BEFORE THE OFFICE OF ADMINISTRATIVE HEARINGS
FOR THE MINNESOTA PUBLIC UTILITIES COMMISSION
STATE OF MINNESOTA

In the Matter of the Further Investigation in to
Environmental and Socioeconomic Costs
Under Minnesota Statute 216B.2422, Subdivision 3

OAH Docket No. 80-2500-31888
MPUC Docket No. E-999-CI-14-643

Direct Testimony and Exhibits of

Professor Roy Spencer

June 1, 2015

PROFESSOR ROY SPENCER

OAH 80-2500-31888

MPUC E-999/CI-14-643

TABLE OF CONTENTS

I. INTRODUCTION

Q. Please state your name, address, and occupation.

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I have been a Principal Research Scientist at the University of Alabama in Huntsville since 2001, and prior to that I was a Senior Scientist for Climate Studies at NASA's Marshall Space Flight Center (1997-2001).

Q. Please describe your educational background and professional experience.

A. I have a Ph.D in Meteorology, and twenty-five years of experience monitoring global temperatures with Earth orbiting satellites, nine years as the Science Team Leader for the AMSR-E instrument flying on NASA's Aqua satellite, and seven years researching climate sensitivity with satellite measurements of the radiative budget of the Earth and deep ocean temperatures using a 1D climate model. My CV, including a list of my peer-reviewed publications, is attached as Spencer Exhibit 1.

II. OVERVIEW OF OPINIONS

Q. What are the purposes of your testimony in this proceeding and will you summarize your principal conclusions and recommendations?

A. My testimony will address the validity of climate model projections of global and regional temperatures used in the determination of the social cost of carbon (SCC). Three independent classes of temperature observations show that the climate models used by governments for policy guidance have warmed 2 to 3 times faster than the real climate system over the last 35 to 55 years, which is the period of greatest greenhouse gas emissions and atmospheric greenhouse gas concentrations. Recent research suggests that the climate models are too sensitive to these emissions, and that increasing greenhouse gases do not cause as much warming and associated climate change as is commonly believed. These results suggest that any SCC estimates based upon such models will be biased high.

Q. Have you prepared a report that contains your opinions?

A. Yes, details of my findings are attached as Spencer Exhibit 2. A brief introduction of concepts and a summary of my findings follow, below.

Q. Are you familiar with the history of the IPCC climate change models and predictions?

A. Yes, I am familiar with the IPCC climate models and their predictions.

III. <u>TEMPERATURE DATA</u>

Q. **How do IPCC model projections compare to observed temperature globally?**

A. The models, on average, produce surface warming rates at least twice those observed since the satellite record began in 1979. Models, on average, produce deep-atmosphere (tropospheric) warming rates about 2-3 times those observed over the same period. If we restrict the period to just the last 18 years, the models have totally failed to explain the hiatus. These are major discrepancies which have serious implications for using climate models to project future impacts on society.

Q. Do you have an opinion as to why the IPCC model projections differ from observed temperature?

A. I believe that the models have been programmed to be too sensitive, that is, they produce too much warming for a given "forcing", say, increasing atmospheric carbon dioxide. This overestimation of climate sensitivity is due to the poor state of knowledge of feedbacks in the climate system.

Q. How does the hiatus in warming reflect on the IPCC models?

A. The hiatus was not predicted by the models or by the IPCC reports, and it remains largely unexplained. No matter the cause, the hiatus invalidates the current model state-of-the-art for the purpose of climate change prediction, and for social cost of carbon estimates which rely upon those predictions.

Q. How is global temperature measured and monitored, and what are the methods?

A. Global temperatures over the time scales of interest in my testimony are measured with (1) surface-based thermometers, (2) weather balloons, also called radiosondes, and (3) satellite-borne passive microwave radiometers.

Q. Are there any important differences between these data collection methods?

A. Yes, *surface thermometers* are capable of directly measuring temperatures near the surface of the Earth, but tend to have long-term spurious warming effects over land from urbanization effects. Only the U.S. and Europe are well sampled by thermometers, while most other countries have fair to poor coverage. Oceans are not well sampled with surface thermometers, especially the southern hemisphere oceans where there is little ship traffic. *Weather balloons* and *satellites* measure deep-layer atmospheric temperatures, with scattered weather balloon stations restricted to land and island locations, while the satellites provide nearly complete global coverage (except for small regions at the poles).

Q. In light of these differences, what do you believe is the most reliable temperature measurement?

A. I believe that the satellites provide the most detailed and reliable record of global temperature variations since they were first launched in late 1978.

Q. Are recently observed temperature data relevant to determining the social cost of carbon?

A. Yes, global temperature trends measured over recent decades are directly relevant to calculations of the social cost of carbon, which will be roughly proportional to the magnitude of warming trends. As such, there would be no social cost of carbon if there were no warming trend.

Q. How do climate change models use temperature data?

A. Climate models use temperature data to test the models' behavior and predictions, that is, to test whether the models are performing realistically. When large discrepancies between models and temperature observations are discovered, then the models must be modified to behave more realistically. Importantly, while all climate models mimic the *average* state of the climate system reasonably well, they so far have little skill in predicting what is needed for SCC estimates: climate *change*.

Q. To what extent have global temperatures increased during the last 18 years?

A. Contrary to almost all expectations, there has been no statistically significant warming in either the RSS or UAH satellite data for the last 18 years, nor in the weather balloon data, leading to the well-know "hiatus" in global warming. There has been relatively weak warming in the surface thermometer data over the same period of time, although its magnitude and statistical significance is questionable.

Q. Why do you believe there has been a lack of warming since 1997?

A. I believe the lack of warming is due some combination of low climate sensitivity and a natural cooling effect, such as stronger La Nina event in recent years.

IV. CLIMATE SENSITIVITY AND PREDICTIONS OF FUTURE IMPACTS

Q. What is climate sensitivity?

A. Climate sensitivity is usually defined as the amount of global-average warming that would eventually result from a doubling of atmospheric carbon dioxide concentration relative to pre-industrial times. So, it is the magnitude of the temperature change resulting from a known level of “forcing”. The term “forcing” implies an energy imbalance, such as would occur if a pot of water on the stove had the heat turned up.

Q. How does climate sensitivity factor into models that try to predict future damages from anthropogenic carbon dioxide and other greenhouse gas emissions?

A. Climate sensitivity is the most important variable that determines the level of global warming and associated predicted climate change in response to carbon dioxide emissions, or any other climate forcing. If the real climate system is relatively insensitive, then future damages from carbon dioxide emissions will be small.

Q. How are climate sensitivity values determined?

A. Climate sensitivity is extremely difficult to determine, and its estimates are based upon past climate change events, specifically, how large of a temperature change they entailed, and the magnitude of the forcing that was presumed to cause them. Unfortunately, even if we knew accurately how much *temperature change* has occurred in the past (which we don't), in order to calculate sensitivity we also must know accurately the magnitude of the *forcing* that caused it, a much more uncertain task.

Q. Has any particular climate sensitivity value been proven?

A. No one has been able to prove a value for climate sensitivity, partly because of the uncertainties in measurements of past temperature change events and knowledge of the magnitude of the forcing that caused those events.

Q. Is there general agreement about climate sensitivity, and what does the current IPCC report say about climate sensitivity?

A. There is very little agreement about equilibrium climate sensitivity (ECS), although most IPCC researchers believe it falls somewhere in the (fairly wide) range of 1.5 to 4.5 deg. C for a doubling of atmospheric CO2, despite recent global temperature trends which suggest lower sensitivity. Specifically, the latest (AR5) IPCC report states that there is "medium confidence that the ECS is likely between 1.5°C and 4.5°C".

Q. What does the latest, peer-reviewed research suggest for climate sensitivity?

A. An increasing number of peer-reviewed studies are suggesting much lower climate sensitivity than the IPCC and its models assume, possibly as low as 1 deg. C or less for a doubling of atmospheric CO2.

Q. What are feedbacks and what is their impact on climate sensitivity?

A. Climate sensitivity completely depends upon feedbacks, which quantify how things like clouds, water vapor, etc. change with warming to either reduce or amplify warming caused by a forcing. Climate sensitivity is difficult to determine because feedbacks are difficult to determine.

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Exhibit 1

to

Direct Testimony of

Professor Roy Spencer

June 1, 2015

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RESEARCH AREAS:

Satellite information retrieval techniques, passive microwave remote sensing, satellite precipitation retrieval, global temperature monitoring, space sensor definition, satellite meteorology, climate feedbacks.

EDUCATION:

1981: Ph.D.	Meteorology, U. Wisconsin - Madison
1979: M.S.	Meteorology, U. Wisconsin - Madison
1978: B.S.	Atmospheric and Oceanic Science, U. Michigan - Ann Arbor

PROFESSIONAL EXPERIENCE:

8/01 - present:	Principal Research Scientist The University of Alabama in Huntsville
5/97 – 8/01:	Senior Scientist for Climate Studies NASA/ Marshall Space Flight Center
4/87 - 5/97:	Space Scientist NASA/Marshall Space Flight Center
10/84 - 4/87:	Visiting Scientist USRA NASA/Marshall Space Flight Center
7/83 - 10/84:	Assistant Scientist Space Science and Engineering Center, Madison, Wisconsin
12/81 - 7/83:	Research Associate Space Science and Engineering Center, Madison, Wisconsin

SPECIAL ASSIGNMENTS:

Expert Witness, Senate Environment and Public Works Committee, (7/22/2008)
Expert Witness, U.S. House Committee on Oversight and Government Reform, (3/19/07).
Expert Witness, U.S. House Resources Subcommittee on Energy and Mineral Resources,(2/4/04).
Expert Witness, U.S. House Subcommittee on Energy and Environment (10/7/97)
U.S. Science Team Leader, Advanced Microwave Scanning Radiometer-E, 1996-present
Principal Investigator, a Conically-Scanning Two-look Airborne Radiometer for ocean wind vector retrieval, 1995-present.
U.S. Science Team Leader, Multichannel Microwave Imaging Radiometer Team, 1992-1996.
Member, TOVS Pathfinder Working Group, 1991-1994.
Member, NASA HQ Earth Science and Applications Advisory Subcommittee, 1990-1992.
Expert Witness, U.S. Senate Committee on Commerce, Science, and Transportation, 1990.
Principal Investigator, High Resolution Microwave Spectrometer Sounder for the Polar Platform, 1988-1990.
Principal Investigator, an Advanced Microwave Precipitation Radiometer for rainfall monitoring. 1987-present.
Principal Investigator, Global Precipitation Studies with the Nimbus-7 SMMR and DMSP SSM/I, 1984-present.
Principal Investigator, Space Shuttle Microwave Precipitation Radiometer, 1985.
Member, Japanese Marine Observation Satellite (MOS-1) Validation Team, 1978-1990.
Chairman, Hydrology Subgroup, Earth System Science Geostationary Platform Committee, 1978-1990.

Executive Committee Member, WetNet - An Earth Science and Applications and Data System Prototype, 1987-1992.

Member, Science Steering Group for the Tropical Rain Measuring Mission (TRMM), 1986-1989

Member, TRMM Space Station Accommodations Analysis Study Team, 1987-1991.

Member, Earth System Science Committee (ESSC) Subcommittee on Precipitation and Winds, 1986.

Technical Advisor, World Meteorological Organization Global Precipitation Climatology Project, 1986-1992.

REFEREED JOURNAL ARTICLES/ BOOK CONTRIBUTIONS (lead author)

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AWARDS:

1996: AMS Special Award "for developing a global, precise record of earth's temperature from operational polar-orbiting satellites, fundamentally advancing our ability to monitor climate."

1991: NASA Exceptional Scientific Achievement Medal
1990: Alabama House of Representatives Resolution #624
1989: MSFC Center Director’s Commendation

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- NASA Advanced Microwave Scanning Radiometer-E Science Team Leader	(NNG04HZ31C)
- NASA Discover Program	
- NOAA Microwave Temperature Datasets	(EA133E-04-SE-0371)
- DOE Utilization of Satellite Data for Climate Change Analysis	(DE-FG02-04ER63841)
- DOT Program for Monitoring and Assessing Climate Variability & Change	(DTFH61-99-X-00040)

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Exhibit 2

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June 1, 2015

How well do climate models explain recent warming?

Future climate change scenarios relied upon for SCC calculations ultimately depend upon computerized climate models, which produce rates of warming that vary with each model's equilibrium climate sensitivity (ECS). Climate-based calculations by governments tend to roughly follow the average of all projections produced by the variety of models tracked by the United Nations Intergovernmental Panel on Climate Change (IPCC), the latest report of the IPCC being the 5th Assessment Report[1] (AR5) in 2013.

Of critical importance to the question of just how large the SCC should be, then, is how well the climate models' projections of global (and regional) temperatures have fared when compared to observations. The three most-cited methods for observing global- and regional-average temperature changes are (1) surface-based thermometers, (2) satellite observations of deep-layer atmospheric temperatures, and (3) upper-air weather balloons (radiosondes).

While the models are truly global in extent, accurate comparisons between them and observations are somewhat hindered by less than complete global coverage by the observational networks: the satellites provide nearly complete global coverage, the surface thermometers provide less complete coverage (densest coverage in the U.S.), and weather balloons provide spotty coverage at best. While the weather balloons provide the least-dense coverage, they are immune to the urbanization effects[2] which are widely believed to cause spurious long-term warming in the surface thermometer record.

It has now been well established that recent global temperature trends from the observational networks are well below the IPCC average climate model projections upon which the SCC is based.

This is true of all three types of observational networks. The discrepancy is generally a factor of 2 to 3, that is, models tend to produce at least twice as much warming as the observations over the last several decades, which is the period during which human emissions and atmospheric concentrations have been the greatest.

The global average surface temperature comparison between a 90-model average[3] and observations is shown in Fig. 1, using the most recent thermometer dataset (HadCRUT4) used by the IPCC in their assessments. Note that the models have been warming at about twice the rate as the observations since the late 1990s.

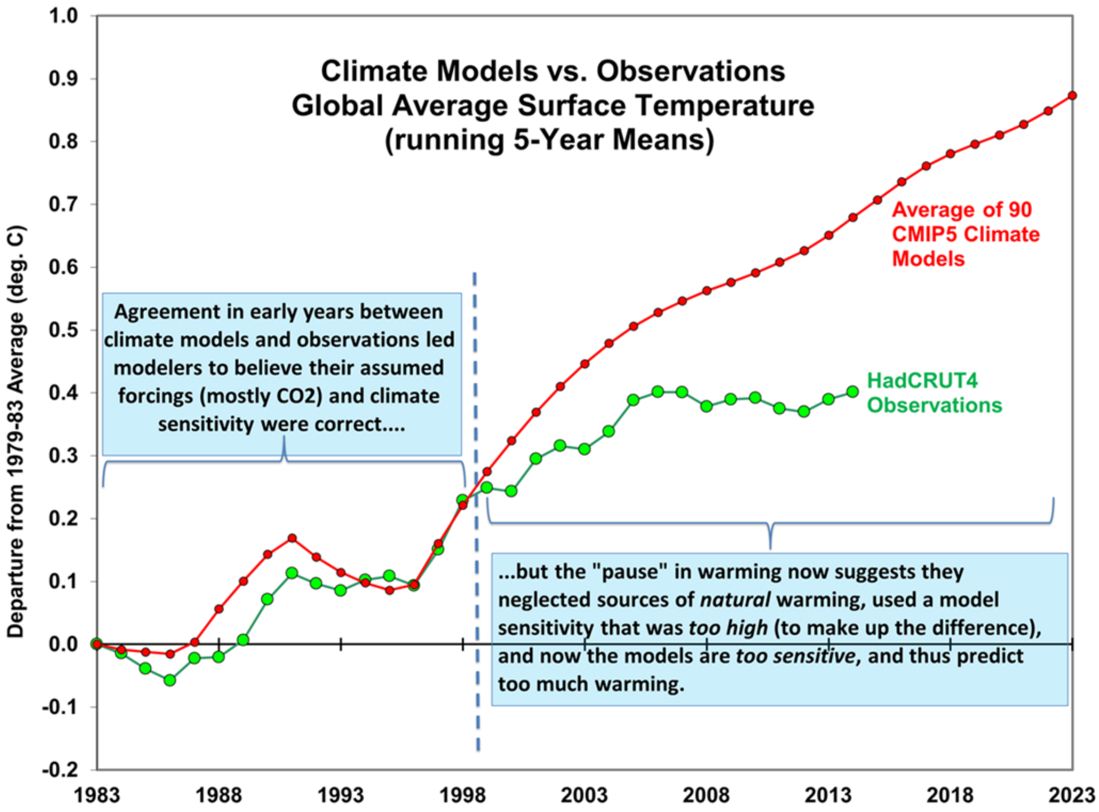

Fig. 1. Running 5-year mean global average temperature changes since 1979-1983, in models versus observations.

The discrepancy between models and observations is also evident in regional comparisons, for example the U.S. Midwest corn belt temperatures[4] (Fig. 2), which traditionally includes 12 states: Minnesota, the Dakotas, Wisconsin, Nebraska, Iowa, Illinois, Indiana, Ohio, Michigan, Kansas, and Missouri. In this case, summertime (June-July-August) warming since 1960 has been about 2.4 times as strong in the models as in the observations. While warming is of the greatest concern in the U.S. Midwest during the summer, due to excessive heat effects in cities and on agriculture, model projections of that warming over the last 50 years has been exaggerated.

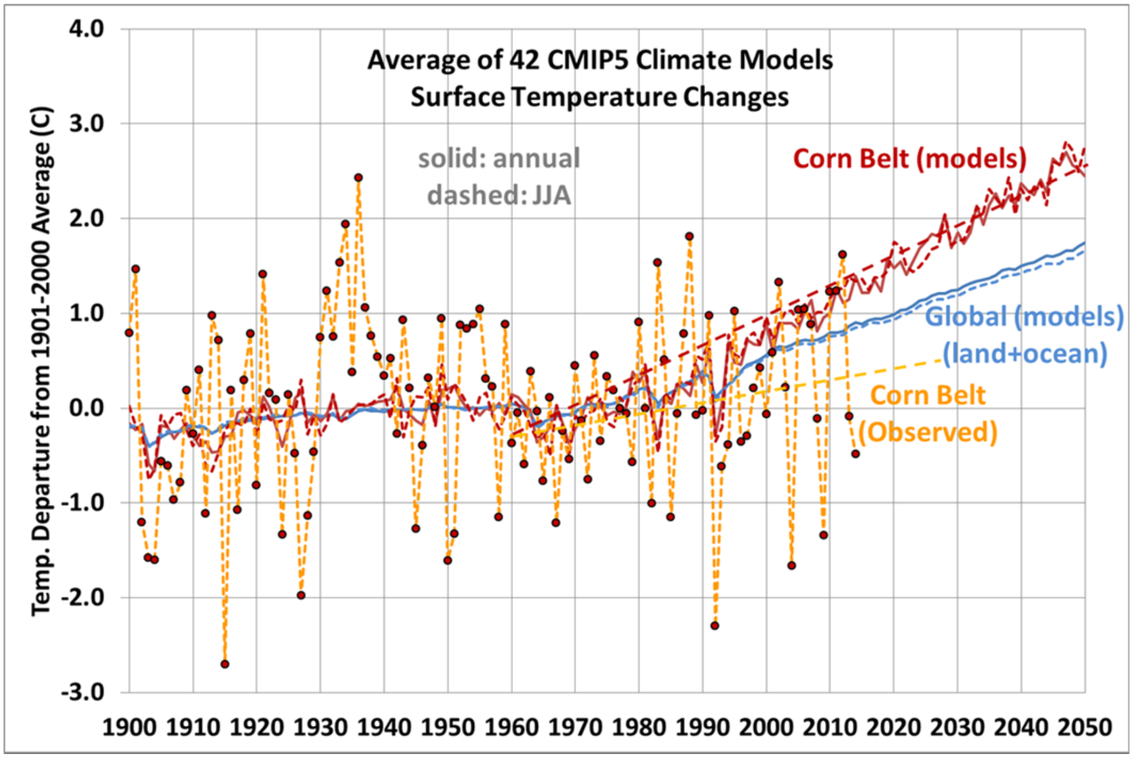

Fig. 2. Global average surface temperature variations in the U.S. Corn Belt as projected by models (red) and as observed with thermometers (orange). The corresponding global averages (blue) are also shown to illustrate how land areas like the Corn Belt are expected to warm faster than the oceans.

When we change from surface temperatures to deep-layer atmospheric temperatures, the discrepancy between models and observations becomes even larger. For the mid-troposphere, Fig. 3 shows that the models have warmed at least 3 times as fast as the satellites[5,6] or weather balloons have measured since satellite monitoring began in 1979.

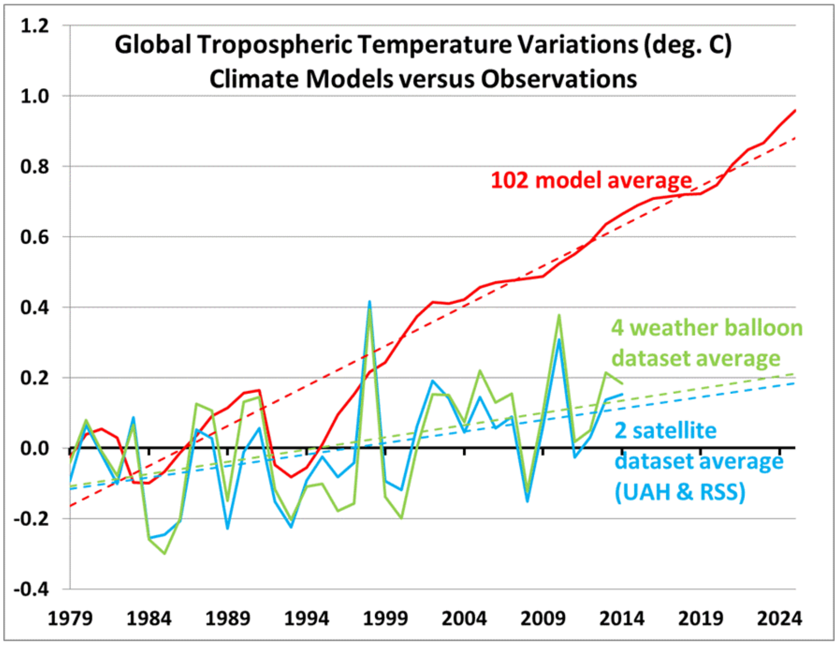

Fig. 3. Yearly global average temperature during 1979-2014 of the deep troposphere (approximately from the surface to 10 km in altitude) as measured by satellites and weather balloons, versus the average of 102 climate models tracked by the IPCC.

These large discrepancies between the models and observations suggest a fatal flaw in the current climate model state-of-the-art. For models to have utility, they must be able to accurately predict some outcome, which they haven't. At best, they have produced warming in the last 50 years, and there has been some level of warming observed in the last 50 years, but such a trivial coincidence in an ever-changing climate system could have just as easily been predicted with the flip of a coin. It's when we examine the details of the predictions that we find failure: even NOAA has admitted[7] that "The simulations rule out (at the 95% level) zero trends for intervals of 15 yr or more", and yet we now stand at 18 years without warming in the real climate system.

What is the Hiatus in Warming?

Most of the disagreement between models and observations can be traced to a lack of warming after about 1997. This "hiatus" in warming does not exist in the climate models, and suggests either (1) a natural cooling mechanism is canceling anthropogenic warming, or (2) the real climate system is less sensitive to greenhouse gas emissions than the models are, or both. No matter the cause, the inability of the models to reproduce the hiatus raises serious concerns about the reliance of SCC calculations on climate model projections.

Why Are Models Producing Exaggerated Warming?

There are a number of theories regarding why the models have produced too much warming. The IPCC continues to stand by the models, claiming they will eventually be proved correct, although their most recent report (AR5) suggests they are starting to back off of their warming predictions somewhat.

But there are now a number of published papers supporting the explanation that the climate system sensitivity (ECS) is not as high as assumed in the models, as Richard Lindzen is presenting in his testimony. In other words, that adding CO2 to the atmosphere simply does not cause as much climate change as is popularly believed by most climate researchers.

Our own paper[8] on the subject took into account deep-ocean warming measurements and the observed natural climate forcing caused by El Nino and La Nina to arrive at an ECS of 1.3 C for a doubling of CO2, which is about 50% of the IPCC central estimate for ECS.

It should be noted that, while most of the physical processes contained in climate models are indeed well understood, the feedback processes controlling ECS are highly uncertain…for example whether cloud changes will amplify (the IPCC position) or mitigate (my position) global warming and associated climate change. So, while the *average effect* of clouds on the average climate system is reasonably well understood, the *effect of clouds on climate change* is only crudely represented in models, partly because our understanding of cloud feedbacks is so poor.

There are many reasons why feedbacks (and thus climate sensitivity) are difficult to determine. First, feedbacks (a response of the system) are in general indistinguishable from forcings. While net feedbacks oppose forcings, what we measure is the sum of the two in unknown proportions. Secondly, there are many kinds of variations going on simultaneously in the climate system -- a volcano here, an El Nino there – each with its own unknown mixture of forcings and feedbacks. Third, feedbacks due to different forcings are assumed to be the same…but they might not be. The sensitivity to increasing CO2 might be different from the sensitivity to a change in the sun's brightness…we simply don't know. Finally, the temperature response to a forcing takes time to develop…from months over land to many years over the ocean. This further complicates connecting a temperature response to some previous forcing. These are some of the reasons why determining feedbacks, and thus climate sensitivity, is so difficult.

Continuing with the example of clouds, we have demonstrated [9,10] both theoretically and observationally that the common belief that warming causes clouds to dissipate, leading to even more warming (thus implying positive cloud feedback) might be the result of confusion regarding cause versus effect, that is, forcing versus feedback. There are natural decreases in global cloudiness which lead to warming, giving the illusion of positive cloud feedback even when negative cloud feedback exists. This type of misunderstanding regarding the sign of cloud feedbacks might have been programmed into climate models, which then produce exaggerated warming in response to increasing atmospheric carbon dioxide. This is only one example of the many potential pitfalls in modeling the response of the climate system to increasing carbon dioxide.

What is the Bottom Line for Basing Current SCC Estimates on Climate Models?

Reliance of SCC estimates on climate models which have demonstrable biases in their warming estimates is difficult to justify. The utility of climate models for climate prediction must be based upon the models' track record of success, that is, providing predictions with some demonstrable level of accuracy. It is not sufficient for the models to reasonably replicate the *average* climate – they must provide useful predictions of climate *change*. Since the models continue to produce warming rates at least twice that observed, it calls into the question the quantitative basis for using them as input to current Social Cost of Carbon estimates.

