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On

Climate Change Science – a Historical Perspective

My name is Michael Oppenheimer. I am the Albert G. Milbank Professor of Geosciences and International Affairs at Princeton University and a member of the faculties of the Department of Geosciences, the Woodrow Wilson School of Public and International Affairs, and the Princeton Environmental Institute. I would like to thank Chairman Rouda and the members of this subcommittee for inviting my testimony at this hearing. The views expressed in this testimony are my own. I am not speaking as an official representative of Princeton University. Let me first describe my professional background. Full curriculum vitae accompany to this testimony.

I received an S.B. from MIT and a PhD in chemical physics from the University of Chicago and served as a postdoctoral fellow and then Atomic and Molecular Astrophysicist at the Harvard Smithsonian Center for Astrophysics, researching Earth's upper atmosphere. Subsequently, I served as Chief Scientist for the Environmental Defense Fund, a private, not-for-profit research and advocacy environmental organization (where I continue to serve as an advisor on scientific matters). In 2002, I became a professor at Princeton University where I direct the Center for Policy Research on Energy and the Environment. I have published about 200 articles in professional journals. Almost all of those published over the past 30 years cover aspects of climate change science and climate change policy. My current research focuses largely on projecting sea level rise and coastal flood levels in a warming world with special emphasis on the contribution of the Greenland and Antarctic ice sheets; the risk to coastal areas from sea level rise; and adaptation to climate change, sea level rise, and extreme climate events. I have served in various capacities as an author of assessments produced by the Intergovernmental Panel on Climate Change (IPCC) since its First Assessment Report in 1990. Currently, I am a Coordinating Lead Author of IPCC's upcoming Special Report on Oceans, Cryosphere, and Climate Change, to be issued in September, with responsibility for the chapter assessing sea level rise. Last month, along with six other experts in diverse fields, I published a book on scientific assessments, *Discerning Experts: The practices of scientific assessment for environmental policy*.

Purpose of This Testimony

I was asked to describe highlights in the development of climate change science by the late 1980s to illustrate how much scientists understood at that time. Accordingly, I will begin by briefly establishing the state of science up to 1980. Then I will point to three key scientific developments during the 1980s that provided concrete evidence of the high risk of unrestrained emissions of the greenhouse gases, particularly carbon dioxide from fossil fuel combustion. The First Assessment Report of the Intergovernmental Panel on Climate Change[1], published in 1990, provides a compelling summary of this evidence. I'll then use the example of attribution of global mean warming to human activity, and how the evidence strengthened throughout subsequent IPCC assessments, to illustrate the way scientific understanding has progressed since the 1980s, step by step, in narrowing uncertainty in many (but not all) key aspects of our understanding. To remind the committee that important uncertainties remain, I will discuss recent findings of accelerating ice loss from the Antarctic ice sheet and the growing contribution of both the Greenland and Antarctic ice sheets to sea level rise. These findings demonstrate the increasing risk of continued emission of carbon dioxide and other greenhouse gases.

The bottom line is this. Thirty years ago, it was already known that:

1. By trapping heat, greenhouse gases had maintained a climate in which civilization developed and thrived. Much of the difference in surface temperature between Venus (hot) and Mars (cold) on the one hand, and Earth (moderate) on the other, was due to the particular greenhouse gas levels on Earth.

2. Atmospheric concentrations of the primary human made greenhouse gas, carbon dioxide, were increasing, primarily as a result of the combustion of coal, oil, and natural gas to produce energy.

3. Earth's global mean (average) temperature had increased by about 0.4 degrees Celsius since the late 19th century and sea level had risen as well.

4. The increase in carbon dioxide in the atmosphere would last for millennia, a very, very long time, unless a way to artificially remove and store it were developed.

5. If emissions were not reduced substantially, Earth's climate would become warmer in the next century than it was over the entire history of civilization and possibly warmer than it had been for several million years.

6. Resulting climate changes were expected to increase the frequency of very hot days and lead to impacts on water availability, crop yields, sea level, and natural ecosystems.

In other words, the broad outlines of a problem bearing high risk for humans and society were already clear even if many important details remained to be fleshed out.

Finally, the committee has asked for my view on the role of so-called climate skeptics or contrarians in obscuring the reality of climate change from the general public. While I am not an expert in public opinion, I am an educator and a long time observer of and participant in the public conversation on climate change who has some views to offer on the subject at the end of this testimony.

Early Scientific Developments

Scientific understanding of climate change due to the buildup of greenhouse gases in the atmosphere goes back to 1824 when the great mathematician and scientist Fourier likened the behavior of the atmosphere to a glass cover over a jar or vessel that allows sunlight in but traps heat inside, eventually dubbed the "greenhouse effect". The carbon dioxide concentration in the atmosphere at the time was about 280ppm (parts per million or about 0.03% of air). Today it is approaching 410ppm.

