings.edu/wp-content/uploads/2016/06/04_determining_proper_scope_climate_change_benefits.pdf

140 Smith, Anne E. and Paul M. Bernstein. "Sensitivity of the Social Costs of Carbon to Analysis Framing Decisions." Paper presented at the 8th Annual Conference of the Society for Benefit-Cost Analysis. Washington, D.C. March 17, 2016. Available at: https://benefitcostanalysis.org/sites/default/files/public/A2.4%20Smith_SBCA%20SessionA.2%20SCC%20Sensitivity%20to%20Framing%20March%2017%202016%20final.pdf

141 Ibid.

only, which alone reduced the SCC from $43 to $7/ton. When all these changes were combined, the effect was to reduce the SCC by 97%, from $43 to about $1.30.[142]

Smith and Bernstein's analysis did not change any assumptions regarding climate sensitivity or other relevant climate parameters that might have been mis-specified in the IAMs used by the IWG. Kevin Dayaratna, Ross McKitrick and David Kreutzer assessed the effects of using more recent empirical estimates of the ECS, conditioned on more-reliable estimates of ocean heat uptake (OHU), to calculate updated SCC estimates using two of the IWG models—Bill Nordhaus's DICE model and Richard Tol's FUND model.[143] They found that for DICE, the average SCC falls by 30%–50% and for FUND the SCC falls by over 80%. Moreover, at a 7% discount rate and using the more recent empirical ECS estimate, FUND generates an SCC of minus $1.10 for 2020 (and it remains negative through 2050).

If all of the adjustments made by Smith and Bernstein were combined with those made by Dayaratna et al.—all of which seem very reasonable based on the foregoing discussion—it seems likely that the SCC would fall to well below $1. Indeed, the SCC could well be negative, as Dayaratna and Kreutzer found for numerous iterations of the FUND model (making reasonable assumptions about parameter values).[144] However, given uncertainties in the various parameters used, it seems difficult to avoid the conclusion that for practical purposes the SCC is effectively $0.

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142 Smith, Anne E. and Paul M. Bernstein. "Sensitivity of the Social Cost of Carbon to Analysis Framing Decisions." 8th Annual Conference of Society for Benefit-Cost Analysis. Washington, D.C. March 17, 2016. Available at: https://benefitcostanalysis.org/sites/default/files/public/A2.4%20Smith_SBCA%20SessionA.2%20SCC%20Sensitivity%20to%20Framing%20March%2017%202016%20final.pdf

143 Dayaratna, Kevin, Ross McKitrick and David Kreutzer. "Empirically-Constrained Climate Sensitivity And The Social Cost Of Carbon." *Climate Change Economics*. Forthcoming (Version of February 27, 2017 available at: http://www.rossmckitrick.com/uploads/4/8/0/8/4808045/empirical_scc_cce_preprint.pdf)

144 Dayaratna, Kevin and David Kreutzer. Unfounded FUND: Yet Another EPA Model Not Ready for the Big Game. Washington, D.C.: Heritage Foundation, 2014. Available at: http://www.heritage.org/environment/report/unfounded-fund-yet-another-epa-model-not-ready-the-big-game

PART 4

ESTIMATING THE SCC USING CATASTROPHIC CLIMATE CHANGE SCENARIOS

MIT economist Robert Pindyck has criticized the use of IAMs to calculate the SCC, noting in a 2013 paper that they, "have crucial flaws that make them close to useless as tools for policy analysis."[145] More recently, he went further saying:

> *[C]alling these models "close to useless" is generous: IAM-based analyses of climate policy create a perception of knowledge and precision that is illusory, and can fool policy-makers into thinking that the forecasts the models generate have some kind of scientific legitimacy. IAMs can be misleading—and are inappropriate—as guides for policy, and yet they have been used by the government to estimate the social cost of carbon (SCC) and evaluate tax and abatement policies.*[146]

However, instead of rejecting the use of an SCC, Pindyck has proposed that the SCC be based on expert evaluation of "the possibility of a catastrophic climate outcome."[147] Professor Pindyck subsequently elicited "expert opinions" on two questions: "(1) the

[145] Pindyck, Robert S. "Climate Change Policy: What Do the Models Tell Us?" *Journal of Economic Literature* 51(3). 860–872. 2013.