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BEFORE THE OFFICE OF ADMINISTRATIVE HEARINGS
FOR THE MINNESOTA PUBLIC UTILITIES COMMISSION
STATE OF MINNESOTA

In the Matter of the Further Investigation in to
Environmental and Socioeconomic Costs
Under Minnesota Statute 216B.2422, Subdivision 3

OAH Docket No. 80-2500-31888

MPUC Docket No. E-999-CI-14-643

Direct Testimony and Exhibits of

Professor Richard Lindzen

June 1, 2015

PROFESSOR RICHARD LINDZEN

OAH 80-2500-31888

MPUC E-999/CI-14-643

TABLE OF CONTENTS

I. INTRODUCTION

Q. Please state your name, address, and occupation.

A. My name is Richard S. Lindzen. My business address is Bldg. 54, Room 1724, M.I.T., Cambridge, Massachusetts 02139. I am a meteorologist and the Alfred P. Sloan Professor of Meteorology in the Department of Earth, Atmospheric and Planetary Sciences at the Massachusetts Institute of Technology.

Q. Please describe your educational background and professional experience.

A. I obtained three degrees from Harvard University between 1960 and 1964, culminating with a Ph.D. in Applied Mathematics in 1964. After I obtained my doctorate, I served in various meteorological research positions, including as a NATO post-doctoral fellow at the University of Oslo and as a research scientist at the National Center for Atmospheric Research. For almost 50 years, I have taught meteorology at MIT, Harvard, the University of Chicago, and other distinguished universities. My full professional history is detailed in my CV, which is attached as Lindzen Exhibit 1.

II. OVERVIEW OF OPINIONS

Q. What are the purposes of your testimony in this proceeding?

A. The purposes of my testimony in this proceeding are to testify about scientific bases for concerns about increasing levels of CO2 and to assist in the proper calculation of the “social cost of carbon” (SCC).

Q. Could you summarize your opinions?

A. The global temperature predictive models relied upon by the Intergovernmental Panel on Climate Change (IPCC) are flawed, as they, among numerous other problems, overestimate increases in global temperatures. Recent, observational data proves that the IPCC models overestimate global temperature increases and overstate any effect of anthropogenic greenhouse gases relative to natural factors. Therefore, the economic damages models that rely on IPCC estimates are also flawed.

- There is no indication that the Earth's climate is "changing" in any manner that is not otherwise naturally-occurring and consistent with climate change patterns that occurred long before the recent concern over anthropogenic emissions.
- The IPCC's estimation of "climate sensitivity," or the increase in temperature that will occur upon a doubling of atmospheric carbon dioxide concentrations, is done incorrectly. The IPCC's conclusions are based on an incomplete and incorrect understanding of the impact of natural phenomena (e.g., clouds, aerosols, and volcanic activity) that are crucial to the determination of sensitivity.
- Recent data and studies show that any increase in temperature upon a doubling of carbon dioxide concentrations will probably result in only mild warming at most, which will be beneficial to the planet and to society as a whole.
- Current economic damages models attempting to determine a "social cost" of carbon are inherently biased high because they rely on IPCC's flawed and overestimated conclusions regarding the

effect of increases of carbon dioxide concentrations on global climate.

Q. Could you summarize your principal conclusions as to the concerns about climate change expressed by the United Nations Intergovernmental Panel on Climate Change (IPCC)?

A. The bases for CO2 concerns are substantially overstated. The last four United Nations Intergovernmental Panel on Climate Change (IPCC) reports have all been summarized with the iconic claim that man-made emissions account for most of the warming since the 1970s. But the warming referred to is small and is not something that can be perceived within the noise of normal climate variability. Moreover, the IPCC claim relies on climate models that suffer from serious flaws. The models do not comport with observational data, and all IPCC models fail to predict the cessation of discernible warming over almost the past 20 years. The models appear to replicate the previous warming only by the fairly arbitrary inclusion of uncertain aerosols (reckoned to be anthropogenic emissions as well) in the models and choosing these to cancel excess warming. However, recent studies reduce the uncertainty associated with aerosols and make it implausible for them to serve as the “fudge factor” that climate modelers have assigned to them. These recent aerosol studies limit climate sensitivity values (the amount by which a doubling of CO2 from preindustrial levels would raise equilibrium global temperatures) extremely unlikely to exceed 2C.

Further, the IPCC’s argument for attributing the warming since the 1970s to anthropogenic causes depended on the assumption that natural variability is small. In fact, natural variability (given the absence of warming over the past 18 years) is at least as large as any anthropogenic contribution. Hence, the IPCC's argument for the attribution of recent warming to anthropogenic factors breaks down. That is to say, we can no longer claim that man's contribution to warming has been identified in the data.

Q. Could you summarize your principal conclusions as to naturally caused climate change versus anthropogenic climate change?

A. Earth's climate is always changing. Although the IPCC and others have pointed to warming since the 1970s, in fact, there was an almost indistinguishable period of warming from presumably non-man-made causes between 1895 and 1946. The two periods (1895-1946 and 1957-2008) are essentially indistinguishable, though the early one is acknowledged by the IPCC to be natural while the other is claimed to be due in large measure to humans. Put simply, there is nothing seemingly unusual or unprecedented about the recent warming episode, and like the earlier episode, it appears to have ended (in the case of the most recent episode, about 18 years ago). Of course, it has long been recognized that Earth has had many warm periods (the Medieval Warm Period, the Holocene Optimum, several interglacial periods, and the Eocene (which was much warmer than the present). Tellingly, climatologists in the past referred to the warm periods as 'optima' since they were associated with thriving life forms. Most plant forms evolved during periods of high CO2 (often ten times present levels).

Q. Could you summarize your principal conclusions as to climate "sensitivity values" and feedback mechanism?

A. On its own (i.e., without the operation of so-called "feedback mechanisms"), a doubling of CO2 is generally claimed to lead to a warming of about 1C. This is generally considered too small to promote great concern. The IPCC's projected climate sensitivity values (between 1.5C and 4.5C) rest on assumed feedback mechanisms that are unproven and speculative. These asserted feedbacks relate to clouds (and water vapor), and, to a much lesser extent, changes in surface properties. However, as the IPCC acknowledges, all the feedbacks depend on unresolved features which have to be parameterized and are highly uncertain. Scientists do not agree on the existence and magnitude of these feedbacks, as the presidents of the National Academy of Sciences in the U.S. and the Royal Society in the U.K. have acknowledged.

In my opinion, the IPCC's estimated sensitivity values are substantially overstated because they depend on feedback effects that have not been shown to exist. For example, studies show that warming leads to reduced cirrus cloud coverage, which acts to counteract the warming (i.e., acts as a negative feedback) by allowing more infrared radiation to escape into outer space. This is known as the "Iris effect."

In my opinion, a climate sensitivity value of 2C or more is highly unlikely. Evidence indicates that climate sensitivity may fall within a range of from about 0.85C to 1.5C. I note that a value of 1.5C is within the IPCC's own projections.

Q. Could you summarize your principal conclusions as to the relative roles of temperature versus fossil fuel emissions in determining increases in atmospheric CO2?

A. Even the connection of fossil fuel emissions to atmospheric CO2 levels is open to question. In the ice core records of the ice ages, it appears that CO2 levels may follow temperature increases, rather than vice versa. Recent studies suggest that only about half of atmospheric CO2 concentrations may be due to fossil fuel emissions. For example, although data from the Oak Ridge National Laboratory shows that CO2 emission rates of increase roughly tripled between 1995 and 2002, the rate of increase in atmospheric CO2 concentrations remained essentially unchanged during that time. It appears that we are currently unable to relate atmospheric CO2 levels to emissions and even less to relate CO2 levels to temperature and still less to regional changes.

In any event, the contribution of U.S. emissions is already less than those of the rapidly developing countries, and any reductions that the US makes (and much less that Minnesota makes) will have an undetectable influence on global mean temperature regardless of what climate sensitivity is and what geochemical model one uses.

Q. Could you summarize your principal conclusions as to the concerns about droughts, flooding, other extreme weather phenomena, and sea ice?

A. Concerns arising from the potential impact of global warming on drought, flooding, storminess, sea ice, and similar issues are largely unproven. There is no evidence that these matters are increasing due to warming (or in most cases increasing at all). Even where trends exist, such as summer Arctic ice cover, the reduction has reversed in the last few years; also, Antarctic sea ice has been increasing throughout the satellite era. Sea level rise has been occurring since the end of the last glaciation. Changes in instrumentation make it impossible to say whether the rate is actually increasing. Warming should actually reduce the incidence of extreme weather.

Q. Could you summarize your principal conclusions as to the costs and benefits of controlling CO2 emissions?

A. Over the past 200 years, there has been modest warming of about 0.8C, and there has been a general improvement in the human condition. Costs of warming are unproven and are generally based on model projections and speculations concerning impacts rather than observed data. In contrast, the benefits of both warming and increased CO2 are clearer. CO2 is a plant fertilizer, and the increasing levels over the past two centuries are significant contributors to increased agricultural productivity. Noteworthy is the fact that levels of CO2 below 150 parts per million by volume would probably end life on the planet – an unusual property for something commonly referred to as a pollutant. Warming also leads to decreased winter mortality. Warming itself, at the levels that might realistically be anticipated (i.e., under 2C for the foreseeable future) is estimated to be net beneficial. The policy risks of limiting the clean burning of fossil fuels are clear and are likely to exceed such risks of climate change as may exist, particularly when the economic and social impacts of higher energy prices are considered.

Q. Have you prepared a report that contains your opinions?

A. Yes. My report is attached as Lindzen Exhibit 2.

Q. Are you familiar with the history of the IPCC climate change models and predictions?

A. Yes. I have been involved with the IPCC models, predictions, and reports for more than 20 years. In 1995, I contributed to the IPCC Second Assessment. In 2001, I was a lead author in a chapter of the IPCC report.

Q. Do you have an opinion regarding their accuracy or their suitability as a basis for regulatory action to reduce greenhouse gas emissions?

A. Yes. Because the models use an inappropriately high climate sensitivity and do not properly address feedbacks, aerosols, and other factors and issues outlined in my report, the IPCC models should not be used to estimate the social cost of carbon. They do not provide accurate or reliable information. Indeed, the IPCC insists that its model results be considered as ‘scenarios’ rather than predictions.

III. CLIMATE SENSITIVITY

Q. What is climate sensitivity?

A. Climate sensitivity is a measure of the change in global equilibrium temperature (i.e., the amount of warming) that would result if CO_2 concentrations doubled from preindustrial levels of approximately 275 ppm.

Q. Has any particular climate sensitivity value been proven?

A. No.

Q. What does the current IPCC report say about climate sensitivity?

A. The IPCC notes that its models display a sensitivity range between 1.5C and 4.5C.

Q. What is the role of feedback mechanisms in determining climate sensitivity?

A. Without feedback mechanisms (primarily the effect of water vapor), a doubling of CO_2 concentrations is generally expected to lead to an increase of 1C. This amount of warming is generally considered too small to be of great concern. Accordingly, the IPCC projections depend heavily on the existence of positive feedback mechanisms, which are speculative and unproven.

Q. What does the latest, peer-reviewed research suggest for climate sensitivity values?

A. Recent research demonstrates that a climate sensitivity value of 2C or more is highly unlikely. Evidence indicates that climate sensitivity may fall within a range from about 0.85C to 1.5C.

Q. What are aerosols and what is their impact on climate sensitivity?

A. Aerosols are minute particles suspended in the atmosphere. Climate modelers have often arbitrarily included the effects of aerosols in their models and used them essentially as a “fudge factor” to “cancel” excess warming and allow their models to more closely match observational data. However, new evidence, including a recent paper (Stevens, 2015), reduces the uncertainty that previously allowed climate modelers to use aerosols to cover up deficiencies in the models. These studies point to low climate sensitivity values which would imply minimal danger or even net benefit from climate change.

IV. TEMPERATURE

Q. What is the Earth's experience with warm periods?

A. Earth has had many warm periods, including the Medieval Warm Period, the Holocene Optimum, several interglacial periods, and other periods. During the Eocene, the Earth was much warmer than it is today. This is no dispute about the existence of natural warming in the thermometric record. Climate always changes.

Q. Have observed temperatures been consistent with IPCC model predictions?

A. No. Figure 9 of my testimony demonstrates that the models have consistently "run hot" or significantly overestimated warming for decades. There has been no warming for at least the last 18 years, which the models cannot explain. Further, the models produce substantially divergent results for the future. The models do not provide a reliable basis for predictions.

V. EXTREME WEATHER, CHANGES IN SEA ICE, AND OTHER PHENOMENA

Q. Are there other indicators of climate change associated with rising CO2 emissions, such as sea level rise, unusual storm activity, or Arctic ice cover losses?

A. No. There is no evidence of increases in hydro-meteorological disasters. Antarctic sea ice has been increasing throughout the satellite era, and summer artic ice cover reduction has reversed in the last few years. Sea level rise has been occurring since the end of the last glaciation. The primary driving force for storm development is the temperature difference between the tropics and the poles, a difference that should be decreasing if there is global warming, which is supposed to be greater at the poles.

BEFORE THE OFFICE OF ADMINISTRATIVE HEARINGS
FOR THE MINNESOTA PUBLIC UTILITIES COMMISSION
STATE OF MINNESOTA

In the Matter of the Further Investigation in to
Environmental and Socioeconomic Costs
Under Minnesota Statute 216B.2422, Subdivision 3

OAH Docket No. 80-2500-31888

MPUC Docket No. E-999-CI-14-643

Exhibit 1

to

Direct Testimony of

Professor Richard Lindzen

June 1, 2015

Curriculum Vitae

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Date of Birth: 8 February 1940
Place of Birth: Webster, Massachusetts
Married with two sons; wife's name is Nadine

EDUCATION:

A.B.(*mcl*) in Physics, l960, Harvard University.
S.M. in Applied Mathematics, l96l, Harvard University.
Ph.D. in Applied Mathematics, l964, Harvard University. Thesis title: *Radiative and photochemical processes in strato- and mesospheric dynamics*.

WORK EXPERIENCE:

l964-l965.	Research Associate in Meteorology, University of Washington.
l965-l966.	NATO Post-Doctoral Fellow at the Institute for Theoretical Meteorology, University of Oslo.
l966-l967.	Research Scientist, National Center for Atmospheric Research.
April-June l967.	Visiting Lecturer in Meteorology, UCLA.
l968-l972.	Associate Professor and Professor of Meteorology, University of Chicago.
Summers l968, l972, l978.	Summer Lecturer, NCAR Colloquium.
October-December l969.	Visiting Professor, Department of Environmental Sciences, Tel Aviv University.
l972-l982.	Gordon McKay Professor of Dynamic Meteorology, Harvard University.
February-June l975.	Visiting Professor of Dynamic Meteorology, Massachusetts Institute of Technology.
January-June l979.	Lady Davis Visiting Professor, Department of Meteorology, The Hebrew University, Jerusalem, Israel.

September l980-June l983.	Director, Center for Earth and Planetary Physics, Harvard University.
July l982-June l983.	Robert P. Burden Professor of Dynamical Meteorology, Harvard University.
July l983- .	Alfred P. Sloan Professor of Meteorology, Massachusetts Institute of Technology.
June 1988- .	Distinguished Visiting Scientist at Jet Propulsion Laboratory.

HONORS:

Phi Beta Kappa
Sigma Xi
NCAR Outstanding Publication Award, l967
AMS Meisinger Award, l968
AGU Macelwane Award, l969
Alfred P. Sloan Fellowship, l970-l976
Vikram Amblal Sarabhai Professor at Physical Research Laboratory, Ahmedabad, India, 1985
AMS Charney Award, 1985
Japanese Society for the Promotion of Science Fellowship, Dec. 1986-Jan. 1987
Member, National Academy of Sciences
Fellow, American Academy of Arts & Sciences
Fellow, American Meteorological Society
Fellow, American Geophysical Union
Fellow, American Association for the Advancement of Science
Sackler Visiting Professor, Tel Aviv University, January 1992
Landsdowne Lecturer, University of Victoria, March 1993
Member, Norwegian Academy of Science and Letters
Bernhard Haurwitz Memorial Lecturer, American Meteorological Society, 1997
Leo Prize of the Wallin Foundation (first recipient), 2006
Distinguished Engineering Achievement Award of the Engineers' Council, February 2009

MEMBERSHIP:

American Meteorological Society
National Academy of Sciences
American Academy of Arts and Science
American Association for the Advancement of Science
American Geophysical Union
European Geophysical Society
World Institute of Sciences
Norwegian Academy of Science and Letters

OTHER:

Consultant to the Goddard Laboratory for Atmospheres.
Member, International Commission on Dynamic Meteorology
Corresponding Member, Committee on Human Rights, National Academy of Sciences
Lead author of the 2001 Report of the Intergovernmental Panel on Climate Change
Member, Science, Health, and Economic Advisory Council, The Annapolis Center
Member, Climate Change Science Program Product Development Advisory Committee of the Department of Energy (term ended in 2009)

Previous service includes serving on editorial board of *Dynamics of Atmospheres and Oceans* and **PAGEOPH**, membership on the Rocket Research Committee, the US GARP (Global Atmospheric Research Program) Committee, the Assembly of Mathematical and Physical Sciences, the executive committee of the Space Studies Board, and the executive committee of the Board on Atmospheric Sciences and Climate of the National Research Council, serving as a member of the Woods Hole Oceanographic Institution Corporation and serving on the council of the American Meteorological Society, Atmospheric Dynamics Committee of the AMS, MIT representative to UCAR, serving as a Distinguished Visiting Scientist at the Jet Propulsion Laboratory.

CURRENT RESEARCH INTERESTS:

The general circulation of the earth's atmosphere.
Climate dynamics.
Hydrodynamic shear instability.
Dynamics of the middle atmosphere.
Dynamics of planetary atmospheres.
Parameterization of cumulus convection.
Tropical meteorology.

MIT ACTIVITIES

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Member, Board of MIT Hillel Foundation

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Donna Blake, Siu-Shung Hong, John Boyd, Lloyd Shapiro, Edwin Schneider, Margaret Niehaus, Jeffrey Forbes, Duane Stevens, Ian Watterson, Arthur Hou, Brian Farrell, Petros Ioannou, Arthur Rosenthal, Ka-Kit Tung, David Jacqmin, Ronald Miller, Arlindo DaSilva, Christopher Snyder, De-Zheng Sun, Daniel Kirk-Davidoff, Constantine Giannitsis, Gerard Roe, Nili Harnik, Pablo Zurita-Gotor, Roberto Rondanelli

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PUBLICATIONS

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BEFORE THE OFFICE OF ADMINISTRATIVE HEARINGS
FOR THE MINNESOTA PUBLIC UTILITIES COMMISSION
STATE OF MINNESOTA

In the Matter of the Further Investigation in to
Environmental and Socioeconomic Costs
Under Minnesota Statute 216B.2422, Subdivision 3

OAH Docket No. 80-2500-31888

MPUC Docket No. E-999-CI-14-643

Exhibit 2

to

Direct Testimony of

Professor Richard Lindzen

June 1, 2015

Scientific bases for concern over increasing levels of CO2

Richard S. Lindzen, Alfred P. Sloan Professor of Atmospheric Sciences, Emeritus
Massachusetts Institute of Technology

Contents

1. Bases for CO2 concerns – climate sensitivity

2. Climate change v. anthropogenic climate change.

3. Sensitivity and feedbacks

4. The relative roles of temperature v. emissions in determining increases in atmospheric CO2.

5. Climate and extreme weather, sea ice, etc.

6. Benefits v. costs

1. Bases for CO2 concerns – climate sensitivity.

The last 4 United Nations Intergovernmental Panel on Climate Change reports have all been summarized with the iconic claim that man-made (ie anthropogenic) emissions account for most of the warming since the 1970's. This is usually rephrased to claim that the earth is warming and man is responsible. Each report claims slightly increased subjective confidence in this claim, and the claim is generally presented as the reason for concern (viz IPCC, 2013). This section examines this claim in detail. We note several crucial problems with the claim:

- Even if true, the warming referred to is small and (as shown in Section 2) not unique.

- The claim refers to models with markedly different sensitivities to added greenhouse gases. Yet all the models appear to replicate the recent warming. This is achieved by fairly arbitrary inclusion of uncertain aerosols (reckoned to be anthropogenic emissions as well) in the models and choosing these to cancel excess warming. Recent studies reduce the uncertainty associated with aerosols and limit one to low sensitivity which would imply minimal danger or even net benefit.

- The claim explicitly depends on other (natural) sources of climate change are small. The assumption is based on the fact that the models used display very little natural variability, but this is contradicted by the absence of warming in the data for the past 18 years. Therefore, even the argument for the attribution of the small warming to anthropogenic emissions breaks down.

The first thing that has to be recognized is that increasing CO2 and even warming per se are not bases for concern. Neither is the unquestioned existence of the greenhouse effect. Concern depends on at least two factors: 1. Warming due to increasing CO2 has to be large compared to natural variability; and 2. There has to be a clear connection between such warming and concerns over such matters as extreme weather. The second item is the focus of Section 5. In addition, there has to be a clear quantitative relation between specific emissions of CO2 and CO2 levels in the atmosphere. This is discussed in Section 4. With respect to the first item, the fact that the greenhouse effect implies that additional CO2 will cause some warming is insufficient evidence for concern. The amount of warming associated with specific additions of CO2 is of crucial importance. This is what is referred to as climate sensitivity. As a matter of convention, sensitivity is often defined as the equilibrated warming resulting from a doubling of CO2. Because of the logarithmic dependence of warming on CO2 concentration, it does not matter what the base value is for a doubling. That is to say, doubling from 1000 ppmv to 2000 ppmv will have the same value as doubling from 280 ppmv to 560 ppmv. Because of the heat capacity of the oceans, it takes time to reach equilibrium, and that time increases sharply as the equilibrium sensitivity increases. The characteristic time to reach equilibrium is generally taken as the time to reach about 2/3 of the equilibrated value. For a sensitivity of 5 degrees C, this is on the order of many decades, while for a sensitivity of 1 degree C, it is only on the order of a few years. For sensitivities less than 1 degree C, the response is almost immediate. For certain purposes, therefore, one sometimes uses transient sensitivity: ie, the warming reached by a certain date (for example by 2100).

Climate claims are produced by models wherein the equations for the motion, composition and radiative transfer are numerically approximated. These models are referred to as General Circulation Models known as GCMs (though these days it is often assumed that GCM stands for Global Climate Model). IPCC claims are based on a large number of such models – differing pronouncedly in quality. In climate GCMs, climate sensitivity is nominally determined by the model based on its approximations and parameterizations of the physics. Note that the processes determining sensitivity are cloud scale processes that none of the models can actually resolve. To resolve processes like clouds, turbulence, etc. would require resolution on the order of meters or less. The models usually don't have resolution better than 100 km. Thus, they require fairly ad hoc approximations when dealing with unresolved scales. Despite this, the models are indeed complex. This complexity is needed, in principle, to provide information on regional scales, and to deal with other details. However, the success of models to provide regional information is doubtful since different models differ even with respect to sign on such matters. This is acknowledged in the Working Group 1 reports of the IPCC (Working Group 1 deals with the science as opposed to Working Group 2 which deals with the impacts based on usually worst case scenarios or Working Group 3 which deals with mitigation).

If one wishes to focus on global mean temperature, and assumes climate sensitivity, then much simpler models suffice. These very simple models are known as energy balance models. Such models are used by the IPCC for scenario development. We will use such a model to examine the problems in inferring sensitivity from the observed temperature change. That said, we will also see that the observed temperature is most easily simulated with low sensitivity – that is to say that such models do not require extreme adjustments with aerosols in order to simulate observations.

The IPCC presents estimates of radiative forcing (a precise definition of radiative forcing is given in Section 3) by both greenhouse substances and substances that reflect incoming solar radiation. Their estimates are shown in Figure 1. It is the balance between the net incoming solar radiation and the outgoing long wave (infrared) radiation emitted by greenhouse substances that determine the system temperature. Note that greenhouse substances actually cool the system. The greenhouse effect stems from the fact that increasing the amount of greenhouse gases elevates the level from which they cool, and since the temperature of the troposphere (the lowest 7-16 km of the atmosphere depending on latitude) decreases with height, the new level is cooler, and, therefore emits less radiation. This reduction in cooling is what is commonly referred to as warming.

Several things should be noted from Figure 1. First, CO2 is not the only anthropogenic greenhouse gas. While it is the most important one, it contributes (as of 2014) only about 1.7 Watts per square meter. Other gases bring the value to about 2.8 Watts per square meter.