In the 1850s, another great scientist, John Tyndall, focused on the importance of water vapor and carbon dioxide in determining the atmosphere's greenhouse effect and Earth's climate. These developments culminated in 1896 when yet another brilliant scientist, Svante Arrhenius, who later won the Nobel Prize for other worked, published the first quantitative estimates of future global warming due to carbon dioxide from coal combustion. In other words, the foundational theory of climate change was already in place over one hundred years ago. A full accounting of these and other early scientific developments by historian Spencer Weart, under sponsorship by the American Institute of Physics, is found at https://history.aip.org/history/climate/timeline.htm and the links therein.

Modern Climate Science Emerges

Scientific progress on climate change accelerated beginning in the 1950s when Roger Revelle and Hans Suess published a series of papers[2] pointing out that, contrary to previous critics of Arrhenius' theory, the emitted carbon dioxide would *not* dissolve entirely and harmlessly in the ocean, and instead some would remain in the atmosphere to warm the Earth. Based on carbon isotope analysis, they also showed that the carbon dioxide concentration in the atmosphere, then about 315ppm, had been measurably affected by fossil sources, such as emissions from combustion of coal, oil, and natural gas. These findings were followed by C.D. Keeling's direct measurements of CO_2 atop Mauna Loa in Hawaii that, by the 1960s, showed conclusively an inexorable increase in atmospheric CO_2. Aided by the development of the high-speed computers, scientists at NOAAs Geophysical Fluid Dynamics Laboratory (GFDL) built the first climate model containing a realistic representation of atmospheric convection, producing the first plausible projection of the effect of doubling carbon dioxide levels - about a 2^0C global mean warming. More sophisticated models that replicated the atmosphere's overall circulation began to emerge. These models presented increasingly credible estimates of future warming. (Much of the early work was done at US government laboratories but scientists abroad began to catch up). In 1979, a panel of the National Academy of Sciences stated, "We estimate the most probable global warming for a doubling of CO2 to be near 3°C with a probable error of ± l .5°C." The report's summary concluded as follows:

> To summarize, we have tried but have been unable to find any overlooked or underestimated physical effects that could reduce the currently estimated global warmings due to a doubling of atmospheric CO2 to negligible proportions or reverse them altogether. However, we believe it quite possible that the capacity of the intermediate waters of the oceans to absorb heat could delay the estimated warming by several decades. It appears that the warming will eventually occur, and the associated regional climatic changes so important to the assessment of socioeconomic consequences may well be significant, but unfortunately the latter cannot yet be adequately projected.[3]

In other words, already by 1979, a scientific consensus emerged that carbon dioxide emissions would lead to a significant warming of the Earth. The precise timing and resulting damages to society remained uncertain but it was clear to anyone listening that climate change would inevitably accompany continued growth in emission of carbon dioxide and eventually pose a significant risk to societies.

Key Scientific Developments of the 1980s

So much important science emerged in the 1980s that I could not cover it all. Instead, let me point to three developments that were critically important to cementing the scientific consensus. By 1981, at least two independent analyses revealed a long term warming of Earth by about 0.4^0C since 1880.[4] Second, an ice core retrieved from the Antarctic ice sheet containing samples of the ancient atmosphere trapped in air bubbles provided a record of carbon dioxide and temperature dating back 160,000 years. This discovery provided convincing evidence that natural increases and decreases in carbon dioxide went hand-in-hand with increases and decreases in Earth's temperature.[5] The size of these swings was later shown to be consistent with the climate sensitivity (to a doubling of CO_2 levels) of the same climate models that predicted a substantial future warming due to carbon dioxide buildup. Third, climate models began to incorporate ocean heat transport in order to estimate the aforementioned delay of warming. Contingent on assumptions about future emissions of the greenhouse gases, these increasingly reliable models projected a significant additional warming by the early decades of the 21st century, as indeed has occurred.[6]

Putting all the evidence together, by the late 1980s, it was known that atmospheric carbon dioxide, then about 350ppm, was increasing and the only plausible explanation was fossil fuel combustion along with a lesser contribution from deforestation. Climate models projected a significant warming due to the increasing greenhouse effect. Earth was observed to be warming (and sea level was rising), but there remained a question of whether the warming could be definitively attributed to the carbon dioxide buildup that was increasing the greenhouse effect. However, there was little dispute that continued carbon dioxide emissions would warm Earth to levels not experienced in the 10,000 year history of civilization, all in the space of 5-10 decades. At the middle to high end of estimates of climate sensitivity, it was already understood that the warming could bring Earth to temperatures not experienced in several million years by the end of the 21st century.