[146] Pindyck, Robert S. "The Use and Misuse of Models for Climate Policy." Washington, D.C.: National Bureau of Economic Research. NBER Working Paper No. 21097. April 2015.

[147] Ibid.

probabilities of alternative economic outcomes of climate change, and in particular extreme outcomes, but not the particular causes of those outcomes; and (2) the reduction in emissions that would be required to avoid those extreme outcomes."[148] From these expert opinions, he found:

> *#1 Although there is considerable heterogeneity across experts, many view the likelihood of an extreme outcome—a climate-induced reduction of GDP 50 years from now of 20% or more—as quite high (e.g., could occur with a probability of 20% or greater). As a result, the estimates of the average SCC are large, above $200 per metric ton. SCCs based on the responses of economists are lower (around $170), but those based on responses of climate scientists and residents of Europe were $300 or more.*
>
> *#2 However, the SCC estimates are much smaller ($100 or less) when based on a trimmed sample that excludes outliers, and is limited to respondents who expressed a high degree of confidence in their answers regarding the probabilities of alternative impacts. But even this trimmed sample yields an SCC that is well in excess of the roughly $40 numbers that have come from recent IAM-based analyses.*[149]

There are several problems with this approach.

4.1 CONCERN ABOUT POTENTIALLY CATASTROPHIC CLIMATE CHANGE SHOULD BE CONSIDERED IN THE CONTEXT OF CONCERN ABOUT CATASTROPHES IN GENERAL

All manner of other possible catastrophes, both man-made and natural, can be imagined, including—but by no means limited to:

Nuclear war or terrorism. Errant states and terrorist organizations might use nuclear bombs to kills thousands or millions of people. North Korea has recently tested intercontinental ballistic missiles that could reach Europe and parts of the U.S. While some of these tests have failed, it seems plausible that future developments will result in North Korea achieving its objectives.[150] Meanwhile, about six tons of plutonium may or may not be

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[148] Pindyck, Robert S. *The Social Cost of Carbon Revisited.* Washington, D.C.: National Bureau of Economic Research. Working Paper 22807. Available at: http://web.mit.edu/rpindyck/www/Papers/SCCRevisitedNov2016.pdf

[149] Ibid. at 5.

[150] Fisher, Max, "The North Korea Paradox: Why there are no good options on nuclear arms." *The New York Times*. 4/17/2017. Available at: https://www.nytimes.com/2017/04/17/world/asia/north-korea-nuclear-weapons-missiles-sanctions.html

"missing"—and could be in the hands of terrorists or others who have malicious intent.[151] Some of this plutonium could be used to make dirty bombs that could cause widespread death. Meanwhile, there is evidence that criminals are trafficking in other forms of radioactive material, including Uranium-235 and Cesium- 135, which could also be used to make dirty bombs.[152]

A strike by a "near earth object" such as an asteroid, meteor, or comet. In 1908, a meteor strike above a sparsely populated regions of Siberia known as Tunguska devastated an area of 830 square miles, killing hundreds of people and felling about 80 million trees.[153] It is estimated that strikes of this magnitude occur about once per century (though only one third of those occur over land).[154] If one such strike were to hit a densely populated area, it could kill hundreds of thousands, or even millions of people. Were a much larger object to hit earth, the consequences could be far worse. A strike in the Yucatan peninsula (modern-day Mexico) about 66 million years ago, which caused a crater over 110 miles in diameter known as Chicxulub, is credited with wiping out about 70% of all terrestrial species, including most dinosaurs.[155] A similar strike today would likely have similar consequences.