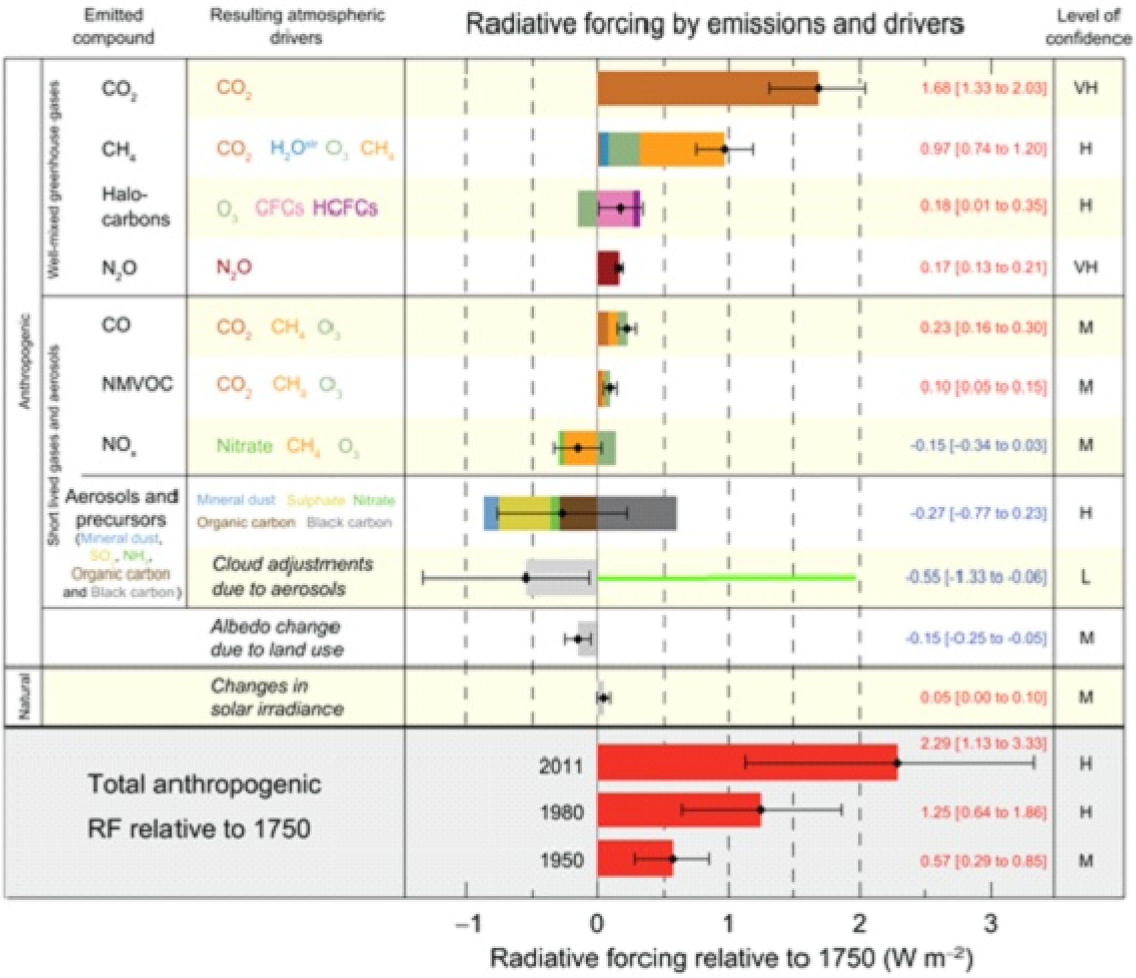


Figure SPM.5 | Radiative forcing estimates in 2011 relative to 1750 and aggregated uncertainties for the main drivers of climate change. Values are global average radiative forcing (RF[14]), partitioned according to the emitted compounds or processes that result in a combination of drivers. The best estimates of the net radiative forcing are shown as black diamonds with corresponding uncertainty intervals; the numerical values are provided on the right of the figure, together with the confidence level in the net forcing (VH – *very high*, H – *high*, M – *medium*, L – *low*, VL – *very low*). Albedo forcing due to black carbon on snow and ice is included in the black carbon aerosol bar. Small forcings due to contrails (0.05 W m^{-2}, including contrail induced cirrus), and HFCs, PFCs and SF$_6$ (total 0.03 W m^{-2}) are not shown. Concentration-based RFs for gases can be obtained by summing the like-coloured bars. Volcanic forcing is not included as its episodic nature makes is difficult to compare to other forcing mechanisms. Total anthropogenic radiative forcing is provided for three different years relative to 1750. For further technical details, including uncertainty ranges associated with individual components and processes, see the Technical Summary Supplementary Material. {8.5; Figures 8.14–8.18; Figures TS.6 and TS.7}

Figure 1. Radiative forcing from IPCC (2013). The green line was added to the aerosol contribution to indicate that aerosols can cause the freezing of supercooled water into ice particles and thus contribute to warming as well as cooling.

The second thing to note is that aerosols are a poorly known source of cooling (though the latest IPCC report has substantially reduced this uncertainty), and a recent paper (Stevens, 2015) further reduces the uncertainty. This reduced uncertainty will prove important to our discussion since the uncertainty allowed modelers to use aerosols to cancel excess warming. Finally, it should be noted that all the items in Figure 1 represent small perturbations to the overall radiative budget which involves balances between insolation and outgoing infrared radiation on the order of 200 Watts per square meter. The large values are associated with what are far and away the most important greenhouse substances which are water vapor and clouds. These will be of central importance when we turn to what determines climate sensitivity in Section 3: namely feedbacks.

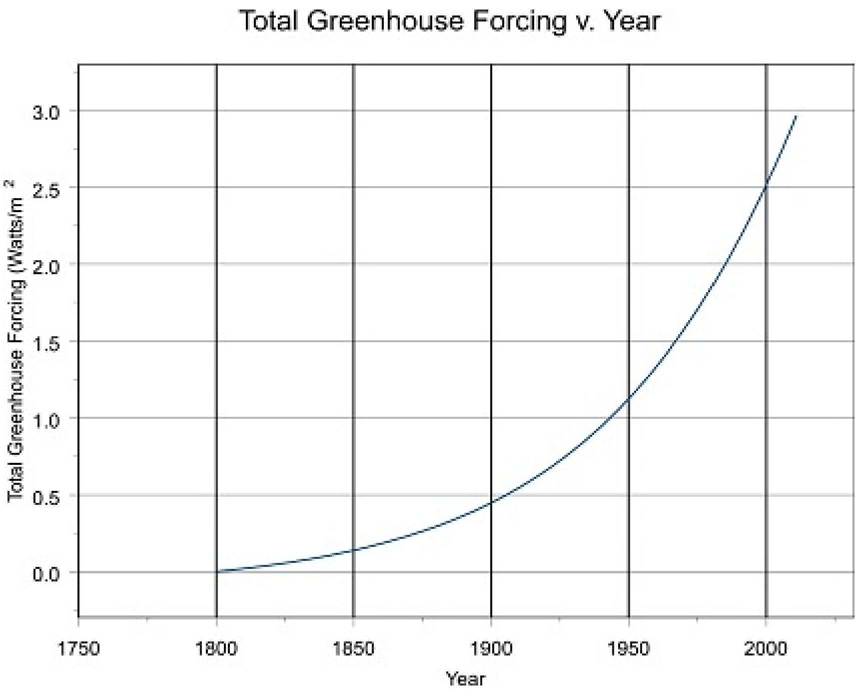


Figure 2. Total greenhouse forcing as function of time.

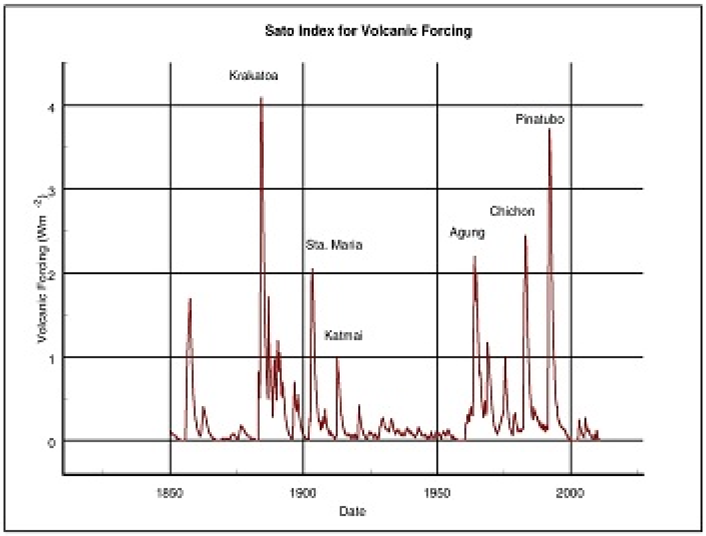


Figure 3. Volcanic forcing (Sato index from NASA/GISS)

Figure 2 shows a smoothed time series for the evolution of anthropogenic greenhouse forcing (including all IPCC sources). The smoothing simply means that small irregularities in the evolution of greenhouse forcing are ignored; they are irrelevant to our discussion. The value reached in 2014 is 2.8 Watts per square meter, which is about 75% of what is commonly expected from a doubling of CO2. Most models also include forcing by volcanoes. This forcing is shown in Figure 3. We calculate the response to these forcings using the energy balance model described in Lindzen and Giannitsis (1998). This is effectively the same model widely used for scenario development by the IPCC. Figure 4 shows the response to anthropogenic greenhouse gases. Recall that global mean temperature (or, more accurately, global mean temperature anomaly) increased about 0.75C since the end of the little ice age in the 19th Century. We see that models with sensitivity in excess of about 1C all show greater warming. However, the difference between higher and lower sensitivity is less than one might expect because higher sensitivities are associated with slower responses. This

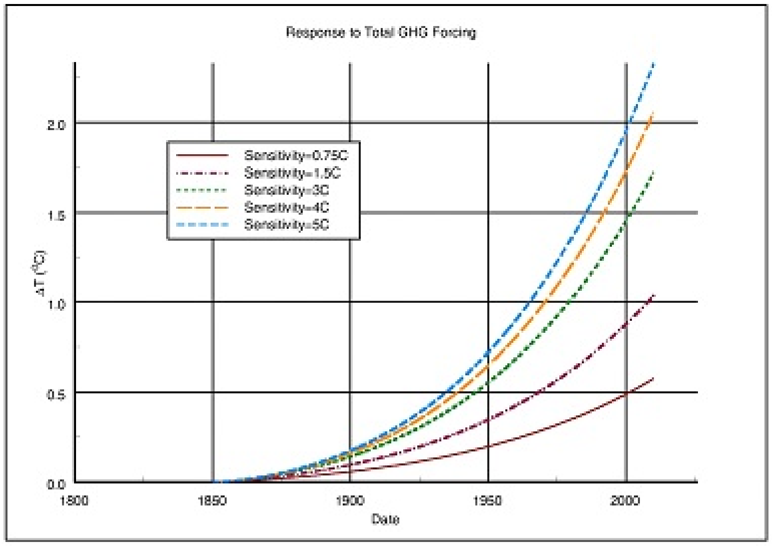


Figure 4. Temperature response to greenhouse forcing.

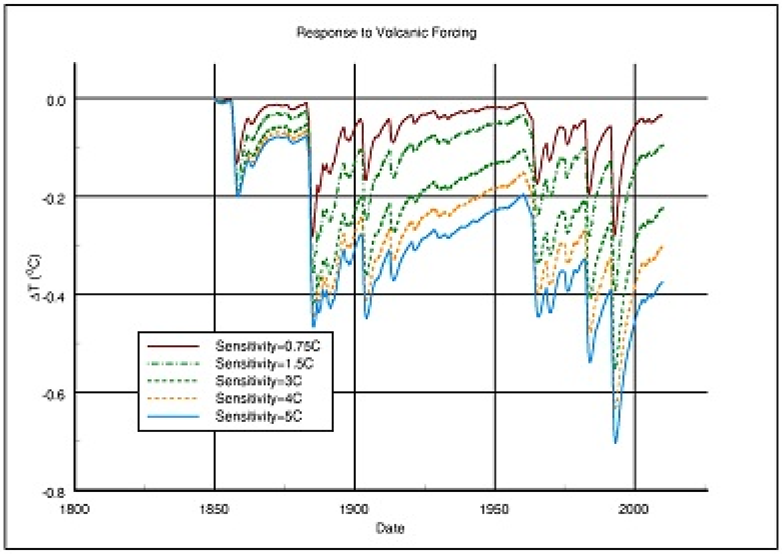


Figure 5. Temperature response to volcanic forcing.

why transient sensitivity is smaller than equilibrium sensitivity. Figure 5 shows the response to volcanic forcing. Volcanic activity tends to cluster (which is typical of random processes). For low climate sensitivity, the response to volcanos is largely restricted to the life time of the volcanoes, but for high sensitivity, the response persists for a long time, and provides a significant contribution to cooling. This serves to reduce the difference in total response corresponding to different sensitivities as we see in Figure 6 which shows the response to combined greenhouse and volcanic forcing. Of course, once again all sensitivities above 1C exceed the observed warming. However, modelers use aerosols to reduce the warming as shown in Figure 7. Table 1 shows what fraction of the greenhouse warming had to be removed in order achieve modest agreement with observations. Notice that the aerosol compensation needed to achieve agreement by the present does not increase much for high sensitivities because of the fact that response time increases with sensitivity. However, given the

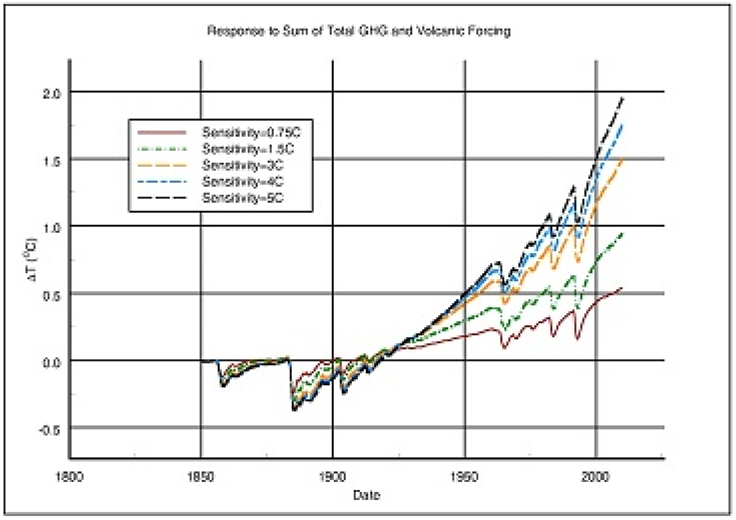


Figure 6. Temperature response to sum of greenhouse and volcanic forcing.

recent results of Stevens (2015), the aerosol compensation called for by high sensitivity models might not be available. Thus, it will not be possible to bring these models into agreement with observations. The IPCC claims significant confidence that only by a combination of greenhouse warming and aerosol cooling (both subsumed under the ambiguous label of anthropogenic influences) can the observed warming of the period since the 1970's be accounted for. However, their claim is based on the fact that the models have very little internal variability so that almost all of the recent warming can be attributed to anthropogenic forcing. Natural internal variability refers to changes in temperature that occur without external forcing. Such changes occur, for example when heat is exchanged between the surface and the deeper oceans, leaving the surface disequilibrated.

The behavior of the temperature in Figure 7 does not resemble the observed temperature in detail because modelers apply adjustments in a variable fashion to achieve better agreement. Observed temperature behavior is shown in Figure 8. However, model results when extended to the future diverge strongly as seen in Figure 9.

So, where does all this leave us? **First**, for purposes of perspective, it is worth noting that the temperature changes we are discussing are small.

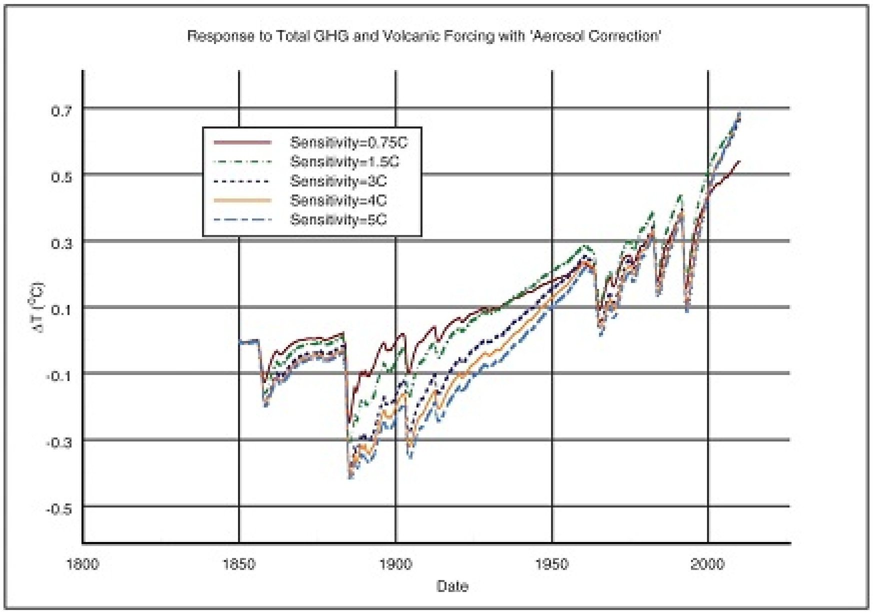
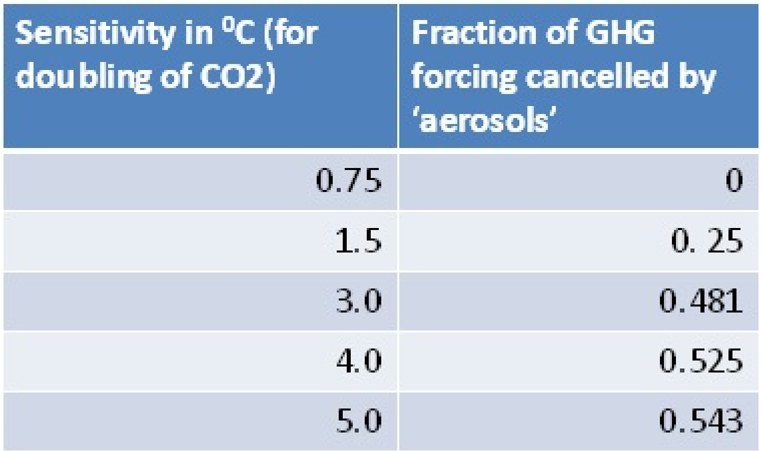


Figure 7. Temperature response 'adjusted' with aerosols.



Sensitivity in ^{0}C (for doubling of CO2)	Fraction of GHG forcing cancelled by 'aerosols'
0.75	0
1.5	0. 25
3.0	0.481
4.0	0.525
5.0	0.543

Table 1. Cancellation by aerosols for various choices of sensitivity.

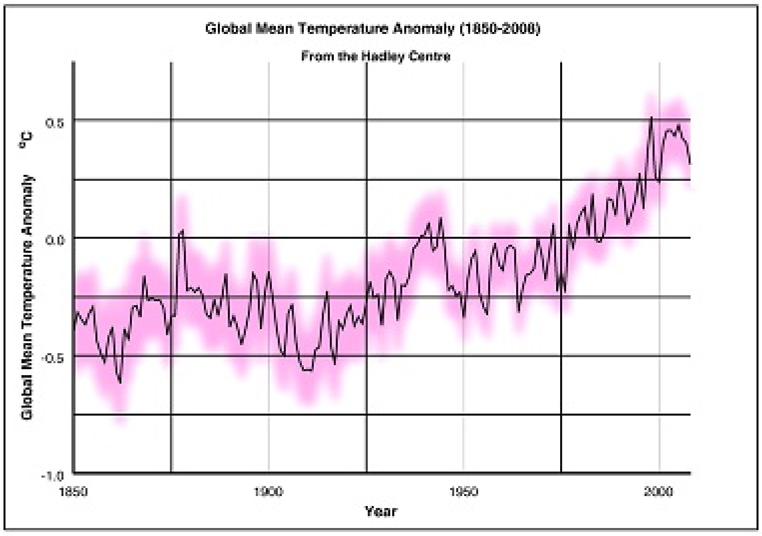


Figure 8. Observed temperature behavior. Pink envelope indicates statistical uncertainty bounds.

In Figure 10, which shows the temperature record for February 2013 in Boston, and also shows daily high and low, the average high and low, and the record breaking highs and lows for each day, the the thickness of the red line constitutes the range of change of global mean temperature anomaly for the past 150 years. The same situation would pertain to any year and month. The warming that is discussed with respect to the issue of global warming is not something that can be perceived within the noise of normal variability. **Second**, if we wish to account for the observed warming over the past 150 years on the basis of greenhouse gases, volcanoes and aerosols, then the new bounds on aerosols rule out sensitivities over about 2C. **Third**, given that all IPCC models fail to predict the cessation of discernible warming over almost the past 20 years, we have to conclude that natural variability is at least as large as any anthropogenic contribution. But, the IPCC argument for attributing the warming since the 1970's to anthropogenic forcings depended on the assumption that natural variability was small (based on the model behavior). This, we now see, is untrue, and hence the IPCC argument for the attribution of recent warming to anthropogenic forcing breaks down. That is to say, we can no longer claim that man's contribution to warming has been identified in the data. **Fourth,** ironically, the presence of natural variability now provides for a remote possibility of higher sensitivity, provided that natural variability provided part of the cancellation of the excess warming associated with high sensitivity. This has been suggested in a recent paper (Brown et al, 2015)). The idea is that the same natural variability that accounts for the cessation of warming over the past 18 years, might also have cancelled warming that might otherwise have occurred during the earlier period. Not only does this destroy the original argument for attribution, but it also involves special pleading of a particularly egregious sort since it is just as likely that natural variability accounted for much of the warming episode itself, in which case the sensitivity would have to be very low.

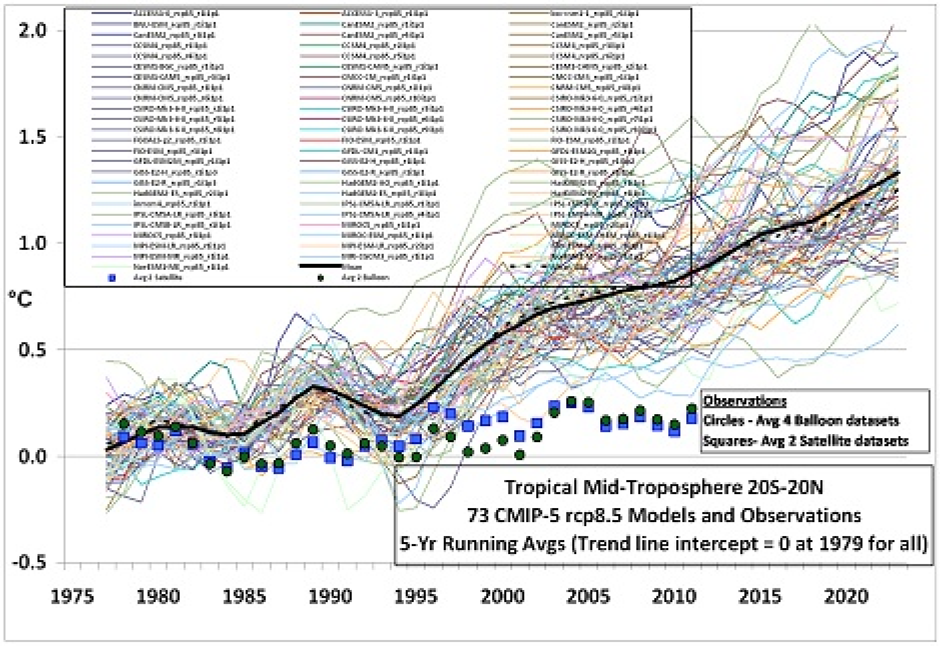


Figure 9. Observed model projections compared with observed temperature.

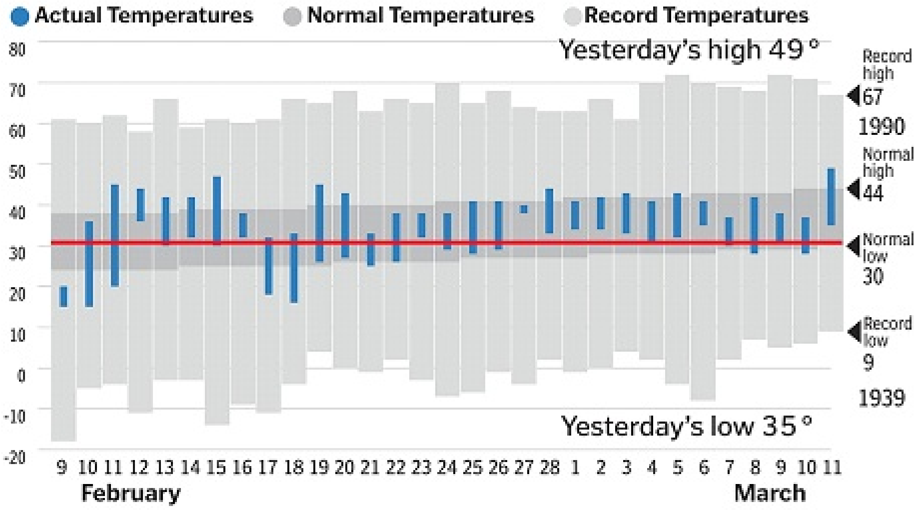


Figure 10. Boston temperatures for the period Feb 9 - March 11 2013. Blue bars show temperature range for day; dark gray bars show average highs and lows for a given date; light gray bars show record highs and lows for a given date. The thickness of the red line represents the range of global mean temperature since 1850.

Still, when everything is considered, it would appear that equilibrium sensitivity in excess of about 2C depends on the arbitrary coincidence of factors and is thus highly unlikely. Many recent peer reviewed papers indeed noted the that climate sensitivity is likely to small (Lewis, 2013 , Lewis and Crok, 2014, Lewis and Curry, 2014 Annan and Hargreaves, 2011, Ring et al, 2012, Aldrin et al, 2012). Further support for low sensitivity will be presented in Section3. Indeed, the lower value of sensitivity (ie, 1.5C), is currently within the range of IPCC projections. Thus, the danger that might be associated with a highly sensitive climate is implausible, but not yet rigorously impossible. As usual, it is difficult if not impossible for science to prove things to be impossible. Such a situation is far removed from either settled science or any likelihood of apocalypse. This is separate from the issue of whether any proposed emissions policy would discernibly influence the situation. However, if the situation is that there is no impending danger, then even this would not matter.

2. Climate change v. anthropogenic climate change.

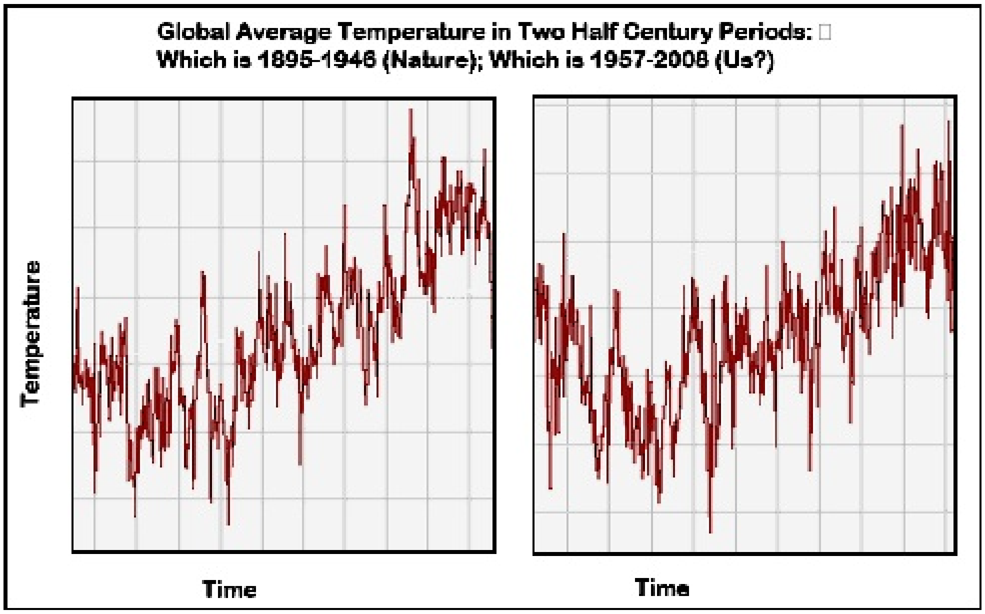


Figure 11. Time history of temperature for two periods in the instrumental record. One warming episode refers to a period where the warming could not be due to anthropogenic emissions; the other has been claimed by the IPCC to be due to man. Note that time and relative temperature scales are identical in both graphs.