The world took notice of these scientific developments. Already in 1985, a large group of climate experts convened under UN auspices had called for nations to consider developing a framework convention aimed at slowing emissions and avoiding a large warming. Reflecting the need for a body with international representation to assess the science, the Intergovernmental Panel on Climate Change was established under UN auspices in 1988 and its first assessment, published in 1990, reflected the view in the scientific community that the risk from greenhouse gas emissions was increasing. In 1991, countries did in fact convene negotiations aimed at developing the UN Framework Convention on Climate Change. President George H.W. Bush signed this treaty at the Earth Summit in Rio de Janeiro in 1992 and the US Senate ratified it not long thereafter.

Scientific Developments since 1990

The release of IPCC's Second Assessment in 1996 firmly established that climate science had taken a giant leap forward in just the few short years since IPCC's First Assessment. Most notably, based on innovative statistical methods for analyzing temperature changes both at the surface and in the upper atmosphere worldwide, the report was able to put the "attribution" question to rest: "The balance of evidence suggests a discernible human influence on global climate". While the statistical attribution referred to patterns of warming, the report further identified 18 other aspects of global and regional climate such as cloudiness, snow cover, glacier length, and precipitation intensity in which scientists had detected trends associated with this warming. Climate change had become pervasive and detectable across the climate system.

As an example of this continuing increase in our understanding, let me trace IPCC's progressive strengthening of the crucially important finding that humans *were already* changing the climate.

The Third Assessment, published in 2001, further solidified human responsibility for climate change: "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities."

The Fourth Assessment, published in 2007, strengthened this finding further: "Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations."

Finally, in the Fifth Assessment published in 2013: "It is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together."

Each successive report also expanded list of the characteristics of the climate system for which changes, such as increased intensity of precipitation, were detected and attributed directly to human emissions. Similarly, trends in some large and critically important global systems like coral reefs and the Arctic were attributed to climate change overall.

In other words, science has continued to solidify as details of the observed and project climate change emerge from increasing observations and more sophisticated models. Scientific developments proved that the early scientific consensus was correct in general and also with respect to many specific details. On some key details, however, early assessments actually underestimated the reality, such as the rate of disappearance of summer sea ice in the Arctic.

Uncertainty on some important questions remains a fact of climate science, for example, the future rate of disintegration of the large ice sheets in Greenland and Antarctica and the resulting effect on sea level rise. Global mean sea level rise is largely caused by three processes:

- ocean water warmed by climate change takes up more volume
- mountain glaciers melt as they warm and feed rivers that drain this meltwater into the ocean
- ice sheets in Greenland and Antarctica melt or discharge icebergs faster at their peripheries as they warm while gaining mass at higher elevations through increased snowfall from the warmer, moister atmosphere.

IPCC's first three assessments generally estimated that losses due to melting would be offset by gains and the Antarctic ice sheet in particular would remain stable or increase in mass, making a negative contribution to sea level rise. However, a spate of new observations of the ice sheets beginning in the mid-1990s revolutionized our understanding – ice sheets were, on balance losing considerably more mass than they were gaining, a trend that continues to accelerate today (see Figure 1). As a result, sea level rise during the past 25 years was about 3 millimeters per year, almost double the rate of the past century. If 3mm/year (0.12 inches per year) doesn't sound like much, keep in mind that over the course of a century, that amounts to a foot of vertical rise and that for every such foot, erosion and submergence devour about 100 feet horizontally, that is, in the inland direction, along a typical east coast beach. The rate continues to accelerate and parts of the Antarctic ice sheet my already be retreating irreversibly. Reflecting this uncertainty, IPCC's Fourth Assessment could not produce a projection of ice sheet behavior or future sea level rise.

Models of ice sheet behavior that would allow us to project future sea level rise are improving fast but have not entirely caught up to the reality revealed in the recent observations. The Fifth Assessment drew on new approaches to modeling to provide an upper bound on the potential Antarctic contribution during this century but modeling reported in the scientific literature has continued to evolve since then. Different models make different assumptions about the underlying physics of ice sheets. As of the beginning of IPCC's latest cycle of upcoming assessment reports, we did not have an adequate basis for deciding which is correct. Some published projections of global mean sea level rise exceed two meters – an extremely rapid and dangerous sea level rise. I hope IPCC's Special Report on Oceans, Cryosphere and Climate Change and its Sixth Assessment Report will be able to provide further clarity about this critically important impact of climate change.