A giant volcanic eruption. Two massive volcanic eruptions between 535 and 540 AD threw so much sulfate aerosol and ash into the atmosphere that summer temperatures in America, Asia and Europe fell by 1.6–2.5°C (2.9–4.5°F), resulting in widespread crop failure, famine and disease.[156] In the past 2,500 years, there have been approximately 238 eruptions of sufficient magnitude to have a significant cooling effect.[157] A more massive eruption, of the sort that might result if the Yellowstone caldera were to blow, would be truly cataclysmic.[158]

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151 Shachtman, Noah. "U.S. Can't Track Tons of Weapons-Grade Uranium, Plutonium." *Wired*. 09/16/2011. Available at: https://www.wired.com/2011/09/uranium-mia/

152 Falk, Pamela. "The Dirty Bomb Threat: Too Dangerous to do Nothing." *Foreign Affairs*. 4/4/2017. Available at: https://www.foreignaffairs.com/articles/2017-04-04/dirty-bomb-threat

153 Schultz, Colin. "The Last Massive Exploding Meteor Hit Earth in 1908, Leveling 800 Square Miles of Forest." *Smithsonian Magazine*. 2/15/2013. Available at: http://www.smithsonianmag.com/smart-news/the-last-massive-exploding-meteor-hit-earth-in-1908-leveling-800-square-miles-of-forest-18916251/#GrDxi8VEebb5HAie.99.

154 Nelson, Steven. *Meteorites and Meteorite Impacts*. University of Tulane. 2014. Available at: http://www.tulane.edu/~sanelson/Natural_Disasters/impacts.htm

155 Schulte, P. et al. "The Chicxulub Asteroid Impact and Mass Extinction at the Cretaceous-Paleogene Boundary." *Science* 327 (5970) . 1214–1218. 2010.

156 Zielinski, Sarah. "Sixth-Century Misery Tied to Not One, But Two, Volcanic Eruptions." *Smithsonian Magazine*. July 8, 2015. Available at: http://www.smithsonianmag.com/science-nature/sixth-century-misery-tied-not-one-two-volcanic-eruptions-180955858/

157 Sigl, M. et al. "Timing and climate forcing of volcanic eruptions for the past 2,500 years." *Nature* 523. 543–549. 30 July 2015. Available at: https://www.nature.com/nature/journal/v523/n7562/full/nature14565.html

158 Mastin, Larry G. Alexa R. Van Eaton and Jacob B. Lowenstern., "Modeling ash fall distribution from a Yellowstone supereruption." *Geochemistry, Geophysics, Geosystems* 15. 3459–3475. 2014

Massive earthquakes and tsunamis. While not global in nature, some earthquakes can cause enormous damage. An earthquake measuring 9.1 on the Richter scale in Sumatra, Indonesia in December 2004 killed nearly a quarter of a million people and caused about $10 billion in damage.[159] The West Coast of the U.S. is on several fault lines. Were the southern San Andreas Fault to experience a significant slippage, resulting in an earthquake of e.g. 7.8 on the Richter scale, much of southern California would be affected, causing an estimated 1,800 deaths and over $200 billion in damage.[160]

A new pandemic virus or drug-resistant bacterium. A bacterium is thought to have been responsible for the “black death” that wiped out approximately one third of Europe’s population.[161] In 1918, the so-called Spanish ‘flu resulted in the death of between 20 and 40 million people.[162] New viruses and bacteria are constantly evolving. In 2003 a new variety of avian ‘flu, known as H5N1 began infecting humans, with a high mortality rate; since then, over 800 people have been infected, more than half of whom have died.[163] If a deadly new virus or antibiotic resistant bacterium were to become transmissible through the inhalation of exhaled air, the consequences could be catastrophic.

Aberrant technologies. Many dystopian science fiction novels and films envisage a future in which artificially intelligent robots replace or turn on humans; others envisage nanotechnologies or biotechnologies that cause catastrophic damage. While these catastrophes are largely hypothetical, they are not impossible.