Note that only the warming from about 1978 until 1998 is, according to the IPCC, potentially attributable to emissions. The reason for this is seen in Figure 2. Until the 70's, greenhouse forcing was simply too small. However, as can be seen in Figure 8, there was an earlier warming from about 1918 until 1940. In Figure 11, we display the temperature records for the periods 1895-1946, and 1957-2008, periods which surround the two warming episodes. As is evident, the two periods are essentially indistinguishable though one is presumably natural while the other is claimed to be due in large measure to man. Put simply, there is nothing seemingly unusual or unprecedented about the recent warming episode, and like the earlier episode, it appears to have ended (in the case of the most recent episode, about 18 years ago). Of course, it has long been recognized that earth has had many warm periods (the Medieval Warm Period, the Holocene Optimum, several interglacial periods, the Eocene (which was much warmer than the present), etc. The point is simply that climate always changes. While there are occasional disputes about some of the earlier warm episodes, there can be no dispute about the existence of a non-anthropogenic warming episode in the thermometric record.

Tellingly, climatologists in the past referred to the warm periods as ‘optima’ since they were associated with thriving life forms. It is conceivable, however, that man emerged only during the period of glaciation cycles because only in such challenging climates was there an evolutionary advantage for intelligent mammals. Most plant forms, however, evolved during periods of high CO_2 (often ten times present levels). These periods were mostly (though not always) warm periods. However, there is also evidence of cold periods associated with higher levels of CO_2. The famous ice cores from Antarctica do show low values of CO_2 associated with glacial periods and higher values associated with interglacials. However, it appears that changes in CO_2 followed rather than led changes in temperature. This should not be surprising. Increased temperatures are associated with decreasing ability of oceans to hold CO_2, and also with greater rates of biospheric decay on land. This will be an important consideration in Section 4.

3. Sensitivity and feedbacks.

In Section 1, we considered the consequences of different choices of climate sensitivity. In this section we will discuss what physically determines sensitivity. As already noted, greenhouse warming results from the fact that the addition of greenhouse gases (ie gases with absorption and emission in the infrared spectrum characteristic of the earth's temperature), elevates the characteristic level from which radiation is emitted to space. The emitted flux increases sharply with temperature, but the temperature of the troposphere decreases with altitude. Thus, the amount of emitted radiation decreases with the addition of the greenhouse gas (or substance since clouds are a major greenhouse substance). This decrease represents the radiative forcing shown in Figure 1. To compensate for this, the entire troposphere warms in order to bring the radiation to space in balance with the net incoming solar radiation. The usual value given for the radiative forcing due to doubling CO2 is about 3.5 watts per square meter. However, as we see in Figure 1, even this is subject to substantial uncertainty. Moreover, the value depends on ignoring the role of upper level cirrus clouds. Note that, in the absence of upper level cirrus clouds, the characteristic emission level is determined primarily by water vapor with relatively small contributions from CO2. Where upper level cirrus clouds are present, their infrared opacity is so great that the tops of these clouds determine the emission level. Of course, clouds (mostly at lower levels in the troposphere) also reflect sunlight, and thus also play a major role in determining the net incoming solar radiation (ie the incoming solar visible radiation minus that part reflected by the surface, clouds, and aerosols).

Now, all the above factors (upper level cirrus coverage, humidity, low level cloud cover, and surface properties which depend on snow and ice cover) can depend on temperature. Thus, when added greenhouse gases alter temperature, these factors provide feedbacks that can either amplify or diminish the direct effect of the greenhouse gases. Without feedbacks, a doubling of CO2 is generally claimed to lead to a warming of about 1C. This is generally considered too small to promote great concern. The paper that probably did more to promote concern than any other was Manabe and Weatherald (1975). In this paper, a simple one dimensional model was used to show that the assumption of constant relative humidity would lead to a positive feedback that would approximately double the response to increasing CO2. The point is that relative humidity is the ratio of humidity (ie the amount of the main greenhouse gas, water vapor) to its saturated value. But, the saturated value increases with temperature. Thus, if relative humidity were to remain constant, humidity, itself, would increase. This proved extremely important. The mathematical treatment of feedbacks is given in Lindzen et al (2001). It leads to the following equation:

$$\text{Response} = \frac{\text{Zero Feedback Response}}{1 - \text{Sum of feedback factors}}$$

The so-called water vapor feedback contributes 0.5 to the sum of feedback factors (viz Manabe and Weatherald, 1975, as well as IPCC, 2013), and this, by itself, doubles the response. However, for example, adding other feedback factors contributing an additional 0.5 to the sum, would bring the response to infinity, and still more positive feedback would destabilize the climate system. The IPCC model based estimate of sensitivity between 1.5 and 4.5C implies that, in addition to the so-called water vapor feedback of 0.5, there are, in the models, other feedbacks with feedback factors ranging from -.17 up to about +0.28, depending on the model. The crucial point is that the putative existence of starting feedback factor of 0.5 opens up the possibility of very large sensitivities with relatively small additions to the sum of feedback factors. These additional feedbacks are associated in the models with clouds, and, to a much lesser extent, changes in surface properties. However, as the IPCC acknowledges, all the feedbacks depend on unresolved features which have to be parameterized and are highly uncertain. When various scientific bodies refer to consensus, they are referring to the relatively trivial matters such as the observation that CO2 is increasing, that there is a greenhouse effect, and that there has been a small warming since the end of the Little Ice Age in the 19th Century. On the whole, the last item has been a beneficial change. However, in a public message by the presidents of the National Academy of Sciences and the Royal Society, the fact that the actual climate sensitivity is a matter current research is openly acknowledged (Rees and Cicerone, 2010). Quoting from their letter, "Straightforward physics tells us that this rise is warming the planet. Calculations demonstrate that this effect is very likely responsible for the gradual warming observed over the past 30 years and that global temperatures will continue to rise – superimposing a warming on all the other effects that make climate fluctuate. *Uncertainties in the future rate of this rise, stemming largely from the "feedback" effects on water vapour and clouds, are topics of current research*." The peculiarly disappointing aspect of this research is that it has not changed the range of model results since the Charney Report of 1979 (Charney et al, 1979). Following the brief Charney Report, the National Academy assembled a panel to prepare a major study (Nierenberg et al, 1983). The chair of this panel, William Nierenberg, Director of the Scripps Oceanographic Institution, became an outspoken skeptic of global warming alarm.

It is important at this stage to explain why I referred to the water vapor feedback as the 'so-called water vapor feedback.' The point is that the water vapor feedback is only relevant in regions free of upper level cirrus, but, in the tropics where the feedback processes are concentrated, upper level cirrus coverage is highly variable. One cannot evaluate the water vapor feedback without knowing the area over which it applies. The upper level cirrus are produced by ice thrown off of deep cumulus towers. How much ice is thrown off depends on how efficiently rain forms within the towers. Inefficient rain production leaves more liquid to freeze and detrain forming cirrus. The exact nature of these processes is unclear, but studies show that warming leads to reduced cirrus coverage (Rondonelli and Lindzen,2008, Horvath and Soden, 2008) which acts to counteract the warming (ie acts as a negative feedback). This is referred to as the Iris Effect (Lindzen et al, 2001). Since the feedbacks due to water vapor and upper level cirrus cannot be disentangled, the only remaining approach is to consider the two together as a long wave (or infrared) feedback. This combined long wave feedback can be measured from space, and several studies show it to be negative or small rather than positive and large (Lindzen and Choi, 2011, Choi, et al, 2014, Trenberth and Fasullo, 2009). Without the water vapor feedback in the above equation, there is little scope for high sensitivity. Thus, if the water vapor is simply zero (rather than negative as the data suggests), the remaining model feedbacks lead to a range of sensitivity of from about 0.85C to 1.4C. Should the long wave feedback be negative as various studies suggest (Lindzen and Choi, 2011, Choi, et al, 2014, Cho et al,2012) then sensitivity would be even less. There are currently attempts to find new short wave feedbacks that might increase sensitivity (Trenberth and Fasullo, 2009, Bony and Dufresne, 2005), but this would completely change the long-standing basis for concern. No longer would the water vapor feedback be credited with increasing sensitivity, but rather entirely new and hitherto unknown feedbacks would have to be invoked. It seems unlikely that such feedbacks would return sensitivities in excess of 2C. The Iris Effect has been a source of considerable controversy. Interestingly, a recent paper (Mauritsen and Stevens, 2015) notes that the inclusion of the iris effect in their model uniquely corrects a variety of serious model deficiencies (inadequate change in evaporation with changes in temperature, errors in outgoing radiation associated with temperature changes – both major factors in determining climate sensitivity).

Summarizing the situation so far, we find the following:
a. The basis for attributing warming in the period 1978-1998 (the only period the IPCC claims can be attributed to anthropogenic emissions) is no longer valid since natural variability is unambiguously present in nature if not in models.
b. The physical basis for high climate sensitivity, the water vapor feedback, appears to be cancelled and even turned negative by other processes (presumably the variation of upper level cirrus).
c. While the possibility of high climate sensitivity cannot be rigorously disproved, it would depend on processes that have not yet been identified. Feedbacks (other than the water vapor feedback) in current models would be grossly insufficient.

4. The relative roles of temperature v. emissions in determining increases in atmospheric CO2.

Policies stemming from concerns over CO2 assume that we know how to control atmospheric levels of CO2. There are substantive reasons to question even this. Figure 12 shows the estimated emissions published by the Carbon Dioxide Information Analysis Center (CDIAC) at Oak Ridge National Laboratory. Figure 13 shows the atmospheric levels of CO2. Despite a rapid acceleration of emissions in 2002 (the rate essentially tripled), the rate of increase in CO2 remained essentially unchanged. Systematic instrumental observation of CO2 dates back to only 1958. Data for earlier times are obtained from the analysis of air bubbles in ice cores. Dating of such air bubbles is imprecise and involves a spread of about 18-20 years (MacFarling et al, 2006). Subject to this caveat, the data in Figure 14 (which comes from a smoothed and adjusted

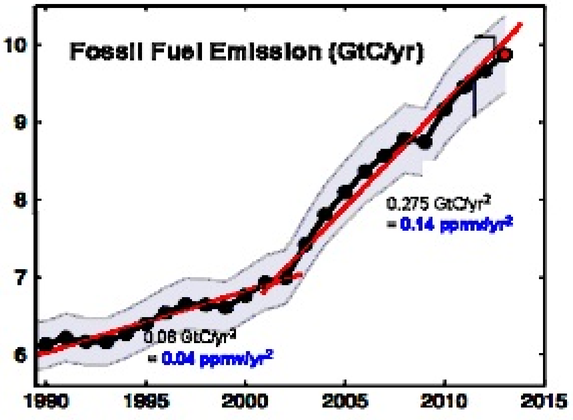


Figure 12. Fossil fuel emission rates v. time.

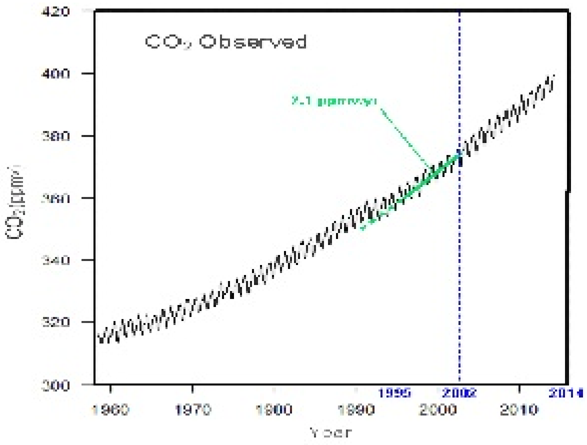


Figure 13. Atmospheric CO2 as a function of time at Mauna Loa Observatory.

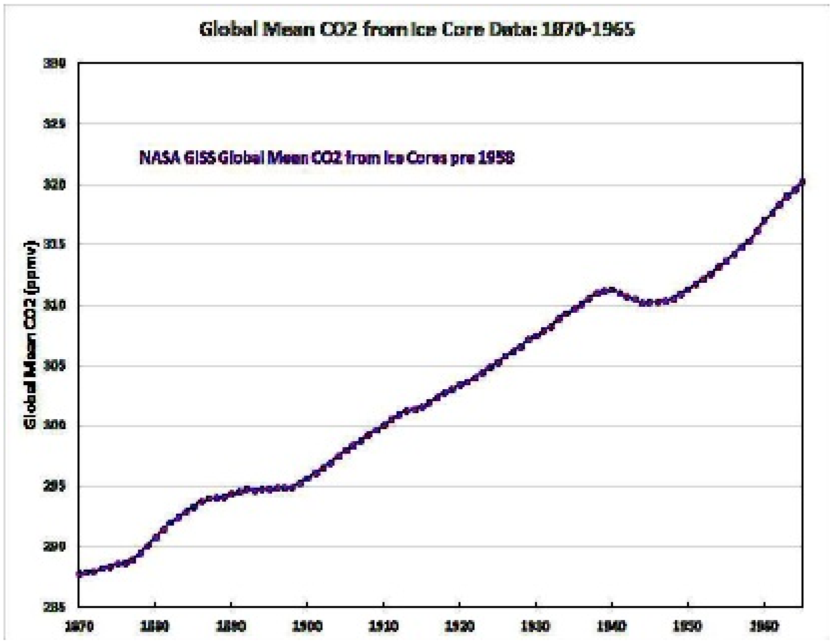


Figure 14. Global mean CO2 obtained from ice cores.

version of this data from NASA's Goddard Institute for Space Studies) shows a noticeable decline in CO2 during the period following 1940. This was a period of modest cooling, and the decline suggests that temperature may be influencing levels of atmospheric CO2. The usual rule of thumb that half of emitted CO2 appears as atmospheric CO2 is based on the Bern model for CO2 geochemistry. This model appears to assume that temperature does not contribute to secular changes in atmospheric CO2. If this assumption is inappropriate (and it certainly seems so), then the contribution of emissions to atmospheric CO2 may be significantly less. The only point here is that even the connection of emissions to atmospheric CO2 is open to question.

That said, it remains the case that the contribution of US emissions is already less than those of the rapidly developing countries, and that any reductions that the US makes (and much less that Minnesota makes) will have an undetectable influence of global mean temperature regardless of what climate sensitivity is and what geochemical model one uses.

5. Climate and extreme weather, sea ice, etc.

As noted in Section 1, warming per se is not catastrophic. Rather, concerns arise from the potential impact of such warming on drought, flooding, storminess, sea ice, etc. Despite assertions by the President's Science Adviser, Dr. John Holdren, there is no evidence that these matters are increasing due to warming (or in most cases increasing at all). On these issues there is often profound disagreement between the IPCC and the political assertions. The absence of evidence for increases in various hydro-meteorological disasters is amply discussed in Pielke, Jr. (2014). Even where trends exist, such as summer arctic ice cover, the reduction has reversed in the last few years; also, antarctic sea ice has been increasing throughout the satellite era. Although satellite data has only been available since the late 70's, anecdotal evidence for summer sea ice reductions in the early 1920's is amply available. Sea level rise has been occurring since the end of the last glaciation. Changes in instrumentation make it impossible to say whether the rate is actually increasing (Wunsch, Ponte and Heimbach, 2007). With respect to extratropical storminess, both basic theory and models imply that global warming will reduce storminess and extremes (viz any textbook on dynamic meteorology: eg Holton and Hakim, 2013, Lindzen, 1990). The issue here is that the primary driving force for storm development is the temperature difference between the tropics and the poles. Since global warming is supposed to be greater at the poles, this difference should be decreasing. Extremes in temperature such as those shown in Figure 10 result from the advection of air from distant points. Reduced storm intensity also reduces the strength of such advection. It is sometimes suggested that warming could contribute to tropical storms because of increases in evaporation and humidity. However, observations show that we have had 10 years of unusually low hurricane activity (Pielke, Jr., 2014) . As the IPCC delicately notes, “There is medium evidence and high agreement that long-term trends in normalized losses have not been attributed to natural or anthropogenic climate change.” (IPCC, SREX, 2012)

6. Benefits v. costs.

In view of the above, it is not evident why one attaches costs to the emissions of CO2. To be sure, the burning of fossil fuels can lead to emissions of actual pollutants, but CO2 is not, itself a pollutant, and effective means of eliminating the actual pollutants are generally required and implemented. Over the past 200 years, there has been modest warming of about 0.8C, and there has been a general improvement in the human condition. Such costs as are inferred are generally based on model projections and speculations concerning impacts rather than observed relations. Moreover, the benefits of both warming and increased CO2 are clearer. CO2 is the basic chemical for photosynthesis. It is essential to plant life, and at least on the order of 150 ppmv are needed to sustain life. CO2 is a fertilizer, and the increasing levels over the past two centuries are significant contributors to increased agricultural productivity (Idso, 2000, Driessen and Arnold, 2014). Warming itself, at the levels that might realistically be anticipated (ie under 2C for the foreseeable future) are estimated to be net benefits. In considering excess deaths attributable to extreme warm events, one should also consider the far larger number of excess deaths due to extreme cold events (Goklany, 2012, Guo et al, 2014). Guo et al (2014) note, quite remarkably, that excess deaths are associated primarily

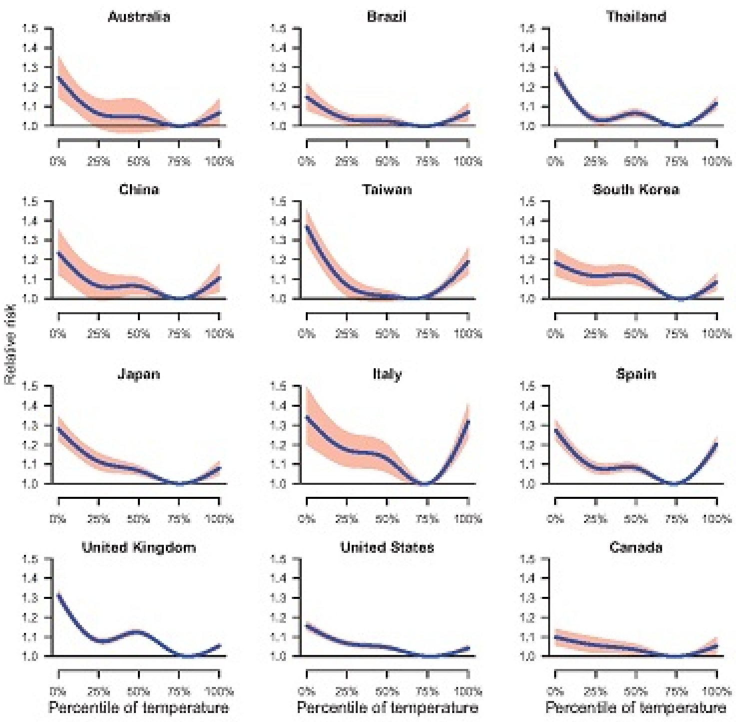


Figure 15. Relative risk of mortality (y-axis) as a function of mean daily temperature plotted as a percentile of the entire temperature record. Temperature for each country was pooled.

with colder temperatures even in warm climates. Figure 15 is taken from Guo et al (2014). Moreover, as noted in Section 5, warming should actually reduce the incidence of extremes. Warming apart, CO2 is not a pollutant. As Casey and Macatangay (2010), note, NASA studies show that concentrations under 5000 ppmv (12.5 times present ambient levels, and much higher than the burning of all fossil fuels would produce) present no risk to health.

In summary, we have well identified benefits – including those from modest warming – and implausible dangers involving uncertain costs. There is, moreover, the evident negative impact of proposed measures on prosperity, and the obvious importance of prosperity for environmental resilience. The policy risks of limiting the clean burning of fossil fuels are clear and are likely to exceed such risks of climate change as may exist.

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BEFORE THE OFFICE OF ADMINISTRATIVE HEARINGS
FOR THE MINNESOTA PUBLIC UTILITIES COMMISSION
STATE OF MINNESOTA

In the Matter of the Further Investigation in to
Environmental and Socioeconomic Costs
Under Minnesota Statute 216B.2422, Subdivision 3

OAH Docket No. 80-2500-31888

MPUC Docket No. E-999-CI-14-643

Direct Testimony and Exhibits of

Professor William Happer

June 1, 2015

PROFESSOR WILLIAM HAPPER

OAH 80-2500-31888

MPUC E-999/CI-14-643

TABLE OF CONTENTS

I. INTRODUCTION

Q. Please state your name, address, and occupation.

A. My name is William Happer, my address is 559 Riverside Drive, Princeton, NJ 08540. I am a physicist by occupation.

Q. Please describe your educational background and professional experience.

A. I received a BS degree in physics from the University of North Carolina at Chapel Hill in 1960, and I received a PhD degree in physics from Princeton University in 1964. I began my academic career in 1964 at Columbia University as a member of the research and teaching staff of the Physics Department. While serving as a Professor of Physics I also served as Co-Director of the Columbia Radiation Laboratory from 1971 to 1976, and Director from 1976 to 1979. In l980 I joined the faculty at Princeton University. On August 5, 1991 I was appointed Director of Energy Research in the Department of Energy (DOE) by President George Bush. While serving in that capacity under Secretary of Energy James Watkins, I oversaw a basic research budget of some $3 billion, which included much of the federal funding for high energy and nuclear physics, materials science, magnetic confinement fusion, environmental and climate science, the human genome project, and other areas. I remained at the DOE until May 31, 1993 to help the Clinton Administration during the transition period. I was reappointed Professor of Physics at Princeton University on June 1, 1993, and named Eugene Higgens Professor of Physics and Chair of the University Research Board, Princeton University’s equivalent of Vice President for Research, from 1995 to 2005. From 2003 until my retirement from teaching in 2014, I held the Cyrus Fogg Brackett Chair of Physics. After retirement, I retained my office in Princeton University, where I have the status of Professor, Emeritus.

From 1987 to 1990 I served as Chairman of the Steering Committee of JASON, a group of scientists and engineers who advise agencies of the Federal Government on matters of defense, intelligence, energy policy and other technical problems. I served as a trustee of the MITRE Corporation from 1993 to 2011, I am the Chair of the Board of the Richard Lounsbery Foundation, and of the Marshall Institute. From 2002 to 2006 I chaired the National Research Council's Standing Committee on Improvised Explosive Devices that supported the Joint Improvised Explosive Devices Defeat Organization of the Department of Defense. I was a co-founder in 1994 of Magnetic Imaging Technologies Incorporated (MITI), a small company specializing in the use of laser polarized noble gases for magnetic resonance imaging. I invented the sodium guidestar that is used in astronomical adaptive optics to correct for the degrading effects of atmospheric turbulence.

I have published over 200 peer-reviewed scientific papers. I am a Fellow of the American Physical Society, the American Association for the Advancement of Science, and a member of the American Academy of Arts and Sciences, the National Academy of Sciences and the American Philosophical Society. I was awarded an Alfred P. Sloan Fellowship in 1966, an Alexander von Humboldt Award in 1976, the 1997 Broida Prize and the 1999 Davisson-Germer Prize of the American Physical Society, and the Thomas Alva Edison Patent Award in 2000, and the Fred Seitz Award of SEPP in 2015. My CV is attached as Happer Exhibit 1.

II. OVERVIEW OF OPINIONS

Q. What are the purposes of your testimony in this proceeding?

A. My purpose is to explain that atmospheric CO_2 gas is not a pollutant but a benefit to the earth.

Q. Could you summarize your principal conclusions and recommendations?

A. The gases CO_2 and water vapor, H_2O, are both emitted by combustion of fossil fuels. Both are greenhouse gases that cause some warming of the earth's surface. Observations over the past two decades show that computer models have exaggerated the warming caused by additional CO_2 by several hundred percent. At the current utilization rate of fossil fuels, many centuries will be needed to cause a temperature increase of 2 C. This modest warming will be beneficial to humanity and other life on earth.

Furthermore, green plants currently have too little CO_2, compared to geological norms. The CO_2 released by combustion of fossil fuels for the next few centuries will partially restore the much larger levels of CO2 that have existed over most of the history of life on earth. Plant growth rates and drought resistance will benefit significantly from the additional CO_2.

Continued releases of CO_2 will continue to benefit the planet for many centuries. CO_2 has no social cost.

Q. Have you prepared a report that contains your opinions?

A. Yes, I have prepared a report with references to the scientific literature that has led me to my conclusions and recommendations. My report is attached as Happer Exhibit 2.

Q. Are you familiar with the history of the climate change models and predictions used by the IPCC?

A. Yes, I am very familiar with the climate models used by the IPCC, and I funded some of the early models when I was Director of Energy Research at the United States Department of Energy from 1990 to 1993. Today, observational data provides good reason to doubt the large warmings predicted by IPCC computer models.

Q. Are you familiar with the models underlying the social cost of carbon?

A. Yes, I am familiar with the models. The economic models make little sense today since they are based on climate models that clearly overestimate the warming from more CO_2 by hundreds of per cents. The economic models also greatly underestimate the very beneficial effects of more CO_2 on agriculture.

III. CO_2 AND WARMING

Q. Can you explain what is meant by the "greenhouse effect" as it relates to the Earth's warming?

A. The greenhouse effect as it relates to Earth's warming is an increase in the average surface temperature of Earth and a moderation of nighttime cooling compared to a hypothetical situation of an atmosphere containing no CO_2, H_2O or clouds.

Q. Can you describe the category of "greenhouse gases"?

A. Greenhouse gases are transparent for visible light but opaque for infrared (thermal) light. Greenhouse gases are molecules with two or more atoms, like H_2O, the most important greenhouse gas of the Earth, and CO_2, the second most important. The most abundant atmospheric gases, N_2, O_2 and Ar are transparent to both visible and infrared radiation and are not greenhouse gases.