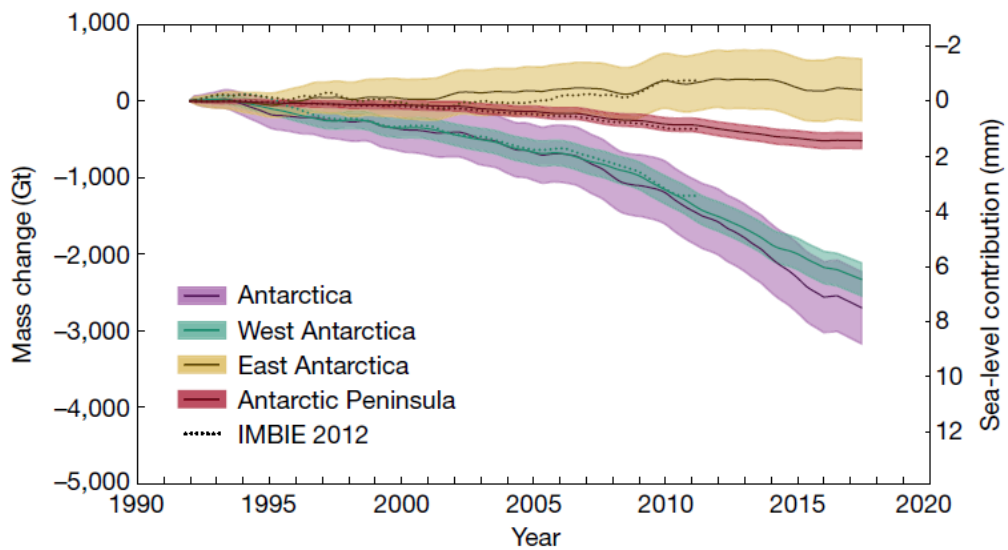

Figure 1 Accelerating mass change for the Antarctic ice sheet as a whole (purple) and its individual regions since 1992 (left, in billions of tons of ice and right, in millimeters of sea level rise). From the IMBIE team, *Nature* **558**, pp. 219-222 (2018).

Skepticism about Climate Science

Let me conclude with a few words about so-called climate contrarianism or extreme skepticism. One can wonder why, in the face of decades of increasing confidence in the scientific basis of the climate change problem, skeptical voices continue to question not just details of the science but the reality of recent climate changes while disparaging the risk associated with future climate change.

Science thrives on skepticism, prying and prodding, subjecting new findings to the test of peer review and older findings to the advance of new discoveries. No field has benefitted more from this traditional approach than climate science. However, there is a great deal of difference between rational skeptics, those conversant with the scientific literature who can be convinced by evidence, who subject their own ideas to rigorous review, and the obdurate, uniformed skeptics whose ideas about climate change never or rarely are found on the pages of a peer reviewed journal.

Regrettably, climate science has been under constant attack since around 1990 by proponents of the latter approach and their facilitators, presumably due to the increasing political stakes attached to the issue. I know of no way to measure exactly how much this misinformation has contributed to slowing progress in dealing with climate change. However, one indication of a serious effect is that survey after survey finds that more Americans believe in the basic facts about climate change than believe that scientists are in agreement about those same facts. For instance, a recent survey found that 58% of respondents believe that global warming is mostly human caused but only 49% believe that most scientists think so.[7] This strongly suggests that the clear message scientists are trying to deliver has been obfuscated by a noxious miasma of contrarianism.

In conclusion, I would like to thank this committee and Chairman Rouda for inviting me to testify and I welcome the opportunity to answer any questions you may have on this subject.

Endnotes

1. All IPCC reports referenced in this testimony are available at www.ipcc.ch

2. R. Revelle & H.E. Suess (1957), Carbon Dioxide Exchange Between Atmosphere and Ocean and the Question of an Increase of Atmospheric CO2 during the Past Decades, Tellus, **9,** 18-27.

3. *Carbon Dioxide and Climate: A Scientific Assessment* (1979). National Academy of Sciences, Washington, DC.

4. J. Hansen et al (1981), Climate Impact of Increasing Atmospheric Carbon Dioxide. *Science* **213**, 957-966.

5**.** J.M. Barnola, et al (1987), Vostok ice core provides 160,000-year record of atmospheric CO_2. *Nature* **329,** 408–414.

6. J. Hansen et al (1988), Global climate changes as forecast by Goddard Institute for Space Studies three-dimensional model. Journal of Geophysical Research (D) **93**, 9341-9364.

7. *Climate Change in the American Mind: March 2018*, Yale Program on Climate Change Communication and George Mason University Center for Climate Change Communication.