In principle, all of these—and other—potential catastrophes are worthy candidates for investments in preventative measures. But attempting to eliminate all catastrophic threats is impossible. Potentially, all of humanity’s resources could be consumed by attempts to address any one of these threats but that is neither desirable nor possible.[164] Instead, it makes sense to prioritize preventative measures based on reasonable estimates of the

159 NOAA. *Sumatra, Indonesia Earthquake and Tsunami*. 26 December 2004. Washington, D.C.: National Oceanic and Atmospheric Administration. https://www.ngdc.noaa.gov/hazard/26dec2004.html

160 Jones et al., Lucile M. *The ShakeOut Scenario.* USGS: U.S. Geological Survey Open File Report 2008–1150. California Geological Survey Preliminary Report 25 version 1.0. 2008. Available at: https://pubs.usgs.gov/of/2008/1150/

161 The bacterium was once widely believed to be Yersinia pestis, spread by fleas living on rats, but convincing evidence suggests that another, unknown bacterium was more likely the cause: C J Duncan, S Scott, “What caused the Black Death?” *Postgraduate Medical Journal* 81. (995). 2005. Available at: http://pmj.bmj.com/content/81/955/315.long

162 *The Influenza Pandemic of 1918.* Stanford University website. No date. Available at: https://virus.stanford.edu/uda/

163 The Writing Committee of the World Health Organization (WHO) Consultation on Human Influenza A/H5. “Avian Influenza A (H5N1) Infection in Humans.” *New England Journal of Medicine* 353. 1374–1385. September 29, 2005; Updated numbers here: http://www.who.int/influenza/human_animal_interface/H5N1_cumulative_table_archives/en/

164 In the recent novel *SevenEves*, Neal Stephenson imagines a scenario in which a particular threat—the disintegration of the moon—results in humanity reorienting itself entirely to address that threat; but in that case, the threat itself could not be averted and instead humanity invested its resources in ways to enable some humans to survive off-planet.

benefits of prevention (i.e. the likely consequences of catastrophe multiplied by the probability of that catastrophe occurring) and the costs of such measures.

Unfortunately, while the likelihood of occurrence of some catastrophes can be calculated—based on historical evidence of previous such events—the likelihood of others is unknown. In the former category are war, impacts by near-earth objects, earthquakes, volcanoes, and pandemics. In the latter are threats from aberrant technologies. Abrupt climate changes have occurred in the past and in principle one could assign a probability to a future naturally occurring abrupt climate change. However, it is not possible to assign a probability to human-caused abrupt climate change based on evidence of past such changes, since there have been none.

Pindyck did not ask the "experts" to evaluate the threat of climate change in the context of other potential catastrophes, let alone other possible investments. As such, the responses he received were almost certainly subject to bias due to inappropriate framing (and specifically a lack of embedding).[165]

4.2 ADAPTATION IS KEY

Adaption will be necessary regardless of the extent of any climate change, so policies that reduce barriers to adaptation are likely to form a large part of any solution even to "catastrophic" climate change (see discussion of the potential effects of an 8°C rise in temperature by 2100 on India, above, for example). But imposing taxes or regulation based on a positive social cost of carbon would increase the cost of carbon-based fuels, which would make adaptation more difficult; for example, higher fuel prices would increase the cost of using mechanized agriculture and air conditioning (for further discussion of this, see Part 5 on regulatory responses).