Q. In your opinion, is CO_2 a conventional "pollutant"?

A. CO_2 is not a conventional pollutant nor is it a pollutant at all. Webster's New Collegiate Dictionary defines the verb "pollute" as "to make or render unclean, to defile." But CO_2, like H_2O, is part of the web of life, transparent, odorless and non-toxic. Exhaled human breath typically contains about 45,000 parts per million (ppm) of CO_2, compared to the 400 ppm that is inhaled. An adult human being exhales about 1 kilogram of CO_2 per day. Examples of real gaseous pollutants are ozone or oxides of nitrogen or sulfur. Examples of real particulate pollutants are smog or fly ash.

Q. Will increases in atmospheric CO_2 concentration result in increasing global surface temperature?

A. Yes, increasing CO_2 will increase the surface temperature. The most important unresolved question is how much the increase will be. A small increase will be a net benefit to the Earth.

Q. Can you explain what it means for there to be a logarithmic relationship between temperature increase and CO_2 concentration?

A. Around the year 1900, the great Swedish chemist Arrhenius guessed that each doubling of CO_2 concentration would cause the same temperature increase. For brevity, we say that the temperature increase ΔT is proportional to the logarithm, log(C) of the CO_2 concentration C. This comes from the mathematical fact that for n doublings, $\log(C^n) = n \log(C)$. Many people mistakenly think that the temperature increase is simply proportional to the concentration of the CO_2. This is only true for extremely small CO_2 concentrations, $C < 1$ ppm.

Many studies since Arrhenius's time have confirmed the validity of the logarithmic relationship for CO_2 concentrations above about 1 ppm. The logarithmic response is a peculiarity of the CO_2 molecule and does not necessarily describe the warming by other greenhouse molecules.

For example, if doubling the CO_2 concentration from the current value of 400 ppm to 800 ppm would increase the temperature by $\Delta T=1$ K, (1 degree Kelvin = 1.8 degree Fahrenheit), adding another 400 ppm of CO_2 would increase the concentration from 800 ppm to 1200 ppm, or by a factor of 3/2. The resulting additional temperature increase would be $\log(3/2)/\log(2) = 0.6$ K, quite a bit less than adding the first 400 ppm of CO_2. So the logarithmic response of temperature increments to CO_2 increments implies law of "diminishing returns" from more CO_2 – the more you increase CO_2, the less sensitive the climate will be to additional increases. At current atmospheric levels of 400 ppm, the Earth's atmosphere is already at a point of diminishing returns for the effects of additional emissions of CO_2.

IV. SENSITIVITY VALUES

Q. What is climate sensitivity?

A. Climate sensitivity S is the warming in degrees Kelvin (K) that would be caused by a doubling of the CO_2 concentration. The sensitivity S is defined by the simple equation, $\Delta T= S \log(C_2/C_1)/\log(2)$, where ΔT is the warming caused if the atmospheric concentration of CO_2 increases from the initial value C_1 to a final value C_2.

Q. How are climate sensitivity values determined?

A. Ideally, climate sensitivity should be determined by experimental observations of how changes of the Earth's temperature are related to changes in the concentrations of CO_2 in the atmosphere. In practice this is very difficult since many other factors besides atmospheric CO_2 affect the Earth's temperature. These factors, few of which are understood very quantitatively, include solar influences, clouds, aerosols, volcanos, massive ocean instabilities like El Ninos, etc.

One can also try to determine the sensitivity purely theoretically, with the aid of computer models that include as much of the climate physics as possible. The physics, including clouds and complicated fluid flow in the atmosphere and oceans, is so complicated that few scientists have much confidence in purely theoretical calculations.

Q. What is the track record of climate models used by the IPCC that have tried to predict climate sensitivity?

A. Nearly all of the IPCC climate models have predicted several hundred percent more warming over the past twenty years than has actually been observed. There is something seriously wrong with the models.

Q. What are “feedbacks”?

A. Feedbacks are changes in the atmosphere that amplify (positive feedback) or attenuate (negative feedback) the direct surface warming from changes of CO_2. For example, if more CO_2 induces more high-altitude water vapor or cloudiness, it would amplify the warming and there would be a positive feedback. If more CO2 were to induce more low-altitude clouds, they would reflect more sunlight and keep the surface from heating as much as before. This would be a negative feedback.

Q. What is the impact of feedbacks on climate sensitivity?

A. With no feedbacks, doubling CO_2 concentrations will increase the average surface temperature by about $S = 1$ K. The IPCC has used large positive feedbacks to claim “most likely” doubling sensitivities of $S = 3$ K or larger. Models with such large doubling sensitivities have predicted several hundred per cent more warming than has actually been observed over the past 10 to

20 years. Observations are consistent with little, and perhaps even negative feedback, corresponding to doubling sensitivities of S = 1 K or less.

Q. What do IPCC climate models assume as to climate sensitivity values?

A. The IPCC states, ``equilibrium climate sensitivity is likely in the range 1.5 K to 4.5 K (high confidence).”

Q. In your opinion, are these assumed values accurate and reliable?

A. Even the lower limit, 1.5 K, is hard to reconcile with the almost complete lack of warming since the year 1998.

A. In your opinion, what is the proper range for climate sensitivity values based on the latest scientific literature?

A. My opinion is that the sensitivity is somewhere between S = 0.5 K and S= 1.5 K, with a most likely value close to the feedback-free sensitivity, which is approximately S = 1 K.

V. WARMING HIATUS

Q. To what extent have global surface temperatures increased during the past two decades?

A. Global warming basically stopped about the time of the last large El Nino event in 1998. There has been no significant warming since.

Q. What do ground-based observations show?

A. Ground-based observations show virtually no warming since 1998. And ground-based warmings are known to have serious systematic errors associated with the loss of observing stations and urban heat island effects, both of which bias the results to more warming than actually exists.

Q. Are the climate model projections compatible with the observed temperatures?

A. No, climate models do not agree with observed temperatures. Climate models predicted far more warming than has actually been observed.

Q. Do you have an opinion as to why the IPCC model projections differ from observed temperature?

A. In my opinion the IPCC climate models have adjusted many poorly constrained parameters to give the maximum possible warming. There is unlikely to be a single cause for their poor performance. But the assumption of large positive feedback is likely to have made the largest contribution to the overestimates. The IPCC has probably also greatly underestimated the role of factors other than CO_2 in controlling the Earth's surface temperature.

A. What are the implications of the hiatus in warming for the reliability and accuracy of the IPCC models?

A. None of the IPCC models accounted for the hiatus. They should not be used as the basis for economic models or policy decisions.

VI. EXTREME WEATHER

Q. What is your opinion as to claims of increased extreme weather events in recent years due to global warming?

A. There is not the slightest evidence for any increase in extreme weather events, as summarized by the Senate Testimony of 1 August, 2012 by John Christy, which I reference in my prepared report.

VII. BENEFITS OF CO_2

Q. Do you have an opinion about increased levels of CO_2 in the atmosphere?

A. More CO_2 in the atmosphere will be a major overall benefit to the Earth because it will cause only small, beneficial warming, and it will greatly increase agricultural productivity.

Q. What are the benefits of additional CO_2?

A. The main benefits are mild warming, more at night than during the day, and more near the Earth's poles than near the equator. This will extend agricultural growing seasons, especially in high latitudes near the Canadian border, Scandinavia, and northern Russia. In addition more CO_2 will increase agricultural productivity, for three main reasons:

i. All green plants use the enzyme rubisco, the most abundant protein on earth. Rubisco was designed several billion years ago when CO_2 levels were higher and O_2 (oxygen) levels were lower. At current low CO_2 concentrations and high O_2 concentrations, rubisco, activated by ATP produced with aid of sunlight in the chloroplasts, often acts on O_2 to make hydrogen peroxide and other harmful compounds (photorespiration) instead of acting on CO_2 to make useful carbohydrates. For this reason C4 plants (which have evolved mechanisms to cope with current low CO_2 levels and high O_2 levels) have displaced many C3 plants in warmer parts of the earth. A more detailed discussion of C3 and C4 plants can be found in my prepared report, but representative C3 plants are all trees, wheat, rice, soybeans and cotton. Representative C4 plants include corn and sugar cane. More CO_2 increases the productivity of both C3 and C4 plants, but especially C3 plants, which have a more efficient photosynthetic pathway if CO_2 levels are high enough and O_2 levels low enough.

ii. Especially in warmer parts of the earth and in the oceans, plants can use up the available CO_2 and waste sunlight. In American corn fields, the CO_2 levels can decrease by a factor of two or three at midday, leading to a decrease in photosynthetic rates.

iii. Current low CO_2 levels have forced plants to grow more stomata in their leaf surfaces. This leads to excess water loss, since up to 100 water molecules can diffuse out of the stomata for every single CO_2 molecule that diffuses in. This is why land plants need some 100 grams of water to make one gram of carbohydrate. If CO_2 levels increase, plants grow leaves with fewer stomata and they do not waste so much water.

Q. What do you mean when you say the earth has been in a "CO_2 famine"?

A. Over most of the past 550 million years, when land plants evolved, CO_2 levels have been much higher than today. As discussed in the answer to the previous question, the low CO_2 levels and high O_2 levels significantly decrease the photosynthetic efficiency of plants, especially in full sunlight, and they force plants to use more water than would be needed for higher CO_2 levels. The modest CO_2 increases over the satellite era, from about 340 ppm to 400 ppm have already caused a noticeable greening, as I discuss in more detail in my prepared report.

Q. Do models that estimate a social cost of carbon consider the benefits of CO_2?

A. Most economic models largely discount the major agricultural benefits of more CO_2. This is partly because most models credulously accept the hugely inflated warming predictions of the IPCC models. Economic models need to be reassessed with the realistic small warming that observations imply will come from more CO_2, and with including the very major agricultural benefits that will come from small warming, more efficient photosynthesis and less need for water.

Q. If the models properly considered these benefits, what would be the impact on the social cost of carbon?

A. If the benefits of more atmospheric CO_2 were properly accounted for, they would far outweigh the losses and the social cost of more CO_2 would be negative.

BEFORE THE OFFICE OF ADMINISTRATIVE HEARINGS
FOR THE MINNESOTA PUBLIC UTILITIES COMMISSION
STATE OF MINNESOTA

In the Matter of the Further Investigation in to
Environmental and Socioeconomic Costs
Under Minnesota Statute 216B.2422, Subdivision 3

OAH Docket No. 80-2500-31888

MPUC Docket No. E-999-CI-14-643

Exhibit 1

to

Direct Testimony of

Professor William Happer

June 1, 2015

Biographical Information May, 2015

DR. WILLIAM HAPPER

Dr. William Happer, Professor Emeritus in the Department of Physics at Princeton University, is a specialist in modern optics, optical and radiofrequency spectroscopy of atoms and molecules, radiation propagation in the atmosphere, and spin-polarized atoms and nuclei.

Dr. Happer received a B.S. degree in Physics from the University of North Carolina in l960 and the PhD degree in Physics from Princeton University in l964. He began his academic career in 1964 at Columbia University as a member of the research and teaching staff of the Physics Department. While serving as a Professor of Physics he also served as Co-Director of the Columbia Radiation Laboratory from 1971 to 1976, and Director from 1976 to 1979. In l980 he joined the faculty at Princeton University. On August 5, 1991 he was appointed Director of Energy Research in the Department of Energy by President George Bush. While serving in that capacity under Secretary of Energy James Watkins, he oversaw a basic research budget of some $3 billion, which included much of the federal funding for high energy and nuclear physics, materials science, magnetic confinement fusion, environmental and climate science, the human genome project, and other areas. He remained at the DOE until May 31, 1993 to help the Clinton Administration during the transition period. He was reappointed Professor of Physics at Princeton University on June 1, 1993, and named Eugene Higgens Professor of Physics and Chair of the University Research Board from 1995 to 2005. From 2003 until his retirement in 2014, he held the Cyrus Fogg Brackett Chair of Physics.

From 1987 to 1990 he served as Chairman of the Steering Committee of JASON, a group of scientists and engineers who advise agencies of the Federal Government on matters of defense, intelligence, energy policy and other technical problems. He was a trustee of the MITRE Corporation from 1993 to 2011, he is the Chair of the Board of the Richard Lounsbery Foundation, and the Chair of the Board of the Marshall Institute. From 2002 to 2006 he chaired of the National Research Council's Standing Committee on Improvised Explosive Devices that supported the Joint Improvised Explosive Devices Defeat Organization of the Department of Defense. He was a co-founder in 1994 of Magnetic Imaging Technologies Incorporated (MITI), a small company specializing in the use of laser polarized noble gases for magnetic resonance imaging. He invented the sodium guidestar that is used in astronomical adaptive optics to correct for the degrading effects of atmospheric turbulence.

He has published over 200 peer-reviewed scientific papers. He is a Fellow of the American Physical Society, the American Association for the Advancement of Science, and a member of the American Academy of Arts and Sciences, the National Academy of Sciences and the American Philosophical Society. He was awarded an Alfred P. Sloan Fellowship in 1966, an Alexander von Humboldt Award in 1976, the 1997 Broida Prize and the 1999 Davisson-Germer Prize of the American Physical Society, and the Thomas Alva Edison Patent Award in 2000.

Dr. Happer was married in 1967 to the former Barbara Jean Baker of Rahway, New Jersey. They have two grown children, James William and Gladys Anne and six grandchildren. The Happers live at 559 Riverside Drive in Princeton, New Jersey.

BEFORE THE OFFICE OF ADMINISTRATIVE HEARINGS
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Exhibit 2

to

Direct Testimony of

Professor William Happer

June 1, 2015

Benefits of CO_2

W. Happer
Professor of Physics, Emeritus
Princeton University

May 12, 2015

1 About the Author

In the summer of 2014 I retired from teaching at Princeton University, where I have been on the faculty since 1980, except for a three-year absence from 1990 to 1993 to serve as the Director of Energy Research at the United States Department of Energy in Washington, DC. My DOE office supervised a research budget of some \$3.5 billion, including environmental and climate science, along with physics, chemistry, biology, and many other scientific areas. I have won a number of awards and I am an elected member of various scientific societies, including the National Academy of Sciences, the American Philosophical Society, the American Academy of Arts and Sciences. I am a fellow of the American Physical Society. I have done research in nuclear physics, atomic, molecular and optical physics, atmospheric physics and other areas. I am probably best known for my invention of the "sodium guide star" concept, used in all modern ground-based telescopes to compensate for deleterious effects of atmospheric turbulence on astronomical observations.

This is a brief essay about the "social cost of carbon," that is, the cost of the alleged harm from emissions of the life-giving molecule carbon dioxide or CO_2. There is no doubt that the concentrations of CO2 are increasing, as shown by Fig. 1. Much of the increase is from combustion of fossil fuels. Those who purport to show a large cost from emissions of CO_2 assume that it will cause catastrophic global warming, flooding from rising oceans, the spread of tropical diseases to temperate latitudes, ocean acidification, and other horrors. But in fact, the alleged harmful effects of CO_2 have been enormously exaggerated. The major benefits of more CO_2 to green plants, and of modest warming to the planet, have been largely ignored. The benefits from more CO_2 far outweigh any harm.

Nearly everyone today is an environmentalist. Most of us recognize that fossil fuels must be extracted responsibly, minimizing environmental damage from mining and drilling operations, and with due consideration of costs and benefits. Similarly, fossil fuels must be used responsibly, deploying cost-effective technologies that minimize emissions of real pollutants such as fly ash, carbon monoxide, oxides of sulfur and nitrogen, heavy metals, and volatile organic compounds. A baby's breath is mostly nitrogen, oxygen, water vapor and carbon dioxide. If fully cleansed of real pollutants, the exhaust from fossil-fuel combustion only differs from a baby's breath by having almost no oxygen, most of which has been

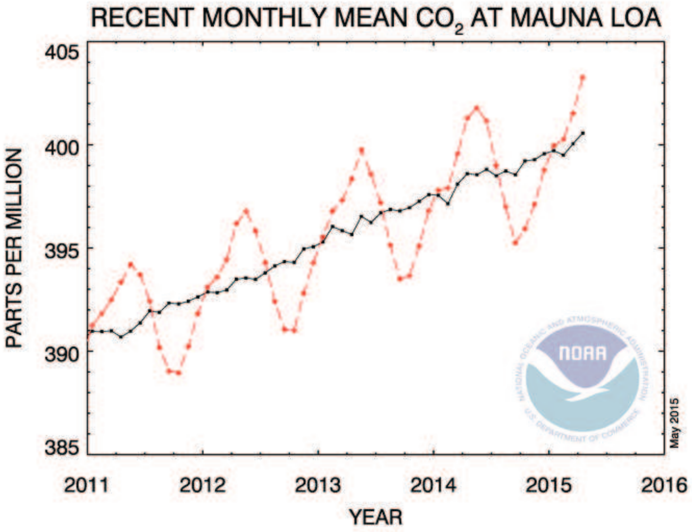

Figure 1: Atmospheric concentrations of CO_2 measured at Mauna Loa, Hawaii [1]. The monthly values start to decrease in the northern-hemisphere spring, with the beginning of photosynthesis during the northern growing season, and the concentration begins to increase in the fall when photosynthesis diminishes but respiration of the biosphere continues. The growth rate of the average value (the line without oscillations) is about 2 parts per million by volume (ppm) per year. This corresponds to about half of the CO_2 emissions from burning fossil fuels, cement manufacture and other human causes. The other half of the emissions is absorbed by the oceans and land surface.

converted into water vapor and carbon dioxide.

2 Warming by CO_2

Of every million air molecules in today's atmosphere, about 400 are molecules of CO_2. We therefore say the CO_2 concentration is $C = 400$ ppm (parts per million). This is an average value, and local values can be very different. For example, exhaled human breath typically consists of 40,000 ppm to 50,000 ppm of CO_2, a fact that should make one wonder about the campaign to demonize CO_2 as a "pollutant." Without strong ventilation, CO_2 levels in classrooms or courtrooms with lots of people commonly reach 5000 ppm with no apparent ill effects. On a calm summer day, CO_2 concentrations in a corn field can drop to 200 ppm because the growing corn sucks so much CO_2 out of the air [2]. The US Navy tries to keep CO_2 levels in submarines below 5000 ppm to avoid any measurable effect on sailors [3].

Pure CO_2 gas is completely transparent, as we know from the fact that human breath, with its 4% CO_2 content, is normally invisible. On a frosty day the chilled outside air can condense the water vapor breath into visible fog.

Around the year 1861, John Tyndall discovered that water-vapor molecules, H_2O, CO_2 and many other molecular gases that are transparent to visible light, can absorb invisible heat radiation, like that given off by a warm tea kettle or by the Earth. Today, we call these *greenhouse gases*. Commenting on greenhouse warming of the Earth by water vapor on p. 359 of his classic book, *Heat, A Mode of Motion* [4], Tyndall makes the eloquent (and correct) statement:

> "Aqueous vapor is a blanket, more necessary to the vegetable life of England than clothing is to man. Remove for a single summer-night the aqueous vapor from the air which overspreads this country, and you would assuredly destroy every plant capable of being destroyed by a freezing temperature. The warmth of our fields and gardens would pour itself unrequited into space, and the sun would rise upon an island held fast in the iron grip of frost."

Tyndall correctly recognized that the most important greenhouse gas of the Earth's atmosphere is water vapor. CO_2 is a modest supporting actor.

The magnitude of the warming from CO_2 is a key issue. If increasing CO_2 causes large warming, harm can indeed be done, and it makes sense to talk about a social cost of carbon. Most studies suggest that warmings of up to 2 K will be good for the planet. So if more CO_2 does not cause warming of more than 2 K, the additional CO_2 will be beneficial and the social cost of carbon will be negative.

The Arrhenius warming formula. The great Swedish chemist, Arrhenius seems to have been the first to make a quantitative estimate of the warming from CO_2 [5]. In 1896, on page 265 of his pioneering paper [6], *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground*, Arrhenius states that decreasing C by a factor of $0.67 = 2/3$ would cause the surface temperature to fall by $\Delta T = -3.5$ K, and increasing C by a factor of $1.5 = 3/2$ would cause the temperature to increase by $\Delta T = +3.4$ K. Summarizing his estimates, Arrhenius stated,

> "Thus, if the quantity of carbonic acid increases in geometric progression, the augmentation of the temperature will increase very nearly in arithmetic progression."

Arrrhenius's conjecture implies a logarithmic dependence of the temperature increase on the CO_2 concentration C, as represented by the simple formula,

$$\Delta T = \frac{S}{\ln(2)} \ln\left(\frac{C_2}{C_1}\right), \quad \text{where} \quad \Delta T = T_2 - T_1, \tag{1}$$

or equivalently,

$$\frac{C_2}{C_1} = 2^{\Delta T/S}. \tag{2}$$

Here T_1 and T_2 are the Earth's equilibrium temperatures at CO_2 concentrations of C_1 and C_2, and $\ln(x)$ denotes the natural logarithm of x, for example, $\ln(2) = 0.6931$. The parameter

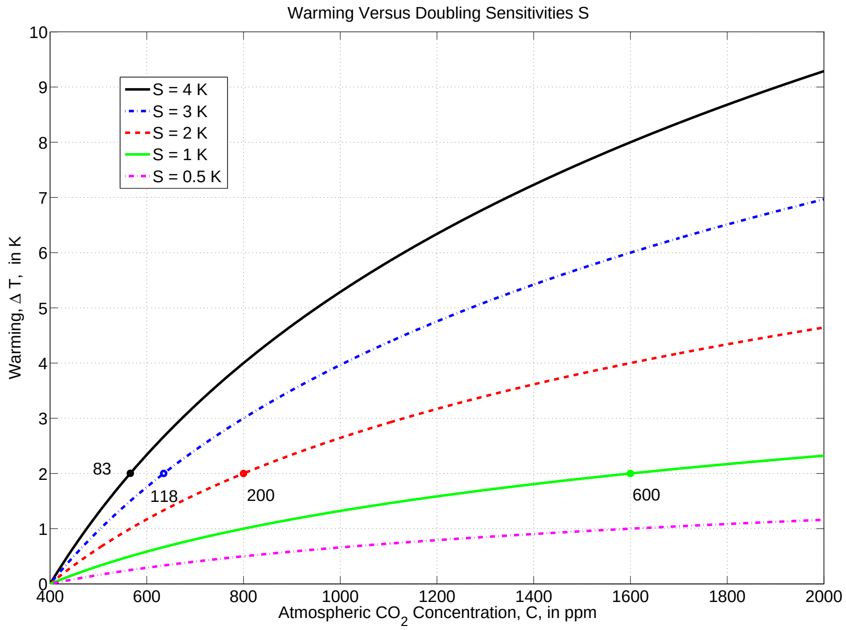

Figure 2: Warming from CO_2 for various assumed doubling sensitivities from Eq. (1). We have used Eq. (7) to calculate the corresponding time (in years) needed to increase the temperature by 2 K. Observations indicate that the doubling sensitivity is close to the feedback-free value of $S = 1$ K, for which 600 years would be needed at the present growth rate, $R = 2$ ppm/year.

S, called the doubling sensitivity and normally given in degrees Kelvin (K), is how much the Earth's surface average surface temperature will increase if the atmospheric concentrations of CO_2 doubles. The warming functions (1) are plotted in Fig. 2 for a range of possible doubling sensitivities.

The warming ΔT of (1) is a value averaged over the entire surface of the Earth and over an entire year. It is a very small number compared to the temperature differences between day and night, or between winter and summer at most locations on the Earth. The warming from CO_2 is expected to be greater at night than during the day, and greater near the poles than near the equator.

If a 50% increase of CO_2 were to increase the temperature by 3.4 K, as in Arrhenius's example mentioned above, the doubling sensitivity would be $S = 5.8$ K. Ten years later, on page 53 of his popular book, *Worlds in the Making; the Evolution of the Universe* [7], Arrhenius again states the logarithmic law of warming, with a slightly smaller climate sensitivity, $S = 4$ K,

> "If the quantity of carbon dioxide in the air should sink to one half its present percentage, the temperature would fall by 4 K; a diminution by one-quarter would reduce the temperature by 8 K. On the other hand any doubling of the percentage of carbon dioxide in the air would raise the temperature of the Earth's surface by 4 K and if the carbon dioxide were increased by four fold, the temperature

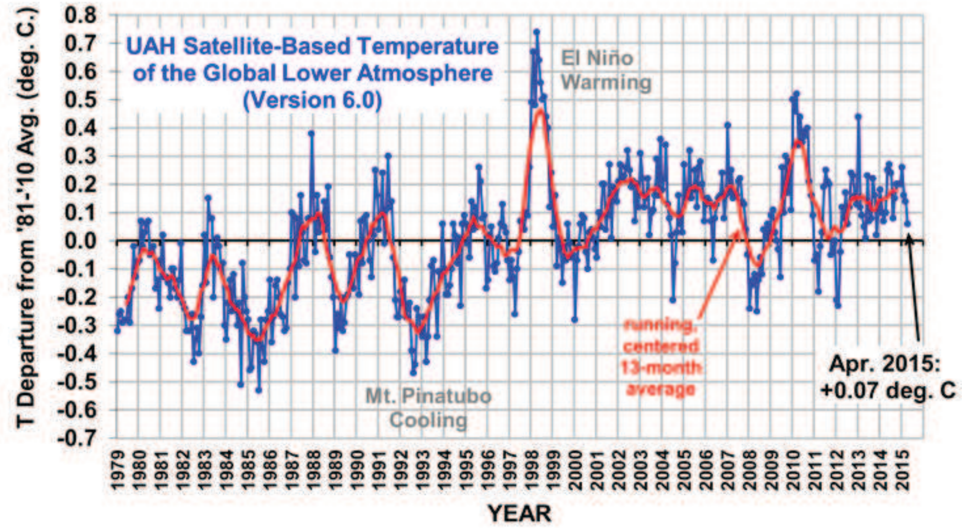

Figure 3: Temperature of the lower atmosphere as observed by satellites. There has been no appreciable warming since the year 1998. From R. Spencer [10].

> would rise by 8 K."

Many subsequent studies of the physics of greenhouse gases have confirmed Arrhenius's conjecture (1) that the temperature increase $\Delta T = T_2 - T_1$ due increasing the concentration of CO_2 from C_1 with temperature T_1 to C_2 with temperature T_2 should be proportional to $\ln(C_2/C_1)$. The logarithmic dependence comes from a peculiar detail of how CO_2 absorbs infrared radiation of various frequencies. This peculiarity is not shared with other greenhouse gases, like the most important one, water vapor H_2O, or the much less important one, methane CH_4. Readers interested in more details about the cause of the logarithmic dependence can find them in a recent paper by Wilson and Gea-Banacloche [8].