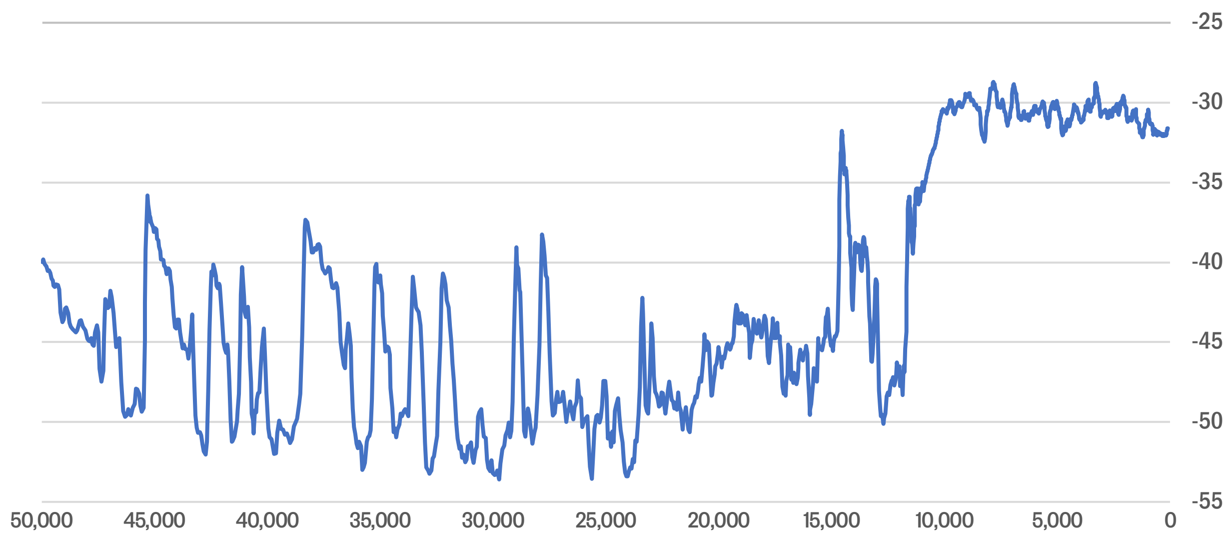
4.3 INTERVENTION MAY (OR MAY NOT) BE NECESSARY OR APPROPRIATE

For more abrupt catastrophic change—of the kind that might result if the permafrost were to thaw rapidly, resulting in a release of methane hydrates that lead to even more rapid

165 Kahneman, Daniel and Jack Knetsch. "Valuing Public Goods: The Purchase of Moral Satisfaction." *Journal of Environmental Economics and Management* 22. 57–70. 1992.

warming,[166] or if the thermohaline current were to shut down, leading to much colder conditions in Northern Europe[167]—more aggressive intervention might be necessary. But the circumstances under which abrupt climate change occurs are not well known, so it is possible that such change could occur with or without changes caused by human emissions of greenhouse gases. Indeed, it is possible that human emissions of greenhouse gases are delaying abrupt cooling.[168] Ice core records from central Greenland show that temperatures have fluctuated dramatically over the past 50,000 years (Figure 21) and while generally stable for the past 10,000 years (Figure 22, blue line), have been declining since their maximum about 8,000 years ago (dotted red line). Longer-term records indicate that such swings are a consistent feature of "deglaciation" (i.e. the end of ice ages).[169]

FIGURE 21: GREENLAND TEMPERATURE (°C) OVER PAST 50,000 YEARS



Source: GISP2 Ice Core Temperature and Accumulation Data. NOAA/NGDC. IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series #2004-013. Boulder, CO: NOAA/NGDC Paleoclimatology Program. Available at: ftp://ftp.ncdc.noaa.gov/pub/data/paleo/icecore/greenland/summit/gisp2/isotopes/gisp2_temp_accum_alley2000.txt

166 While possible, current evidence suggests it is not happening. See: Sumner, Thomas. "Data show no sign of methane boost from thawing permafrost; Carbon dioxide levels rising, though, in response to warming around Alaska's North Slope." *Science News.* December 19, 2016. Available at: https://www.sciencenews.org/article/data-show-no-sign-methane-boost-thawing-permafrost