Convection of the atmosphere, water vapor and clouds all interact in a complicated way with the change of CO_2 to give the numerical value of the doubling sensitivity S. His limited understanding of absorption of radiation by CO_2, and of the structure of the atmosphere, only allowed Arrhenius to make an educated guess of the doubling sensitivity. More than a century after Arrhenius, and after the expenditure of many tens of billions of dollars on climate science, the value of S is still an educated guess. The most recent report of the Intergovernmental Panel for Climate Change (IPCC) states "equilibrium climate sensitivity is likely in the range 1.5 K to 4.5 K (high confidence)" [9]. As the Roman poet Horace remarked: *Parturient montes, nascetur ridiculus mus*, "Mountains will go into labor, a ridiculous mouse will be born."

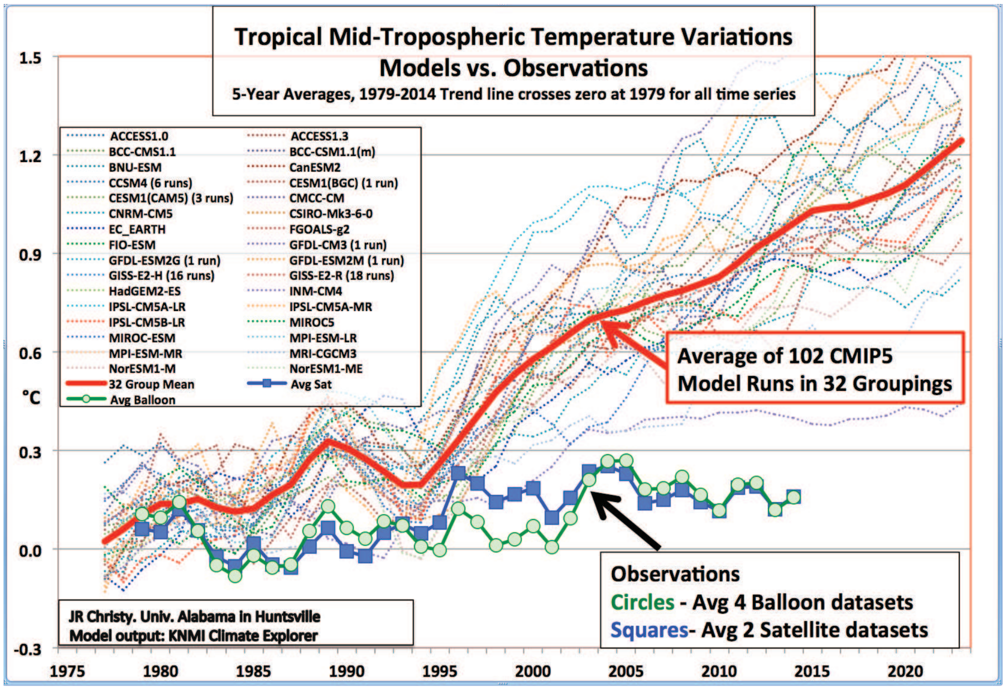

Figure 4: A comparison of satellite and balloon observations of the change in the weighted average temperature of the atmosphere from the surface to 50,000 ft altitude. Courtesy of J. Christy, [11].

3 Overestimate of S

Contrary to the predictions of most climate models, there has been very little warming of the Earth's surface over the last two decades. As shown in Fig. 3 satellite measurements indicate that the lower atmosphere has had no warming for at least 20 years [10]. Models predict that the lower atmosphere (the troposphere) should warm more rapidly than the Earth's surface, the opposite of what has been observed. A comparison of observed temperature trends from satellites and balloons is shown in Fig. 4. The discrepancy between models and observations is also summarized by Fyfe, Gillett and Zwiers [12] as shown in Fig. 5. As one can see from Fig. 5, the warming observed over the period 1993-2012 has been about half the predicted value, while the observed warming during the period 1998-2012 has been about one fifth of the model predictions. And the discrepancy may well be worse than indicated by Fyfe *et al.*[12], who used surface temperature records that are plagued with systematic errors, like urban heat island effects [13], that give an erroneous warming trend to the Earth's surface temperature. The satellite data of Fig. 3 and Fig. 4 does not have these systematic errors.

At this writing, more than fifty mechanisms have been proposed to explain the discrepancy of Fig. 4 or Fig. 5. These range from aerosol cooling, to heat absorption by the ocean. Some of the more popular excuses for the discrepancy have been summarized by Fyfe *et al.*[12]. But the most straightforward explanation is that the doubling sensitivity, which most models assume to be close to "most likely" IPCC value of $S = 3$ K is erroneous

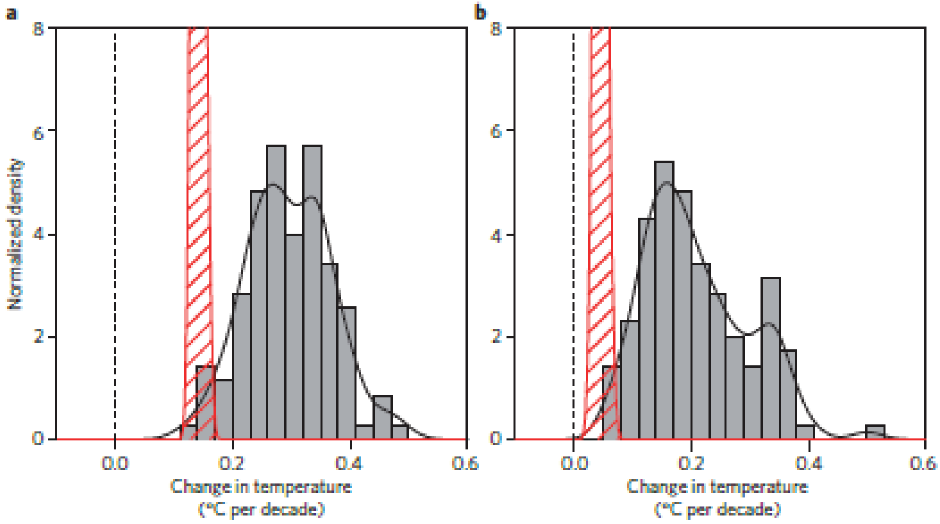

Figure 5: Trends in global mean surface temperature. **a.** 1993-2012. **b.** 1998-2012. Histograms of observed trends (red hatching) are from 100 reconstructions of the HadCRUT4 dataset^1. Histograms of model trends (grey bars) are based on 117 simulations of the models, and black curves are smoothed versions of the model trends. The ranges of observed trends reflect observational uncertainty, whereas the ranges of model trends reflect forcing uncertainty, as well as differences in individual model responses to external forcings and uncertainty arising from internal climate variability. From Fig. 1 of J. C. Fyfe, N. P. Gillet and F. W. Zwiers [12].

and much too large. If one assumes negligible feedback, that is, that other properties of the atmosphere change little in response to additions of CO_2, the doubling efficiency can be estimated to be about $S = 1$ K. The much larger doubling sensitivities claimed by the IPCC, which look increasingly dubious with each passing year, come from large positive feedbacks. The most popular feedback mechanism is an increase of water vapor at higher altitudes of the atmosphere. Changes in cloudiness can also provide either positive feedback which increases S or negative feedback which decreases S. The simplest interpretation of the observational data of Fig. 5 is that the net feedback is small and possibly even negative. For example, recent work by Harde [14] indicates a doubling sensitivity of $S = 0.6$ K.

4 Time Required to Raise the Temperature by ΔT

Fig. 2 shows that much larger CO_2 increases, $\Delta C = C - 400$ ppm, are needed to produce a given temperature increase ΔT for smaller doubling sensitivities S than for larger sensitivities. This is also clear from Eq. (2). In this section we give a simple derivation for for how much time, Δt, is needed to produce a given temperature increment ΔT.

If the CO_2 concentration is C_1, at the present time t_1, the concentration C_2 at a later time t_2 will be

$$C_2 = C_1 + \int_{t_1}^{t_2} R(t)dt \tag{3}$$

where the rate of increase of the concentration at time t is $R = dC/dt$. For a constant rate of increase (3) simplifies to

$$C_2 = C_1 + R\Delta t, \quad \text{where} \quad \Delta t = t_2 - t_1. \tag{4}$$

Substituting (4) into (2) and solving for Δt we find

$$\Delta t = \frac{C_1}{R}\left(2^{\Delta T/S} - 1\right). \tag{5}$$

Using (5) we see that for current CO_2 concentration $C_1 = 400$ ppm, the time to raise the temperature by $\Delta T = 2$ K at the current rate of increase

$$R = 2 \text{ ppm/year}, \tag{6}$$

is

$$\Delta t = 200\left(2^{2\text{K}/S} - 1\right) \text{years}. \tag{7}$$

The solutions to (7) for various possible doubling sensitivities are shown in years on Fig. 2 at the points where the temperature increment functions $\Delta T\ (C,\ S)$ cross the horizontal line corresponding to $\Delta T = 2$ K.

5 Benefits of CO_2.

More CO_2 in the atmosphere will actually be good for the planet. Few realize that the world has been in a CO_2 famine for millions of years, a long time for us, but a passing moment in geological history. Over the past 550 million years since the Cambrian [15], when abundant fossils first appeared in the sedimentary record, CO_2 levels have averaged many thousands of parts per million (ppm) not today's few hundred ppm, which are not that far above the minimum level, around 150 ppm, when many plants die of CO_2 starvation [16]. A typical estimate of past CO_2 levels in is shown in Fig. 6

A particularly dramatic example of the response of green plants to increases of atmospheric CO_2 is shown in Fig. 7 from the work of Idso *et al.* [17]. All green plants grow faster with more atmospheric CO_2. On average it is found that the growth rate is proportional to the square root of the CO_2 concentrations, so the increase in CO_2 concentrations from about 300 ppm to 400 ppm over the past century should have increased growth rates by a factor of about $\sqrt{4/3} = 1.15$ or 15%. Most crop yields have increased by much more than 15% over the past century. Better crop varieties, better use of fertilizer, better water management, etc. have all contributed. But the fact remains that a substantial part of the increase is due to more atmospheric CO_2, as one would expect from inspection of Fig. 7.

We owe our existence to green plants that convert CO_2 molecules and water molecules, H_2O, to carbohydrates with the aid of sunlight. Land plants get the carbon they need from the CO_2 in the air. Most plants draw other essential nutrients, water, nitrogen, phosphorus,

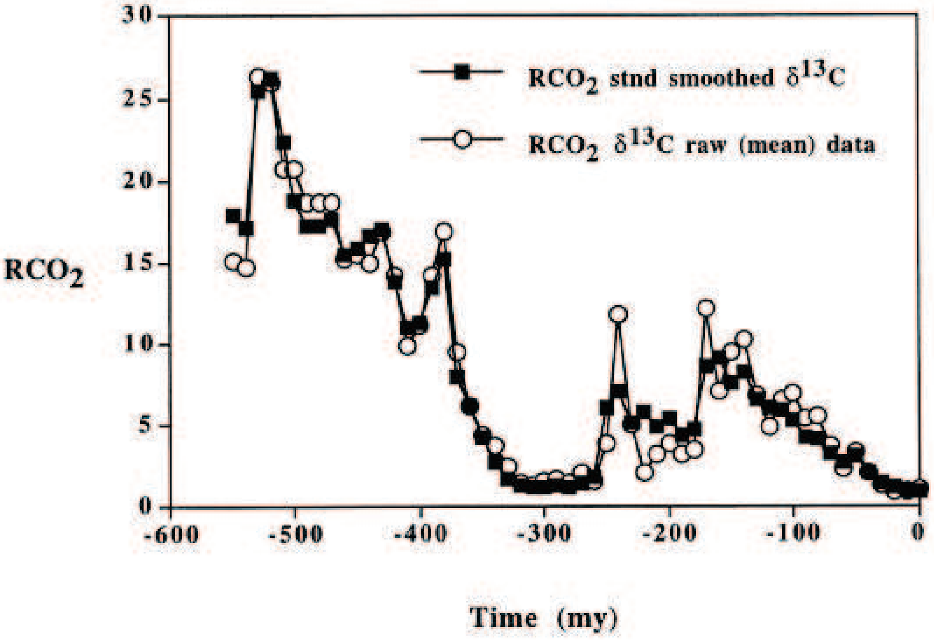

Figure 6: Estimate of past CO_2 levels (1 RCO_2 = 280 ppm, my = million years) during the Phanerozoic, when a clear fossil record can be seen in sedimentary rocks. A typical Phanerozoic CO_2 level is $RCO_2 = 5 = 1400$ ppm, much higher than today's level of 400 ppm. From R. A. Berner and C. Kothavala [15].

potassium, etc. from the soil. Just as plants grow better in fertilized, well-watered soils, they grow better in air with several time higher CO_2 concentrations than present values. The current low CO_2 levels have exposed a design flaw, made several billion years ago by Nature when she first evolved the enzyme, Ribulose-1,5-bisphosphate carboxylase/oxygenase, or "rubisco" for short. Rubisco is the most abundant protein in the world. Using the energetic molecules, adenosine triphosphate or ATP, produced by the primary step of photosynthesis, rubisco converts CO_2 to simple carbohydrate molecules that are subsequently elaborated into sugar, starch, amino acids and all the other molecules on which life depends. The last "c" in the nickname rubisco or "carboxylase" in the full word remind us of rubisco's design target, CO_2.

At current low levels of atmospheric CO_2, much of the available CO_2 is used up in full sunlight and this spells trouble for the plant. The last letter "o" in the nickname rubisco or the "oxygenase" in the full name remind us that an alternate enzyme target is the oxygen molecule O_2. If rubisco, primed with chemical energy from ATP, cannot find enough CO_2, it will settle for an O_2 molecule and produce toxic byproducts like hydrogen peroxide instead of useful carbohydrates. This "photooxydation" is a serious problem. At current low CO_2 levels it leads to a reduction of photosynthetic efficiency by about 25% in C3 plants which include many major crops: wheat, rice, soybeans, cotton and many others. In these plants, the first molecule synthesized from CO_2 has 3 carbons, and they are said to have the C3

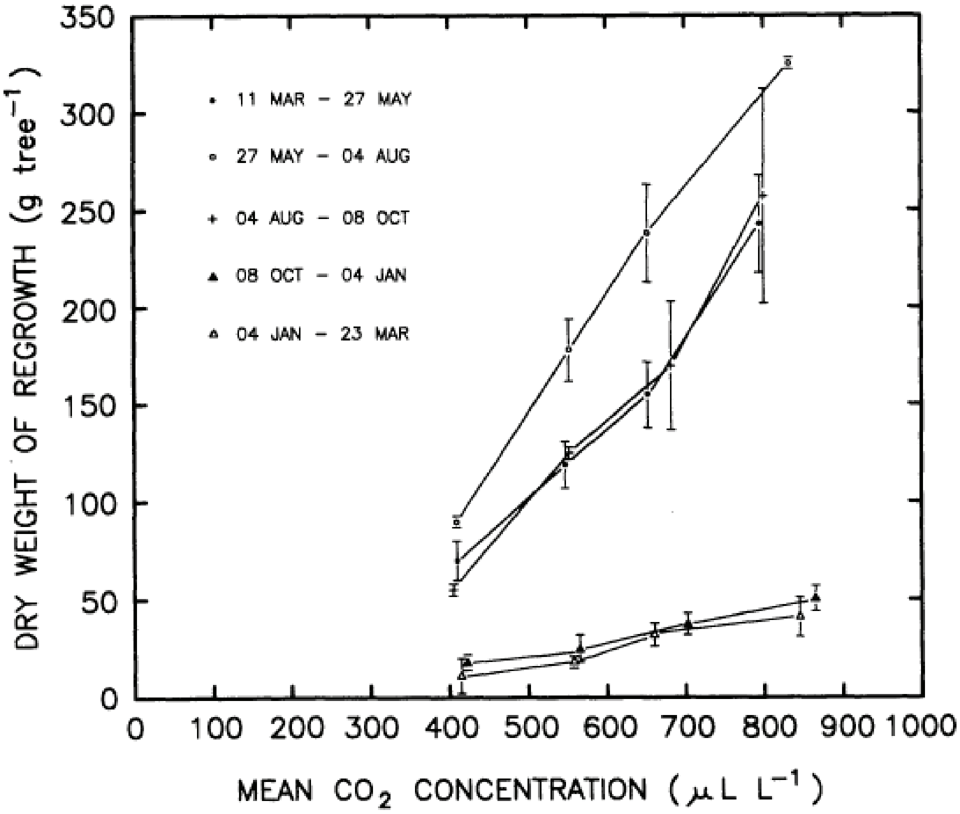

Figure 7: Effect of CO_2 on growth of sour orange trees (*Citrus aurantium L.*) in Phoenix, Arizona1 (1μL L^{-1} = 1 ppm) . From Idso and Kimball [17].

photosynthetic pathway. The low CO_2 levels of the past tens of millions of years have driven the development of C4 plants (corn and sugar cane, for example) that cope with oxygen poisoning of rubisco by protecting it in special structures within the leaf. CO_2 molecules are ferried into the protective leave structure by molecules with 4 carbons, which give the C4 pathway its name. The extra biochemical energy for the more elaborate C4 photosynthetic pathway comes at a cost, but one that is worth paying in times of unusually low CO_2 concentrations, like those today. Thousands of experiments leave no doubt that all plants, both the great majority with the old-fashioned C3 path, but also those with the new-fangled C4 path, grow better with more CO_2 in the atmosphere [18].

But the nutritional value of additional CO_2 is only part of its benefit to plants. Of equal or greater importance, more CO_2 in the atmosphere makes plants more drought-resistant. Plant leaves are perforated by stomata, little holes in the gas-tight surface skin that allow CO_2 molecules to diffuse from the outside atmosphere into the moist interior of the leaf where they are photsynthesized into carbohydrates. A leaf in full sunlight can easily reach a temperature of 30 C, where the concentration of water molecules, H_2O, in the moist interior air of the leaf is about 42,000 ppm, more than one hundred times greater than the 400 ppm concentration of CO_2 in fresh air outside the leaf. And CO_2 molecules, being much heavier than H_2O molecules, diffuse more slowly in air. So depending on the relative humidity of the

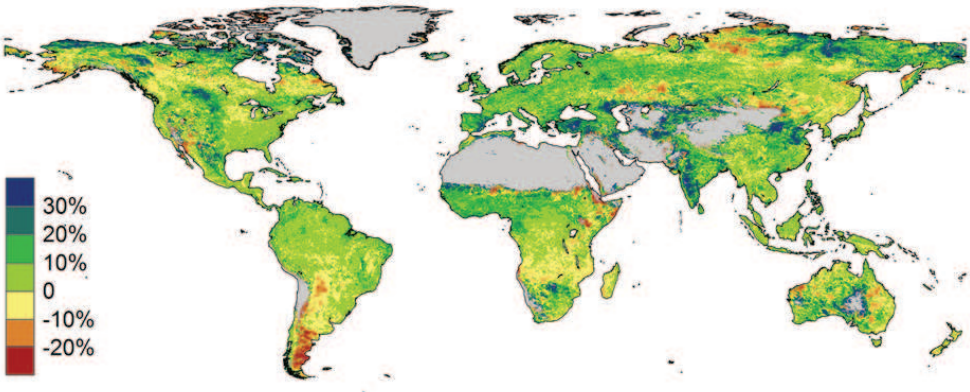

Figure 8: Greening of the Earth as observed by satellites.

outside air, as many as 100 H_2O molecules can diffuse out of the leaf for every CO_2 molecule that diffuses in, to be captured by photosynthesis. This is the reason that most land plants need at least 100 grams of water to produce one gram of carbohydrate.

In the course of evolution, land plants have developed finely-tuned feedback mechanisms that allow them to grow leaves with more stomata in air that is poor in CO_2, like today, or with fewer stomata for air that is richer in CO_2, as has been the case over most of the geological history of land plants. If the amount of CO_2 doubles in the atmosphere, plants reduce the number of stomata in newly grown leaves by about a factor of two. With half as many stomata to leak water vapor, plants need about half as much water. Satellite observations like those of Fig. 8 from R. J. Donohue [19] have shown a very pronounced "greening" of the Earth as plants have responded to the modest increase of CO_2 from about 340 ppm to 400 ppm during the satellite era. More greening and greater agricultural yields can be expected as CO_2 concentrations increase further.

6 Summary

1. Observations over the past two decades show that the warming predicted by climate models has been greatly exaggerated. The temperature increase for doubling CO_2 levels appears to be close to the feedback-free doubling sensitivity of $S = 1$ K, and much less than the "most likely" value $S = 3$ K promoted by the IPCC and assumed in most climate models.

2. If CO_2 emissions continue at levels comparable to those today, centuries will be needed for the added CO_2 to warm the Earth's surface by 2 K, generally considered to be a safe and even beneficial amount.

3. Over the past tens of millions of years, the Earth has been in a CO_2 famine with respect to the optimal levels for plants, the levels that have prevailed over most of the geological history of land plants. More atmospheric CO_2 will substantially increase plant growth rates and drought resistance.

4. Increasing concentrations of CO_2 over the next few centuries will benefit the planet, so there is no social cost of CO_2. More precisely, the social cost of CO_2, per se, is negative.

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BEFORE THE OFFICE OF ADMINISTRATIVE HEARINGS
FOR THE MINNESOTA PUBLIC UTILITIES COMMISSION
STATE OF MINNESOTA

In the Matter of the Further Investigation in to
Environmental and Socioeconomic Costs
Under Minnesota Statute 216B.2422, Subdivision 3

OAH Docket No. 80-2500-31888

MPUC Docket No. E-999-CI-14-643

Direct Testimony and Exhibits of

Professor Robert Mendelsohn

June 1, 2015

PROFESSOR ROBERT MENDELSOHN

OAH 80-2500-31888

MPUC E-999/CI-14-643

TABLE OF CONTENTS

I. INTRODUCTION

Q. Please state your name, address, and occupation.

A. My name is Robert Owen Mendelsohn.

My professional address is Yale School of Forestry and Environmental Studies, 195 Prospect Street, New Haven CT 06511.

My occupation is a professor of environmental economics.

Q. **Please describe your educational background and professional experience.**

A. I graduated in 1973 from Harvard College, BA, Magna Cum Laude.

I graduated in 1979 from Yale Economics Department, PhD.

I was an assistant professor at the University of Washington, Seattle 1979-1983.

I was a visiting assistant professor at University of Michigan 1983-1984.

I have been a professor at Yale University since 1984.

My official title at Yale University is the Edwin Weyerhaeuser Davis Professor at the School of Forestry and Environmental Studies, with appointments in the Department of Economics and the School of Management. For the last 22 years, I have been working on measuring the benefits of mitigating greenhouse gas emissions. I have written 8 books and 63 peer reviewed articles on climate change impacts.

II. OVERVIEW OF OPINIONS

Q. What are the purposes of your testimony in this proceeding?

A. My purpose is to provide insight into how to measure the “Social Cost of Carbon” (SCC) to help guide Minnesota’s decision on how to place a value on a ton of carbon dioxide (CO_2) emission.

Q. Could you summarize your principal conclusions and recommendations?

A. First, using the results of DICE, one of the Integrated Assessment Models that has been used widely to study climate change, my estimate of the SCC is between $4 and $6/ton, under the assumptions identified in Table 1 of my attached report.

Second, my estimate is a conservative one. Recent evidence, as discussed in the reports of Professors Lindzen, Happer, and Spencer, suggest that the climate sensitivity assumed by the Intergovernmental Panel on Climate Change (IPCC) is overstated. Roy Spencer notes that historical observed warming has been much less than climate models predicted. This raises questions about whether the range of climate sensitivity suggested by the IPCC is too high. W. Happer (2015) argues that climate sensitivity is likely to be 1, which would be the effect of just increasing carbon dioxide alone. He argues there are no positive feedbacks from this forcing which would cause the climate sensitivity to be higher. Richard Lindzen (2015) argues in his testimony that the climate sensitivity could be between 0.85C and 1.5C and is very likely less than 2C. If the climate sensitivity is 1.5 (as Dr. Lindzen and others have suggested), the SCC lies between $0.30 and $0.80/ton, as shown in Table 2 of the Report. If the climate sensitivity value is 2.0, the SCC lies between $1.10 and $2.00/ton, as shown in Table 2.

Third, it would be inadvisable to adopt the current Federal SCC as estimated by the Federal Interagency Working Group on Social Cost of Carbon (IWG). Although well intentioned, the IWG made numerous theoretical and modeling errors and significantly overestimated the SCC.

Q. Have you prepared a report that contains your opinions?

A. The attached report contains the details behind my opinion.

III. SOCIAL COST OF CARBON

Q. How is the social cost of carbon defined?

A. The social cost of carbon (SCC) measures the additional damage caused by a ton of carbon dioxide emission. Carbon dioxide emissions last for many decades in the atmosphere. The SCC is the present value of this stream of damage, the sum of the discounted future damage in todays' dollars. The current SCC in 2015 measures the damage from adding a ton of carbon dioxide to the atmosphere today.

Q. Which social cost of carbon is appropriate for policy purposes?

A. What I call the "optimal SCC" is the appropriate social cost of carbon for policy purposes. The optimal social cost of carbon minimizes the present value of the sum of the climate damage and the mitigation cost to society. It reduces emissions until the cost of the last reduction is just equal to the marginal damage removed. The optimal policy equates the marginal cost of mitigation to the social cost of carbon.

If the government intends to use the social cost of carbon as a price for carbon in making future mitigation decisions, the government is going to equate the marginal cost of mitigation to the social cost of carbon. If it measures the social cost of carbon given the optimal path, the program will be perfectly efficient. This is the only measure that will lead to an efficient mitigation program.

Q. How does the cost of carbon in the United States compare to the global social cost of carbon?

A. The American Cost of Carbon reflects the damage just in the United States. If the purpose of a law is to protect American citizens and their interests, it is only the American Cost of Carbon that matters. The American Cost of Carbon is currently about 5% of the global SCC. Most of the current damage from climate change is concentrated in the low latitude countries of the world.

Q. What would happen if the U.S. spent money on mitigation in accordance with a globally or nationally calculated social cost of carbon while the rest of the world did not?

A. If the United States acted unilaterally to control emissions, the US would pay the full cost of these emission reductions, but they would get only about 5% of the benefits. The remaining 95% of benefits would go to people from other countries, primarily living in the low latitudes. With only the United States doing mitigation, the program would be very wasteful because it would rely on high cost mitigation in the United States and not take advantage of the many low cost opportunities to mitigate around the world.

Q. How does the cost of carbon in Minnesota compare to the U.S. national social cost of carbon?

A. I believe that Minnesota is currently a net beneficiary of warming. Minnesota has no coastline along the Atlantic to suffer from sea level rise or future tropical cyclones. A warmer, wetter, CO_2-enriched world would be a clear gain for Minnesota agriculture. Ecological models suggest that Minnesota forests would become more productive and have more standing biomass as a result of near term climate change. A slightly warmer winter is likely to be beneficial as well and would offset possible damage from a slightly warmer summer. The state is not likely to be a net beneficiary if near term emissions are reduced.

Q. What would happen if Minnesota spent money on mitigation in accordance with a globally or nationally calculated social cost of carbon while the rest of the world did not?

A. Minnesota does not contribute enough greenhouse gas emissions to be able to make much difference to global temperatures. So a Minnesota alone mitigation program would be costly to Minnesota and make only the smallest (and likely an imperceptible) change in the climate. Minnesota as a whole would not benefit. The current state cost of carbon is likely negative.

The biggest problem with Minnesota being the only state with a high price on carbon is the economic cost to the state. There are few low cost options to reduce carbon in the state. Minnesota would have to resort to high cost options while the surrounding states did very little. In fact, the surrounding states could very well take advantage of the situation and try to lure Minnesota businesses to move to their state so as to avoid the high price of carbon in Minnesota. This well-known “leakage” problem is one of the reasons why economists argue for a universal price of carbon.

IV. OVERVIEW OF MODELS

Q. Are you familiar with the Integrated Assessment models used by the Interagency Working Group to calculate the federal social cost of carbon?

A. I am familiar with the three Integrated Assessment Models used by the Interagency Working Group: DICE, FUND, and PAGE. I have read papers about all three models and I know the creators of all three models.

Q. Can you describe DICE and how it works?

A. DICE is an Integrated Assessment Model of the global economy that predicts future economic growth, energy demand, and greenhouse gas emissions. The model also captures how emissions alter greenhouse gas concentrations, temperature, and global climate damage. The model is designed to calculate optimal mitigation strategies that balance the cost of emission reductions against the benefit of reduced damage.

Q. Can you describe your past experience with the DICE model?

A. The DICE model is relatively easy to use and so I have combined the model with other research I have done on mitigation. For example, I used DICE to understand how important storing carbon in forests might be as a mitigation strategy. I have also used DICE to understand how changing estimates of land use emissions might affect global mitigation strategies.

Q. Can you describe the FUND model and how it works?

A. The structure of the FUND model is similar to the DICE model in that it has a model of the economy integrated with a model of climate and climate impacts. The most significant difference in the FUND model is that it has a much more detailed model of climate damage. FUND breaks the world into several large regions and calculates the damage in each region by market sectors such as agriculture, forest, water, coastal, and energy as well as by nonmarket sectors such as human health and ecosystems. Like DICE, FUND calculates future emissions of greenhouse gases. It is also an optimizing model designed to calculate the optimal mitigation path. I am familiar with the damage estimates made by FUND and find that they are generally quite consistent with my own research on damage.

Q. Do the FUND and DICE models tend to produce comparable results?

A. The FUND and DICE models react to stimulus in very similar ways. Faster economic growth lead to more emissions, faster technical change in mitigation lead to increases in mitigation over time, and more mitigation leads to lower damage. When comparing them directly, the DICE model assumes that damage increases more rapidly with warming. FUND assumes that damage is minimal at low levels of warming. DICE consequently generates a higher estimate of the social cost of carbon than FUND. I believe that the FUND damage function is more accurate than the DICE damage function, especially for near term temperature changes. But the models are similar.

Q. What is your opinion regarding the reliability of the PAGE model?

A. The PAGE model is a simulation model that was designed to reflect uncertainty that modelers might have about the parameters of the model. The model was not designed to optimize and so is not a reliable model for predicting the optimal path of mitigation. The model was also intended to be a tool for people to explore whatever assumptions they wished to make about parameters. So the model is less careful about grounding assumptions in empirical evidence. It is more of a tool to explore one's imagination about what climate change could be. As such, I have little confidence in the results generated by PAGE in contrast to the two other models used by the Interagency Working Group: DICE and FUND. The PAGE model captures the imagination of academics but is not well grounded in economic theory or empirical evidence.

V. DICE MODEL

Q. Have you prepared calculations of the social cost of carbon using the DICE model?

A. I have downloaded the most recent version of DICE (DICE2013) from Professor William Nordhaus's website in order to calculate the social cost of carbon in DICE.

Q. Does the DICE model include any parameters that can be adjusted?

A. The DICE model comes with baseline assumptions about the important parameters that affect the social cost of carbon. These baseline parameter values reflect the learned opinions of Professor Nordhaus.

However, the model is relatively transparent so that it is possible to adjust these assumptions and test how they affect the social cost of carbon.

Q. What parameters have you adjusted?

A. The key parameters that I have explored include the shape of the damage function, climate sensitivity, and the discount rate.

Q. Does the DICE model contain a "damage function" component?

A. The damage function in DICE predicts the damage each future year based on the GDP of that year and the predicted temperature change that year. The DICE model assumes that damage is proportional to GDP. A doubling of the size of the global economy thus doubles the damage. DICE also assumes that the damage as a proportion of GDP increases with the square of temperature change. A 2°C warming is assumed to cause damage equal to 1% of GDP. A 4°C warming is assumed to increase that percentage to 4% of GDP. Future damage thus accelerates quickly as temperatures warm. Finally DICE assumes that the preindustrial temperature (the global temperature effectively in 1900) was the optimal temperature. Any increase from 1900 is therefore harmful.

Q. Have you made adjustments to the damage function of the DICE model?

A. Empirical research suggests that the optimal temperature for the world may well be slightly higher than the temperature in 1900. A slightly warmer, wetter, and CO_2–enriched world may be a better place. The research indicates that warming of 1.5-2°C may be slightly beneficial. Given that today's temperature is already 0.8°C warmer than in 1900, the research is indicating that another 0.7-1.2°C of warming could lead to small net benefits. Of course, this is not to imply that mankind should try to tamper with the temperature of the planet. It merely notes that there is scant evidence that warming of this magnitude leads to harmful net impacts.

I have consequently developed two alternative damage functions in DICE that adjust the temperature upon which net damages begin. One modified damage function assumes that net damage will not begin until temperature rises above 1.5°C and the other modified damage function assumes net damage does not begin until temperature rises 2°C above 1900 levels.

I then calculate the social cost of carbon with both (the 1.5°C, and the 2.0°C) damage functions.

Q. Can you explain your basis for making those adjustments?

A. Over the last 20 years, I have been measuring climate damage all over the world. I have used empirical research, integrated simulation models, and ecosystem models to capture effects in many of the sectors that will be affected. The results generally favor the assumption in the DICE model that damage is a quadratic function of global temperature change. However, the results do not suggest that the 1900 global temperature was the "optimal" climate. In contrast, the results suggest that a slightly warmer climate is in fact "optimal". That is, net global benefits are maximized at a temperature slightly warmer than 1900 (1.5°C, and the 2.0°C warmer). These temperatures are slightly warmer (0.7°C to 1.2°C) than the temperature we experience today.

Higher levels of carbon dioxide lead to carbon fertilization of plants. That is, higher carbon dioxide levels increase plant productivity and make them slightly more drought resistant. Doubling carbon dioxide is expected to increase crop productivity by 30% and tree productivity by as much as 70%. These effects dominate the initial impacts over the next several decades to the forest and agriculture sectors. The carbon fertilization of trees has also led to an overall increase in ecosystem productivity and standing biomass which is an overall net benefit for ecosystems.

These broad statements about net global impacts summarize a complex set of changes. The impact of climate change is very different across the world. In general, the nations near the low latitudes are already too warm. For them, warming starting in 1900 was immediately harmful. The low latitude countries would benefit from a global temperature that is cooler than the temperature in 1900. For the mid-latitudes, the net effect of warming from 0-2°C is slightly beneficial as the benefits slightly outweigh the damage. For the high latitudes, the evidence suggests that warming of 0-2°C provides larger net benefits. Another point that is important to understand is that the effect of warming is different in each affected sector. There can be some damage in places that generally benefit from warming and some benefits in places that are overall harmed by warming. For example, tropical countries with net damage from warming are nonetheless getting ecosystem benefits from the increase in ecosystem productivity and biomass. Similarly, in places like Minnesota where there are net benefits, there are still damages associated with global warming such as hotter summers. The net measurement is merely an indication of the relative size of the benefits versus the damage.

Q. What is a discount rate?

A. The discount rate is the price of time. It is a reflection of the fact that that there is an interest rate which causes wealth to grow over time. For example, the (inflation adjusted) market rate of interest has been about 5% for more than a century. If society invests in the market rate of interest, resources grow exponentially at that interest rate. The discount rate accounts for this interest rate when comparing future dollars with current dollars. Future dollars are discounted back to today using that very same interest rate. The discount rate affects the social cost of carbon because so much of the damage caused by a ton of carbon dioxide occurs far into the future.

Q. Can policymakers choose whatever discount rate suits them?

A. The interest rate is determined by global savings and investment. It is a market rate that reflects how much people are willing to save and the productivity of capital investments. Society can raise the interest rate by taxing capital and they can lower the interest rate by subsidizing capital. However, if policy makers arbitrarily choose different discount rates for different projects, they are implicitly adjusting the rate of return in just those projects. For example, if the government chooses to use 3% as the discount rate for mitigation and 5% for all other private and public projects, they are implicitly choosing to get a 3% rate of return on mitigation. The mitigation program would consequently be a relatively poor investment of public funds compared to other choices. Society would be better off investing current mitigation into a market fund that would pay for future mitigation. So there are deleterious consequences to selecting different discount rates for different projects which is why the Office of Management and Budget (OMB) encourages all agencies to use the same discount rate.

Q. What discount rates have you considered in your calculations?

A. The discount rate in DICE is calculated internally to be consistent with the growth in GDP per capita. As long as the economy grows at the rate we are familiar with (2% per year), the interest rate is expected to remain at 5%. However, if the growth rate of the economy slows in the far future as DICE predicts, the interest rate will fall to slightly lower levels. My baseline assumption is that the discount rate in DICE (the interest rate) is a reasonably appropriate and conservative estimate of the discount rate.

However, some calculations of the social cost of carbon have used constant discount rates that do not adjust with the growth rate of income. I have calculated what effect choosing alternative constant discount rates have upon the social cost of carbon.

Q. What discount rates are recommended by the federal Office of Management and Budget?

A. The Office of Management and Budget generally argues that public projects should use the market rate of interest (currently 5%). In cases where regulations force private companies to invest in projects with risky benefits, the Office of Management and Budget recommends a 7% discount rate. Because climate change involves scientific uncertainties, a 7% discount rate may be fitting given the inherent risks associated with this uncertainty.

Q. What discount rates are used by the federal government's IWG to calculate the social cost of carbon?

A. The Interagency Working Group uses three constant discount rates to calculate the social cost of carbon: 2.5%, 3%, and 5%.

Q. What is a climate sensitivity value?

A. The climate sensitivity is an atmospheric-oceanic science calculation that expresses the consequence of doubling greenhouse gases on long run temperature. For example, the best guess of the IPCC is that the climate sensitivity is 3. This implies that a doubling of CO_2 in the atmosphere leads to a long run temperature increase of 3°C. Note that it may take many centuries for the climate to reach the long run temperature given any particular level of greenhouse gases.

Q. What climate sensitivity values are used by the IWG?

A. The IWG explore a range of climate sensitivity factors given by a probability function. The mean climate sensitivity in their analysis is 3.5 and the 95% confidence interval is 1.7 to 7.1. These values are slightly higher than what the IPCC recommends which is a best guess of 3 and a likely range of 1.5 to 4.5.

Q. Have you consulted the testimony of Professors Richard Lindzen, William Happer and Roy Spencer in this proceeding?

A. Yes.

Q. What climate sensitivity values do Professors Lindzen, Happer, and Spencer believe are appropriate, based on the scientific evidence?

A. Professor Lindzen argues in his testimony that the climate sensitivity could be between 0.85C and 1.5C and is very likely less than 2C. Professor Happer argues that the climate sensitivity is 1. This is the value that carbon dioxide all by itself would cause. He argues there are no positive feedback effects that would lead to higher values. Dr. Spencer argues that the historic temperature record suggests a much slower path of warming than the climate model predictions. Dr Spencer's observation implies that either the climate models have too high a climate sensitivity (as suggested by both Professor

Happer and Lindzen) or that they have too quick of an adjustment rate for transient temperatures. In either case, damage which depends on the actual temperature is postponed into the future. The SCC should be lower than the Integrated Assessment models currently predict in order to be consistent with the current empirical evidence.

Q. What sensitivity values have you used in your analysis?

A. I have explored a wide range of climate sensitivity values including 1, 1.5, 2, 2.5, 3, and 4.5.

Q. Can you explore the effect of uncertainty using DICE?

A. I have explored how uncertainty about the damage function, climate sensitivity, and the discount rate each affect the optimal social cost of carbon. By varying these parameters, one can test how they affect the possible distribution of the social cost of carbon.

VI. RESULTS

Q. Can you summarize the results of your calculations of the social cost of carbon produced by the DICE model as you have modified it?

A. If I rely on the baseline parameters in DICE, the IPCC estimate of climate sensitivity of 3, and include what I believe to be a more accurate damage function based upon more recent empirical evidence, the resulting social cost of carbon lies between $4-$6/ton. If climate sensitivity is 1.5, the social cost of carbon is between $0.30 and $0.80, as shown in Table 2 of my Report. If the climate sensitivity value is 2.0, the SCC lies between $1.10 and $2.00/ton, as shown in Table 2.

Q. Why is a range of values appropriate?

A. It is not possible to identify a single value of the social cost of carbon given the wide uncertainty about future events. The range of values illustrates the uncertainty surrounding the estimate given our current scientific and economic understanding.

Q. In your opinion, what is the most reasonable and best available estimate of the social cost of carbon, based on the available data and current scientific understanding?

A. My estimate of the social cost of carbon is between $4-6/ton of CO2. This estimate is conservative, in light of the testimony of Professors Lindzen, Happer and Spencer. If the climate sensitivity is 1.5 (as Dr. Lindzen and others have suggested), the SCC lies between $0.30 and $0.80/ton. If the climate sensitivity value is 2.0, the SCC lies between $1.10 and $2.00/ton. These values are consistent with the current Minnesota values for 2014, which were reported to be between a low of $0.44/ton and a high of $4.53/ton

VII. IWG'S SOCIAL COST OF CARBON

Q. Do you agree with the federal social cost of carbon calculated by the IWG?

A. The IWG made many mistakes when calculating the social cost of carbon. The resulting calculations overstate the social cost of carbon a great deal.

Q. What conceptual error did the IWG make in their calculation of the social cost of carbon?

A. The IWG calculated the social cost of carbon assuming zero abatement not only today but forever. Not only in the United States but everywhere. This is a mistake for several reasons. First, we are already doing some mitigation. Second and more importantly, the moment that the federal social cost of carbon was first used for policy, it became an overestimate of damage. That is, the value did not take into account the mitigation that was being done. The IWG made a conceptual error by measuring the wrong SCC.

Q. Did the IWG use the Integrated Assessment Models correctly?

A. The IWG used three Integrated Assessment models (DICE, FUND and PAGE) to calculate the social cost of carbon, but it did not use them correctly.

The IWG substituted many of their own assumptions instead of using the assumptions in each model. For example, the IWG made its own assumptions about GDP, discount rates, and emissions. The IWG assumptions are not consistent with each other much less with the models. For example, different GDP paths imply different future interest rates. The interest rates in the IWG were not consistent with their assumptions about GDP.

The IWG did not use the climate sensitivities in the Integrated Assessment models. The IWG used their own estimate of climate sensitivity.

The only part of each model that the IWG appears to have used is the damage function.

Q. Does the IWG properly account for the uncertainty surrounding the social cost of carbon?

A. Because the IWG did not take into account mitigation, they also failed to capture how society will likely react as it learns more about climate change. They effectively assumed that uncertainty never gets resolved. They assume society is just as uncertain in 2300 about the various parameters of the model as it is today. But society will learn about climate change as the planet warms. We will see how quickly temperature changes. We will see what the damages are. For example, we will find out whether or not there are a trillion dollars of damage per year in 2050 when it becomes 2050. If society finds out that climate change is more harmful than we thought, society will react and do more mitigation. The importance of long term uncertainty falls as we learn and act. By assuming that society will never mitigate greenhouse gases, the IWG has overblown the harm from greenhouse gases and the importance of uncertainty.

Q. Do you believe that the IWG's approach produces a scientifically valid and accurate calculation of the social cost of carbon?

A. The IWG has vastly overstated the social cost of carbon. It states that it uses the DICE and FUND model to calculate the social cost of carbon, but it really has substituted its own unfounded assumptions for both models.

Q. Can you explain your reasoning?

A. The IWG should not have assumed that there will be zero future mitigation. The IWG should not have used such low discount rates. The IWG should have adjusted the damage function downward. The IWG should not have assumed that society would never learn about climate change. All these errors cascade upon each other, over emphasizing effects which might or might not happen hundreds of years from now, and exaggerating the damage of a ton of emission today. For all of these reasons, the IWG vastly overestimated the social cost of carbon.

BEFORE THE OFFICE OF ADMINISTRATIVE HEARINGS
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STATE OF MINNESOTA

In the Matter of the Further Investigation in to
Environmental and Socioeconomic Costs
Under Minnesota Statute 216B.2422, Subdivision 3

OAH Docket No. 80-2500-31888

MPUC Docket No. E-999-CI-14-643

Exhibit 1

to

Direct Testimony of

Professor Robert Mendelsohn

June 1, 2015

2/2015

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BEFORE THE OFFICE OF ADMINISTRATIVE HEARINGS
FOR THE MINNESOTA PUBLIC UTILITIES COMMISSION
STATE OF MINNESOTA

In the Matter of the Further Investigation in to
Environmental and Socioeconomic Costs
Under Minnesota Statute 216B.2422, Subdivision 3

OAH Docket No. 80-2500-31888

MPUC Docket No. E-999-CI-14-643

Exhibit 2

to

Direct Testimony of

Professor Robert Mendelsohn

June 1, 2015

Minnesota SCC Decision

Robert Mendelsohn

Yale University

I. Introduction and Summary

I am the Edwin Weyerhaeuser Davis Professor at Yale University in the School of Forestry and Environmental Studies. I have been a Professor at Yale since 1984. My expertise is in environmental economics where I have specialized in measuring the benefits to society of protecting the environment.

This report provides insight into how to measure the “Social Cost of Carbon” (SCC) to help guide Minnesota’s decision on how to place a value on a ton of carbon dioxide (CO_2) emission. Minnesota has already set an environmental cost of carbon in a range of $0.44 to $4.53/ton. My principal opinions are:

1. Using the results of DICE, one of the Integrated Assessment Models that has been used widely to study climate change, my estimate of the SCC is between $4 and $6/ton, assuming the DICE discount rate (starting at 5% today, falling to 2.7% in 2200), a climate sensitivity of 3 as used by the Intergovernmental Panel on Climate Change (IPCC), and DICE damage functions that I have improved upon based on the available empirical evidence (optimal temperatures are 1.5°C above preindustrial levels and 2.0°C above preindustrial levels), as shown in Table 1 of the Report.

2. My estimate is a conservative one. Recent evidence, as discussed in the reports of Professors Lindzen, Happer, and Spencer, suggest that the IPCC climate sensitivity is overstated. Roy Spencer notes that historical observed warming has been much less than climate models predicted. This raises questions about whether the range of climate sensitivity suggested by the IPCC is too high. William Happer (2015) argues that climate sensitivity is likely to be 1, which would be the effect of just increasing carbon dioxide alone. He argues there are no positive feedbacks from this forcing which would cause the climate sensitivity to be higher. Richard Lindzen (2015) argues in his testimony that the climate sensitivity could be between 0.85C and 1.5C and is very likely less than 2C. If the climate sensitivity is 1.5 (as Dr. Lindzen and others have suggested), the SCC lies between $0.30 and $0.80/ton, as shown in Table 2 of the Report. If the climate sensitivity value is 2.0, the SCC lies between $1.10 and $2.00/ton, as shown in Table 2.

3. It would be inadvisable to adopt the current Federal SCC as estimated by the Federal Interagency Working Group on Social Cost of Carbon (IWG). Although well intentioned, the IWG made numerous theoretical and modeling errors and significantly overestimated the SCC.

II. Foundational Concepts.

A. What is climate change?

In order to measure the damage caused by climate change, one must first define what is meant by climate change. There is a great deal of popular confusion between weather and climate change. Within every climate, there are day to day and year to year changes in temperature and precipitation that we call weather. Weather changes are natural and would occur even without climate change. That is, the weather changes even if there is no climate change. Climate change refers to changes in our 30-year weather. For example, scientists have observed an increase in the planetary 30-year mean temperature over preindustrial temperatures of 0.8°C. This is quite distinct from the fact that summer temperatures are higher than winter temperatures or that one particular day in August may be very hot. In addition to changes in mean values, the climate also entails variance. For example, yearly temperature will vary around the 30-year mean given a particular variance within a single climate. Climate change could entail a change in that variance. Finally, the climate also entails extreme events such as tornadoes and tropical cyclones (hurricanes). Extreme events are rare but natural as well. For example, hurricanes are part of the pre-industrial climate. We have records of them over human history. For example a hurricane heavily damaged the Spanish armada sent by Spain to conquer England in the time of Queen Elizabeth I. The existence of a hurricane does not imply climate change. But climate change can entail a change in the frequency or intensity of extreme events such as hurricanes.

The popular press and therefore the public are confused about weather versus climate change. Every hurricane that hits a major city is reported in the news today as evidence of climate change. Although the damage per storm has increased because there is more in harm’s way today than in the past (Pielke et al. 2008), extreme events such as tropical cyclones have not changed in either their intensity or their frequency in the last 100 years (Landsea et al. 2006). That is, hurricanes are not yet evidence of climate change. Weather events such as floods and droughts continue as in the past (Pielke 2014). The harm that these events cause has increased because there is more in harm’s way, but there is scant evidence that climate change has altered the frequency or intensity of extreme events to date. In short, most of the damage that has been attributed to climate change in the popular press is actually due to weather. Even if we return greenhouse gas concentrations to their 1900 level immediately, the weather will continue because the current weather is part of our current climate.

B. Global, National, or Minnesota Impacts

The SCC is defined as the additional damage caused by a ton of carbon dioxide emission. Carbon dioxide emissions last for many decades in the atmosphere so that it is important to measure these impacts over a long time horizon. The SCC is the present value of this stream of damage, the sum of the discounted future damage in today's dollars. The current SCC in 2015 measures the damage from adding a ton of carbon dioxide to the atmosphere today.

When guiding global policy, the SCC should measure the damage around the globe. This is the damage a ton of emission would theoretically cause across the world. The optimal global greenhouse gas strategy would have every emitter in the world equate their marginal cost of abatement to this single price.

Because federal and state laws and regulations are sometimes written with only national and state goals in mind, it is helpful to define a few other measures of the benefits of greenhouse gas mitigation. The marginal damage just inside the United States of a ton of emissions would be the American Cost of Carbon (ACC). To the extent that federal laws have the explicit intention of protecting American health and welfare, the ACC is the appropriate measure of these benefits. The ACC is currently about 5% of the global SCC. That is, America will endure only 5% of the global damage from climate change over the next century. Most of the damage from climate change will be concentrated in countries in the low latitudes (Mendelsohn et al. 2006).

The marginal damage to Minnesota of a ton of emissions would be the Minnesotan Cost of Carbon (MCC) which is at most 2% (one-fiftieth) of the ACC. Research suggests that damage in America will be concentrated in the warmer states along its southern border (Mendelsohn, Nordhaus, and Shaw 1994; 1996; Mendelsohn and Neumann 1999, Mendelsohn 2003). Minnesota will likely benefit from current emissions although that will not likely remain true indefinitely. At the moment, the maximum Minnesotan share of the global SCC is 0.1% (one one-thousandth) of the SCC but the MCC is most likely negative. Reducing a ton of emissions today is not likely to lead to a net benefit for Minnesota.

It is important to understand which of the above measures to use for public policy. If the United States moves forward unilaterally and the rest of the world watches, the United States could spend a great deal on mitigation but the benefits to Americans would be quite small. The reward to Americans is what the ACC measures. America would receive about 5% of the global benefits. The remaining 95% of the benefits would go to the rest of the world.[1] Finally, if Minnesota leads the world with greenhouse gas mitigation, the benefit to the people of Minnesota would be only the MCC. Reducing emissions today will likely make Minnesota slightly worse off because the state is currently a net beneficiary of warming. I discuss the reasoning behind this conclusion below.

C. Measuring Marginal Damage

The marginal benefit that society reaps from mitigating a ton of greenhouse gas is equal to the damage that ton would cause. The marginal damage rises as emissions increase. Partly

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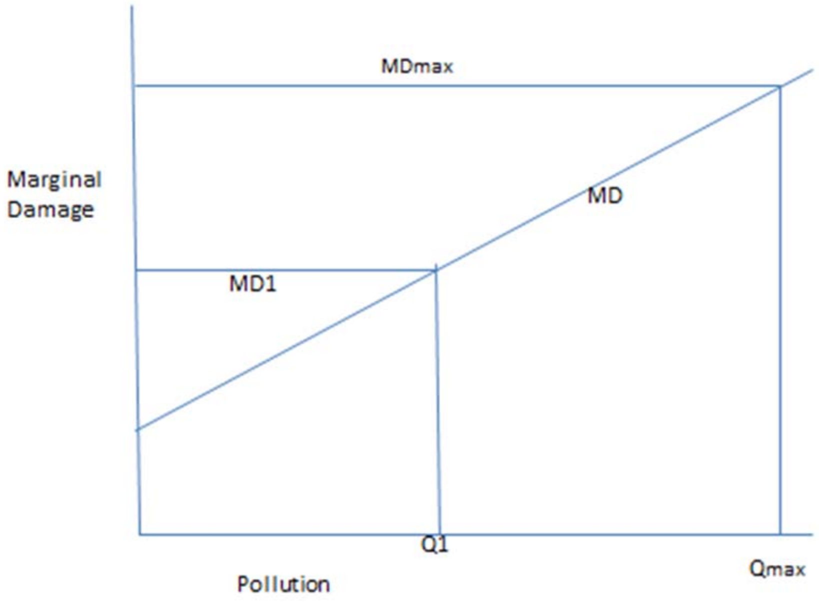
[1] If the entire world engages in mitigation, the entire world would benefit. The world should adopt the most efficient global program which would entail using the optimal global SCC for every emitter.

this is because of the dose response function which tends to be S-shaped. At very low concentrations, emissions tend to do little harm to people and other living things. But as concentrations rise, the harm increases nonlinearly. In addition, people tend not to care much about minor damage from pollution. But as the damage becomes ever more severe, the value that people place on additional damage rises. As air quality deteriorates, people care more and more about protecting the air quality they have left. For both these natural science reasons and because of people’s values, the marginal damage function rises with emissions.