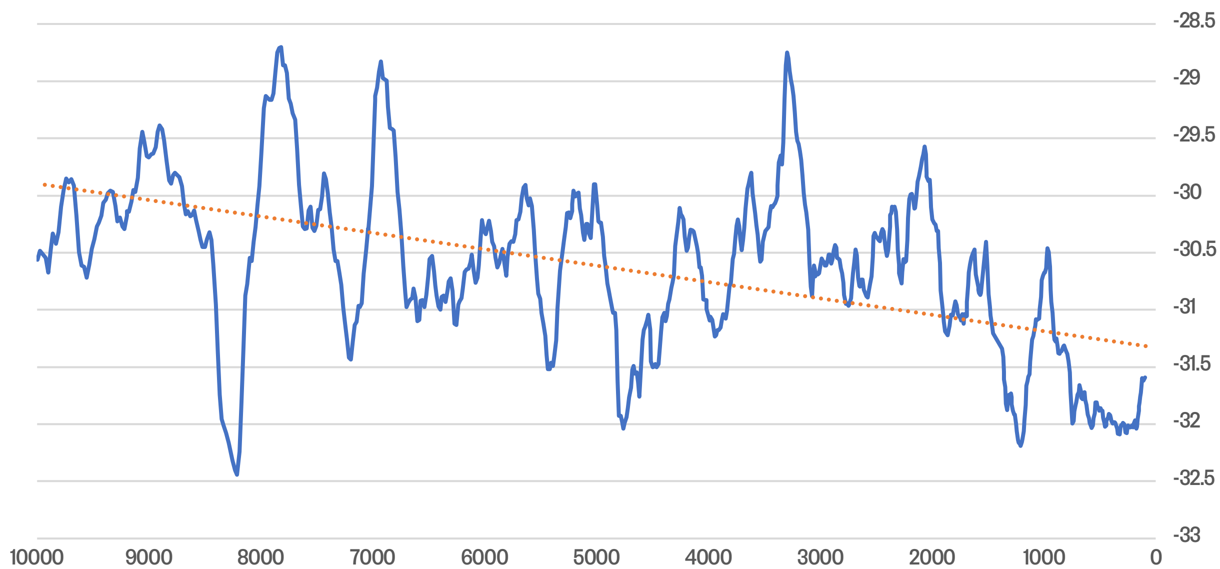
167 This is theoretically possible (see: Marotzke, Jochem. "Abrupt climate change and thermohaline circulation: Mechanisms and predictability." *Proceedings of the National Academy of Sciences* 97(4). 1347–1350. 2000. Available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC34301/) but unlikely (see: Osborn, Tim and Thomas Kleinen. "The thermohaline circulation." Climatic Research Unit Information Sheet no. 7. University of East Anglia: Climate Research Unit. No date. Available at: http://www.cru.uea.ac.uk/documents/421974/1295957/Info+sheet+%237.pdf/320eba6e-d384-497d-b4fc-2d2c187f805e).

168 For example: Ganopolski, A., R. Winkelmann and H. J. Schellnhuber. "Critical insolation–CO_2 relation for diagnosing past and future glacial inception." *Nature* 529. 200–203. January 14, 2016. Available at: http://www.nature.com/nature/journal/v529/n7585/full/nature16494.html. However, in that model, cooling is not expected to occur for 50,000 years, even without human intervention.

169 Barker et al. "800,000 Years of Abrupt Climate Variability." *Science* 334. 347–351. 2011.

The utility of a social cost of carbon is to induce, through taxes or regulation, marginal reductions in emissions of greenhouse gases (or, in the case of a negative social cost of carbon, increases in such emissions). Since the probability of catastrophic climate change cannot be known, the effect of any marginal reduction or increase in GHG emissions on that probability cannot be known. As such, the possibility of catastrophic climate change cannot be used as a means of establishing a social cost of carbon.

FIGURE 22: GREENLAND TEMPERATURE (°C) OVER PAST 10,000 YEARS



Source: GISP2 Ice Core Temperature and Accumulation Data. NOAA/NGDC. *IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series #2004-013*. Boulder, CO: NOAA/NGDC Paleoclimatology Program. Available at: ftp://ftp.ncdc.noaa.gov/pub/data/paleo/icecore/greenland/summit/gisp2/isotopes/gisp2_temp_accum_alley2000.txt

When "experts" assign numbers to the SCC in this way, they are likely simply expressing their own prejudices regarding what they fear, which in turn is affected by current dominant narratives regarding climate change. For example, when Iain Martin of the Grantham Institute for Climate Research and Robert Pindyck sought to evaluate the merits of investing in reducing various potential catastrophes, they assumed that the possibility of climate catastrophe occurring in the next 100 years is 20%.[170] This inevitably resulted in a bias toward action that would reduce the threat of catastrophic climate change. But the

[170] Martin, Ian W. R. and Robert S. Pindyck. "Averting Catastrophes: The Strange Economics of Scylla and Charybdis." *American Economic Review* 105 (10). 2947–2985. 2015.

probability itself (20%) was based on assumptions made by Harvard economist Martin Wetizman, which in turn were essentially plucked out of thin air.[171]

While the probability of abrupt human-induced climate change in the next 100 years cannot be known, it seems unlikely to be anywhere close to 20%, even if equilibrium climate sensitivity is relatively high. This is because the *rate* of warming is proportional to climate sensitivity, so at higher rates of climate sensitivity, the time to equilibrium is longer.[172] As Gerard Roe and Yoram Bauman point out:

> *Economic models that include a climate component, and particularly those that focus on the tails of the probability distributions, should properly represent the physics of this slow response to high climate sensitivity, including the correlated uncertainty between present forcing and climate sensitivity, and the global energetics of the present climate state.* ***If climate sensitivity in fact proves to be high, these considerations prevent the high temperatures in the fat tail from being reached for many centuries.***[173] (Emphasis added.)

Given the uncertainty associated with abrupt climate change and the very slow response of the climate to changes in GHG concentrations (which make attempted adjustments to GHG concentrations extremely inefficient levers of climate), a better approach to address the threat may be "geoengineering"; i.e. intentionally altering the climate. For example, if the threat is abrupt global warming, then releasing massive amounts of sulfate aerosols might help cool the planet and forestall catastrophe.[174] If the threat is abrupt global cooling, then spraying the arctic black to reduce the albedo effect might help warm the planet.[175] But—and this cannot be stressed more strongly—until the actual threat is better characterized, it would be very unwise to do anything other than undertake further research on such possible interventions.

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171 Weitzman, Martin L. "On Modeling and Interpreting the Economics of Catastrophic Climate Change." *Review of Economics and Statistics* 91 (1). 1–19. 2009; "Fat-Tailed Uncertainty and the Economics of Catastrophic Climate Change." *Review of Environmental Economics and Policy* 5 (2). 275–92. 2011.

172 This is a consequence of the inertia of the climate system.

173 Roe, Gerard H. and Yoram Bauman. "Climate Sensitivity: Should the climate tail wag the policy dog?" *Climatic Change* 117. 647–662. 2012.

174 Rasch, Philip J., Simone Tilmes, Richard P Turco, Alan Robock, Luke Oman, Chih-Chieh (Jack) Chen, Georgiy L Stenchikov and Rolando R Garcia. "An overview of geoengineering of climate using stratospheric sulphate aerosols." *Philosophical Transactions of the Royal Society A* 366. 4007–4037. 2008. Available at: http://rsta.royalsocietypublishing.org/content/roypta/366/1882/4007.full.pdf

175 Such an idea was proposed by Jon von Neumann in the 1950s (see: MacRae, Norman. *John von Neumann*. New York: Pantheon, 1992, at p. 368.)

PART 5

THE SOCIAL COST OF CARBON AND REGULATORY REFORM

The IWG's SCC was developed under Executive Order 12866, which requires regulatory agencies to consider the costs and benefits of regulations they are promulgating—and seek the option that maximizes net benefits to society:[176]

> *In deciding whether and how to regulate, agencies should assess all costs and benefits of available regulatory alternatives, including the alternative of not regulating. ... Further, in choosing among alternative regulatory approaches, agencies should select those approaches that maximize net benefits (including potential economic, environmental, public health and safety, and other advantages; distributive impacts; and equity), unless a statute requires another regulatory approach.*

Unfortunately, in applying EO 12866 U.S. federal agencies have not always sought impartially to identify regulations that maximize net benefits to society. This has perhaps particularly been the case when it comes to regulations seeking to address climate change.