Figure 1 illustrates this simple principle. As pollution increases along the horizontal access, the marginal damage people at large would place on the last emission would rise. The marginal damage depends upon where along this figure you measure it. For policy analysis, one should measure the marginal damage associated with each policy choice. That is, one should use the marginal damage that results from the chosen policy.

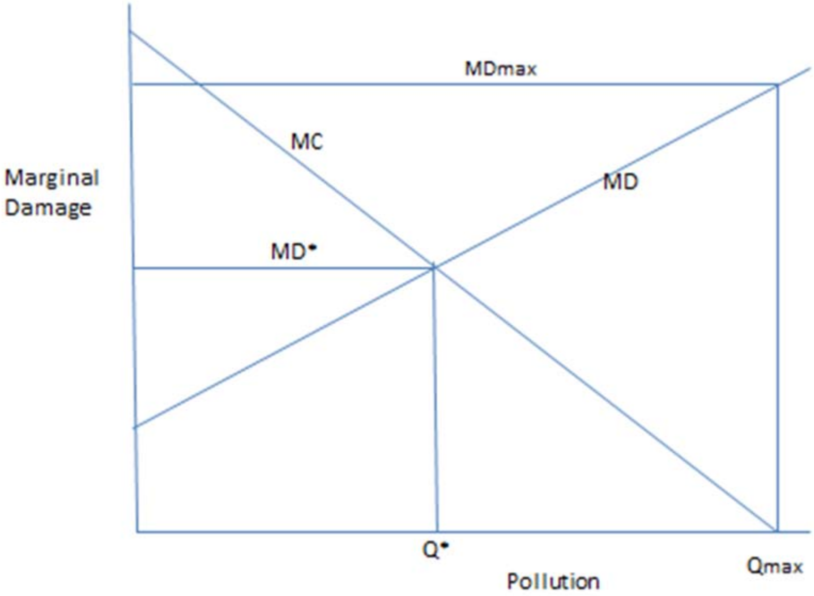
Figure 1: Marginal Damage Function



If there is no mitigation and pollution is at Q_{max}, the marginal damage in Figure 1 would be MD_{max}. This is the damage one would observe if there was no pollution policy. If the policy was Q_1, the correct marginal damage would be MD_1. The marginal damage therefore depends upon the level of mitigation that will be caused by the policy.

If the planned policy equates marginal cost to the social cost of carbon and the social cost of carbon is equal to marginal damage, the policy will be efficient. This optimal policy will maximize the net benefits to society. Figure 2 illustrates this point by adding a marginal cost of mitigation function to Figure 1. The optimal policy, MD*, equates marginal cost and marginal damage. The correct place to measure the SCC is at the optimal mitigation level Q*. The SCC at this point is equal to MD*.

Figure 2 Optimal SCC where MD*=MC



If the government intends to use the SCC to determine the appropriate amount of money to spend on mitigation, the government intends to equate marginal cost to the SCC. The only measure of the SCC that makes sense in this case is MD*. However, some calculations of the SCC use MD_{max} which assumes no mitigation. If the government equates marginal cost to MD_{max}, the government will mitigate and so the assumption of zero mitigation is violated. MD_{max} overestimates the SCC the moment the mitigation begins.

D. Federal SCC

The federal government is in the process of establishing a single value of the SCC across all of its agencies. An initial set of values for the SCC was announced in 2010 (Interagency Working Group on Social Cost of Carbon 2010). A revision was then announced in 2013 (Interagency Working Group on Social Cost of Carbon 2013). There is discussion of yet a third revision to come using the National Academy of Science. Within the two announced reports, there are four different values for the SCC. The SCC values in 2010 are \$7, \$26, \$42 and \$81/ton CO_2. The SCC values in 2013 are \$12, \$43, \$65, and \$129/ton CO_2 (all measured in 2007 USD).

All the measures in both reports reflect uncertainty about future outcomes. However, one outcome the report assumes for certain is that there will be no mitigation. No mitigation in the past, no mitigation now, and no mitigation in the future. In addition, the first three measures in each report correspond to different fixed discount rates. The discount rates weight the importance of far future consequences against current economic choices. The first three measures correspond to using constant discount rates of 5%, 3%, and 2.5%, respectively. The final number in each report evaluates the uncertainty of the calculation using the 3% discount rate. The value specifically represents the upper 95% uncertainty band around the 3% discount rate estimate.

The first set of estimates by the IWG is based on the 2007 versions of three Integrated Assessment Models (IAMs): DICE, FUND, and PAGE. The second set of measures by the IWG is based on the 2010 versions of the same three models. The DICE and FUND models are carefully calibrated economic models. They have been used extensively to estimate the optimal mitigation option for climate change. PAGE is not an optimizing model. It is used primarily to illustrate what might happen if a modeler made very different assumptions. The PAGE model captures the imagination of academics but is not well grounded in economic theory. The two reliable models for estimating the optimal SCC in the IWG exercise are the DICE and FUND models.

Although the IWG was probably well intentioned, they made both conceptual errors and computational errors running the Integrated Assessment Models. The authors of the three IAM models did not make the computations and were not responsible for the results. The most fundamental conceptual error by the IWG is that they measured the wrong SCC. They chose to evaluate the SCC assuming zero mitigation not only today, but also forever.

A second serious problem with the IWG exercise is that they did not run the models correctly. For example, DICE computes both the GDP and the discount rate to make sure that these values are internally consistent with the assumptions. The IWG ignored the estimates by DICE and instead imposed arbitrary and inconsistent assumptions of their own. It was not really the DICE model that generated the results of the IWG reports. The IWG calculations were made given assumptions of the committee.

III. Computing the SCC with DICE

This report relies extensively on the DICE model. The DICE model is the first (Nordhaus 1991) and probably the most well-known climate change Integrated Assessment Model. It has been used by numerous authors to explore mitigation, adaptation, and policy alternatives over the last 24 years. I personally have used the DICE model before to explore the effectiveness of sequestering carbon in forests (Sohngen and Mendelsohn 2003) and to examine how forest management affects the carbon emissions from land use (Sohngen and Mendelsohn 2014). In this report, we utilize DICE2013 which is the most recent version of DICE and is the version used in The Climate Casino (Nordhaus 2013).

The DICE model (Nordhaus 2013) is designed to determine the optimal level of mitigation that equates marginal cost to marginal damage at every moment. The result is a set of prices that rises over time as the concentration of greenhouse gases rise over time. Because these prices are optimal, they are equal to the marginal damage of an emission at each moment of time. They consequently reflect the social cost of carbon at that moment. We focus in this discussion on the price of carbon dioxide in 2015, the current marginal damage of a ton of emission today.

We explore several issues using DICE. First, what role does the damage function have on the social cost of carbon? Second, what impact does climate sensitivity have upon the social cost of carbon? Third, how important is the internal discount rate in DICE? Fourth, how sensitive are the optimal social cost of carbon values in DICE to uncertainty?

A. Damage Function

A feature of DICE that is critical to understanding the social cost of carbon is the damage function. The DICE2013 model assumes that the percent of GDP lost per year to climate damage increases with the square of temperature change. So as global temperature doubles, the damage quadruples. When temperatures are 2°C warmer than preindustrial global temperatures, the model assumes climate damage would be equal to 1% percent of GDP. When temperatures are 4°C, the model assumes damage would be 4% of GDP and when temperatures are 8°C, damages would be 16% of GDP. As discussed below, I believe the empirical evidence suggests it is appropriate to modify these assumptions.

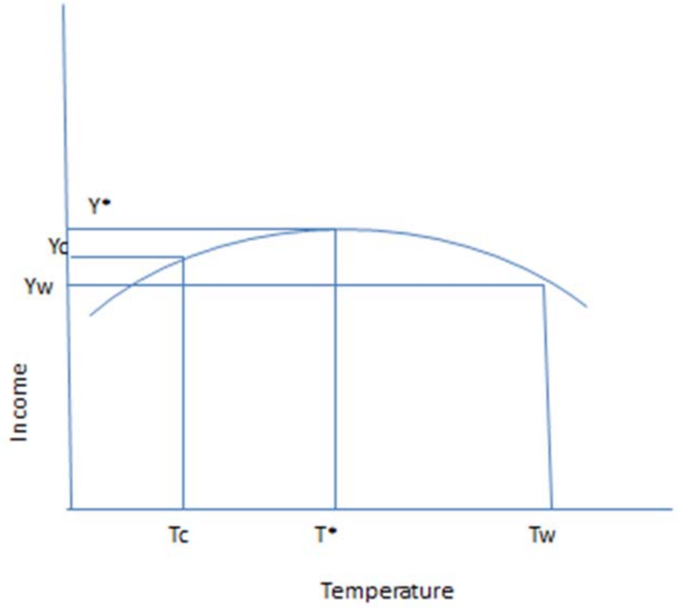
Global temperature today is about 0.8°C warmer than the preindustrial temperature. According to DICE2013, there should already be a global damage from climate change in 2015 equal to $173 billion annually. Clearly damage this great would be conspicuous. In practice, however, it is very difficult to detect this annual global damage today, even with careful scientific measurements.

There are detectable physical effects associated with the 0.8°C warming since preindustrial times. For example, in some places, the warming over the last 100 years has reduced crop yield/ha a few percent (IPCC 2013b) which is clearly a damage. However, carbon fertilization has increased crop yields by a far larger amount across the entire world (Kimball 1983) suggesting a sizable net benefit. The warmer temperatures are encouraging ecosystems to move poleward (IPCC 2013b) which is a change that may lead to damage in some places. For example, plants have flowered earlier, birds have arrived sooner after winter, and birds have over wintered in more northern locations in the northern hemisphere. However, the carbon fertilization of trees has also led to an overall increase in ecosystem productivity and standing biomass (Gerber et al. 2004) which is an overall net benefit for ecosystems.

This myriad of small changes has led to small economic gains and losses across affected sectors and locations. They are small enough that they require very careful measurement to detect. They are dwarfed by the change over the same time period caused by the increase in human population from roughly 1 billion in 1880 to 7 billion today and the increase in economic activity from roughly $1 trillion in 1890 to $75 trillion today (Maddison 2003). In order to measure the damage from climate change over time, one must discern what changes over time are due to the underlying growth in the economy and the human population versus what is due to the change in carbon dioxide, rainfall, and temperature.

Empirical studies done across the world using multiple methods have measured the climate sensitivity of the current economy and ecosystem. These studies reveal a hill-shaped relationship between the human welfare or income in each sector and temperature and precipitation. The response function tends to look like Figure 3. There is an optimal temperature, T*, for every sector. The income of value of that sector is maximized at T*. If a place happens to have a cooler temperature, T_c, then the income will be lower at Y_c. Similarly, if the location is too warm, T_w, the income will also be lower. This response function implies there is an optimal climate for each sector that maximizes income or welfare as a function of both temperature and precipitation. That maximum is different for each sector. For example, agriculture appears to be maximized in temperate wet climates whereas forestry is maximized in subtropical wet climates. Places that are currently too cool will therefore benefit from warming as they rise towards the optimum. Places that are too warm will be damaged by warming as they are pushed further from the optimum. The consequence of climate change is not the same across the planet.

Figure 3: Generic Impact of Climate Change on a Climate-Sensitive Sector



These results provide insight into the effect of the change in climate we have seen to date. The historic damage from warming has been concentrated in the low latitudes, and the historic benefit from warming has been concentrated in the mid- to high latitudes. Minnesota, for example, has likely benefited from global warming to date because of increased agricultural and ecosystem productivity. Looking across the planet, the magnitude of the global benefit to date is slightly higher than the magnitude of the global loss to date. The immediate impact of a warmer, wetter, and carbon dioxide enriched environment is likely to be beneficial from 1.5°C to 2°C above preindustrial levels (0.7°C to 1.2°C warmer than today).

Similar results follow from ecological studies of global ecosystems (Gerber et al 2004). The harm from historical changes in temperature has been more than offset by the benefits of higher levels of CO_2. On average, the warmer, wetter, CO_2 -enriched climate has allowed the world's ecosystems to be more productive with more standing biomass.[2]

How well does the DICE damage function reflect our current understanding of climate damage? DICE clearly captures the insight that higher future temperatures are going to lead to ever increasing harm. The problem with the DICE functional form is that it over-predicts damage in the near term. It effectively assumes that the preindustrial temperature in 1900 was optimal for mankind and all warming since then has been harmful. In this report, we adjust the DICE damage function so that damage does not begin until temperatures warm 1.5°C to 2°C above preindustrial levels. That is, we assume that when global temperature reaches 0.7°C to 1.2°C warmer than today, net global damage will begin.

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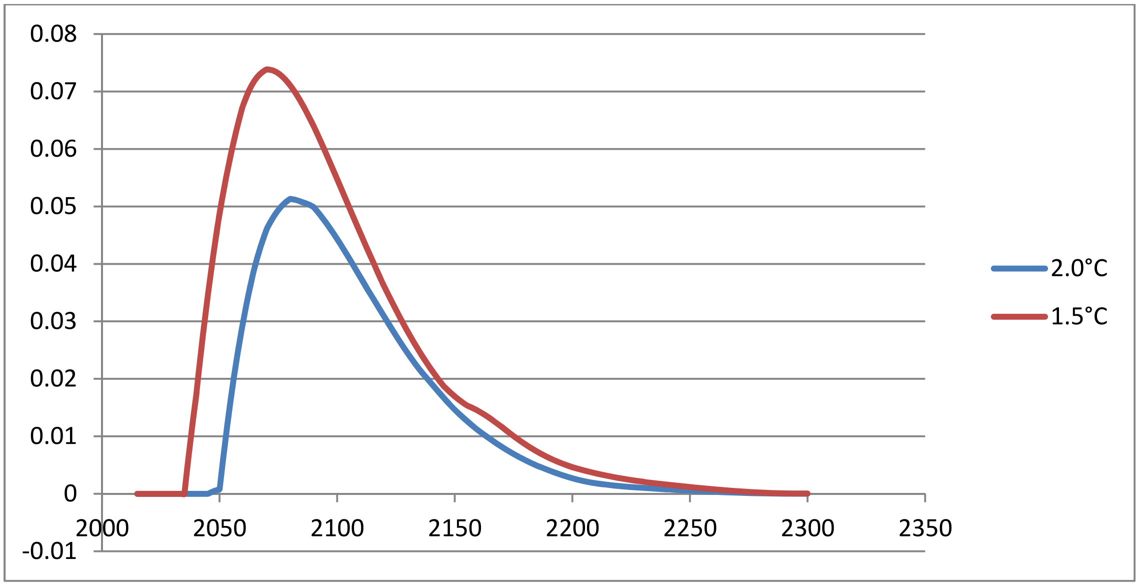
[2] The fact that the net impact of climate change has been slightly beneficial to date does not imply that climate change will remain harmless regardless of increases in temperature. Empirical evidence suggests that, past a certain point, the damage will increase nonlinearly and the benefits will shrink away (IPCC 2013b; Mendelsohn and Neumann 1999; Mendelsohn 2001; Mendelsohn and Dinar 2009).

The modified DICE model predicts the optimal SCC is between $4 and $6/ton. Figure 4, calculates the annual damage that a ton of carbon dioxide emission today is expected to cause into the future. The figure illustrates the present value of the damage each year. The SCC is equal to the sum of all these effects. The damage does not begin until temperatures reach 1.5°C to 2°C above preindustrial levels, rapidly accelerates, and then falls with time. In this optimal scenario, DICE predicts that global temperatures will rise to 4°C to 4.3°C in 2150 and then gradually fall.

Figure 4: Annual Damage of 1 Ton of Emission in 2015



Note: The annual damage is measured in present value dollars. Figure assumes DICE discount rate (starting at 5% today, falling to 2.7% in 2200), a climate sensitivity of 3, optimal mitigation, and damage functions that assume the optimal temperature is 1.5°C above preindustrial and 2.0°C above preindustrial.

B. Discount Rates

The DICE model has its own internal measure of the discount rate that depends on the path of global consumption over time. The discount rate changes as the growth of per capita consumption changes. The model estimates that the current discount rate is 5%. As the rate of GDP growth slows over time, the DICE model predicts that the discount rate should fall to about 3.5% in 2100 and 2.7% in 2200.

The approach taken by the IWG divorces the interest rate from the path of GDP. This is inconsistent with the DICE model and economic theory. The IWG examines a fixed interest rate over all time and explores three constant discount rates of 5%, 3%, and 2.5%. The 5% rate matches the current 2% growth in per capita consumption but is too high for the far future when the economy slows. The 2.5% discount rate may be appropriate for the 23rd century but not for today.

The choice of discount rate matters a great deal to the SCC. This is because most of the damage from a ton of carbon dioxide emissions happens far into the future. The lower the weight given to future effects relative to present effects (the higher the discount rate), the lower will be the SCC.

Table 1 compares the SCC estimates using alternative discount rates and the modified DICE model. For each case, Table 1 compares the SCC calculated with the DICE variable discount rates and the SCC calculated with constant discount rates of 3%, 4%, 5%, and 7%. OMB suggests the 7% is the appropriate discount rate for regulations that force the private sector to make investments in projects with uncertain rewards.

Table 1: DICE SCC estimates by discount rate and damage function

Discount Rate	Damage relative to +1.5°C	Damage relative to +2°C
DICE rate	6	4
3%	15	10
4%	7	4
5%	4	2
7%	1	0.5

Note: Chosen SCC is optimal. Climate sensitivity is assumed to be 3.

Given this set of choices, what discount rate is appropriate for the SCC? The discount rate is the "price of time". The IWG argues that policy makers can choose whatever discount rate pleases them. However, if policy makers choose one discount rate for greenhouse gases and another discount rate for every other public investment, they are implicitly arguing that climate change should have a different "price of time". There is no theoretical support for this idea. If a lower discount rate is used for greenhouse gases than other investments, policy makers are effectively arguing that greenhouse gas mitigation should have a lower rate of return than other public investments in national security, health, education, safety, and infrastructure. It is not at all clear why this is socially desirable.

The discount rate that is internal to DICE (first row) changes over time as the economy changes. It is theoretically sound because it matches the growth in per capita consumption over time. Comparing the SCC in the first row with the remaining rows suggests that the constant discount rate that would yield the DICE SCC is about 4%. With the modified damage functions, DICE predicts the SCC should be $4-$6.

C. Climate Sensitivity

Another important factor to consider in climate models is the climate sensitivity, the long run change in global temperature associated with doubling greenhouse gases. The IPCC (2013a) argues that climate sensitivity lies between 1.5 and 4.5 with a most likely value of 3. A climate sensitivity of 3 implies that doubling greenhouse gases in the atmosphere would increase long run temperature by 3°C. Recent evidence, as discussed in the reports of Professors Lindzen, Happer, and Spencer, suggest that the IPCC climate sensitivity is overstated. Roy Spencer notes that historical observed warming has been much less than climate models predicted. This raises questions about whether the range of climate sensitivity suggested by the IPCC is too high. It also suggests that even if the IPCC has the correct climate sensitivity, the actual increase in temperature will be much slower. W. Happer (2015) argues that climate sensitivity is likely to be 1, which would be the effect of just increasing carbon dioxide alone. He argues there are no positive feedbacks from this forcing which would cause the climate sensitivity to be higher. Richard Lindzen (2015) argues in his testimony that the climate sensitivity could be between 0.85C and 1.5C and is very likely less than 2C.

Table 2 compares the SCC one might get at different climate sensitivities using the modified DICE model. We show the results in Table 2 for the two versions of the modified damage function. If the climate sensitivity is 1.5 (as Dr. Lindzen and others have suggested), the SCC lies between $0.30 and $0.80/ton. This demonstrates that if the climate sensitivity is low, climate change is not a grave problem. If the climate sensitivity value is 2.0, the SCC lies between $1.10 and $2.00/ton. If the IPCC is correct and the climate sensitivity is 3, the SCC lies between $4 and $6/ton. In the unlikely chance that the climate sensitivity is 4.5, the SCC lies between $10 and $14/ton. The value of the SCC is sensitive to low climate sensitivities because they affect temperatures this century.

Table 2 SCC values for different climate sensitivities and damage functions

Climate Sensitivity	Damage Delay to 1.5°C	Damage Delay to 2°C
1.0	.1	0.0
1.5	.8	0.3
2.0	2	1.1
2.5	4	2.3
3.0	6	4

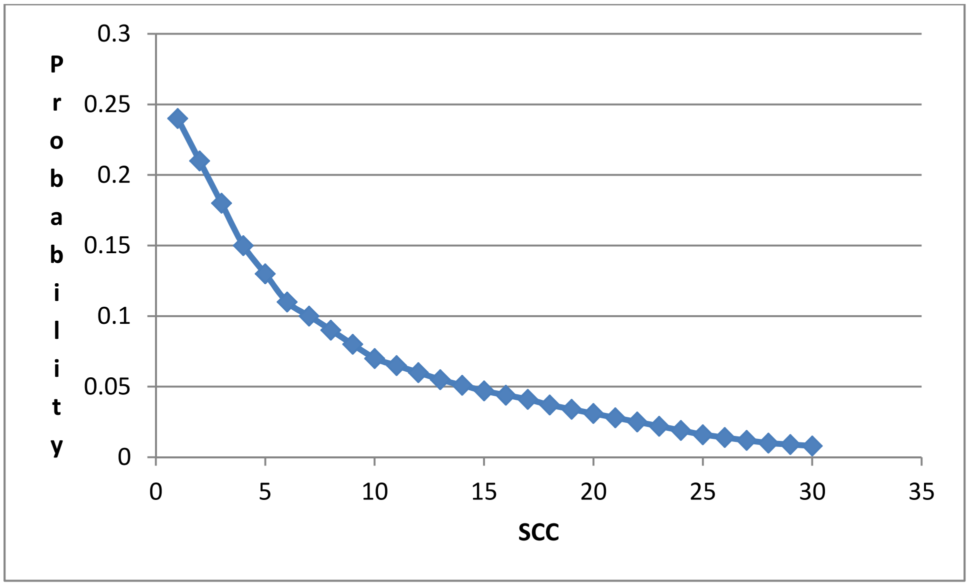
Optimal SCC values calculated using DICE interest rates.

C. Uncertainty

The IWG argues that there is a great deal of uncertainty surrounding far future damage. That is especially true if one assumes that there will be no mitigation. This affects the SCC if one also assumes that the discount rate is too low. However, using the optimal SCC, the DICE model discount rates, and a realistic damage function, we find that far future damage has little bearing on the value of the current SCC. Using these assumptions, it is clear that the SCC is not that sensitive to far future damage. What affects the current SCC is the damage over the next century. What happens beyond 2100 has little effect on the marginal damage of an emission today. The SCC is robust against a range of plausible long range scenarios.

My estimate for the SCC in 2015 is between $4 and $6/ton. It assumes the IPCC estimate of a climate sensitivity of 3 which may be conservative in light of the testimony of Professor Lindzen and Professor Hopper. My estimate also assumes that temperatures increase at the rate predicted by climate models which may be conservative given the empirical evidence of the much slower actual warming trends reported by Professor Spencer. The expected value of the set of optimal runs using DICE in Table 2 is $7/ton. The 95% confidence interval given this uncertainty is between 0 and $15/ton. Taking all the different optimal SCC's in Table 2 yields the probability distribution of the SCC shown in Figure 5.

Figure 5: Probability distribution of SCC



D. Conclusions

Using the internal discount rate of the DICE model (starting at 5% today, falling to 2.7% in 2200), the emission and GDP forecasts of DICE, a climate sensitivity of 3, and a delay of 1.5°C to 2.0°C in the damage function of DICE, my estimate of the SCC is $4-$6. My estimate is conservative given the recent evidence in the reports of Professors Lindzen and Happer, which suggest the IPCC climate sensitivity is overstated. My estimate is also conservative in light of the evidence presented by Roy Spencer that the historic trend of observed warming is much lower than climate models predicted. A slower rate of warming postpones damage further into the future no matter what the climate sensitivity is and leads to a lower SCC.

If the climate sensitivity is 1 as suggested by W. Happer (2015), the SCC is less than $.10/ton. Richard Lindzen (2015) argues in his testimony that the climate sensitivity could be between 0.85C and 1.5C and is very likely less than 2C. If the climate sensitivity is 1.5 (as Dr. Lindzen and others have suggested), the SCC lies between $0.30 and $0.80/ton, as shown in Table 2 of the Report. If the climate sensitivity value is 2.0, the SCC lies between $1.10 and $2.00/ton, as shown in Table 2.

Finally, it would be inadvisable to adopt the current Federal SCC as estimated by the Federal Interagency Working Group on Social Cost of Carbon (IWG). Although well intentioned, the IWG made numerous theoretical and modeling errors and significantly overestimated the SCC.

IV. Experience

I graduated in 1973 from Harvard College, BA, Magna Cum Laude. I graduated in 1979 from Yale Economics Department, PhD. I was an assistant professor at the University of

Washington, Seattle 1979-1983. I was a visiting assistant professor at University of Michigan 1983-1984. I have been a professor at Yale University since 1984.

My official title at Yale University is the Edwin Weyerhaeuser Davis Professor at the School of Forestry and Environmental Studies, with appointments in the Department of Economics and the School of Management. For the last 22 years, I have been working on measuring the benefits of mitigating greenhouse gas emissions. I have written 8 books and 63 peer reviewed articles on climate change impacts. Measuring these benefits requires a careful integration of natural science and economics. The two major results of my research on climate change are that (1) greenhouse gas emissions will cause future impacts but (2) adaptation will dampen the harm that otherwise would happen. As people, firms, and governments come face to face with climate change, they will adjust their investments and behavior to cope with this changing future world. The effort to adapt involves additional cost and some damage will remain, but these losses are small compared to the “potential damage” with no adaptation that most climate studies are fixated on.

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