[176] Executive Order 12688. Federal Register 58 (190). October 4, 1993. Available at: https://www.reginfo.gov/public/jsp/Utilities/EO_12866.pdf

Part of the problem has been the narrow framework within which policies and regulations related to climate change have been developed. Specifically, there has been a presumption that the only policy tool to address climate change is restrictions on GHG emissions. But such restrictions would have potentially huge costs. Using a clone of the DOE's National Energy Modelling System, Kevin Dayaratna, Nicolas Loris and David Kreutzer of the Heritage Foundation estimated the effects of applying a tax on carbon dioxide emissions based on the IWG's SCC, starting at $36/ton of CO_2.[177] They found that by 2035, such a tax in the U.S. would result in:

- An overall average shortfall of nearly 400,000 jobs;
- An average manufacturing shortfall of over 200,000 jobs;
- A total income loss of more than $20,000 for a family of four;
- An aggregate gross domestic product (GDP) loss of over $2.5 trillion; and
- Increases in household electricity expenditures between 13% and 20%.[178]

Moreover, a carbon tax would likely impose far fewer costs than regulations directed at reducing emissions from particular industries or products (which is the primary mechanism currently adopted in U.S. legislation and by U.S. regulators). For example, the cost of reducing a ton of carbon emissions though corporate average fuel economy standards is three to four times the cost of achieving the same reduction through a gas tax.[179] As such, these estimates are likely low compared with the actual costs imposed by more industry- and product-specific regulations.

On the basis of the foregoing analysis, it seems clear that mandatory emissions reductions are not justified and the SCC to be applied by regulatory agencies should be $0. Were such a rate applied, regulations predicated on a positive SCC should be reconsidered. While these regulations often also have purported "co-benefits" of significant magnitude (such as reduced emissions of particulates), those co-benefits could almost certainly be achieved at much lower cost through alternative means. As such, when evaluating these regulations, agencies should compare their cost to alternate regulations that specifically address the co-benefit elements.

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177 Dayaratna, Kevin, Nicolas Loris and David Kreutzer. *Consequences of Paris Protocol: Devastating Economic Costs, Essentially Zero Environmental Benefits.* Washington, D.C.: Heritage Foundation. Backgrounder No. 3080. April 2016. Available at: http://thf-reports.s3.amazonaws.com/2016/BG3080.pdf

178 Ibid.

179 Jacobsen, Mark R., Christopher R. Knittel, James M. Sallee, and Arthur A. van Benthem. *Sufficient Statistics for Imperfect Externality Correcting Policies.* Manuscript: University of California at Berkeley, 2016. Available at: http://www.colorado.edu/econ/seminars/SeminarArchive/2016-17/Jacobsen.pdf

Meanwhile, the potential role of adaptation has rarely if ever been considered. As a result, the universe of "alternate regulatory approaches" has been mis-specified. Governments currently impose numerous regulatory and other restrictions on the development of lower-carbon forms of energy. These restrictions, which will be examined in a forthcoming policy brief, drive up the cost of energy and inhibit economic development, often without commensurate economic or environmental benefits.

PART 6

CONCLUSION

For nearly 40 years, economists have sought to analyze the costs and benefits of human emissions of greenhouse gases.[180] While their efforts have offered some useful insights into the nature of the problems associated with such calculations, they have not generated estimates of the social cost of carbon that could reliably be used to justify interventions such as regulations or taxes on emissions. Indeed, as this paper demonstrates, the most appropriate conclusion is that such regulations and taxes are not currently justified.

As such, existing federal regulations predicated on a positive SCC should be re-evaluated, with the appropriate comparator being regulations that specifically address any co-benefits identified. Going forward, a more fruitful approach to addressing the problem of climate change would address barriers to adaptation, especially those created by government, such as regulations, taxes and subsidies.

[180] For a review of the history, see: Julian Morris. *Assessing the Social Costs and Benefits of Regulating Carbon Emissions*. Los Angeles: Reason Foundation, August 2015. Available at: http://reason.org/files/social_costs_of_regulating_carbon.pdf

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