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A PLAIN ENGLISH GUIDE TO THE SCIENCE OF CLIMATE CHANGE

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Why a Plain English Guide?

Few people would dispute that the concept of Global Climate Change is one of the most complex science-derived issues to wind up at the center of political discourse. The section of the landmark Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) dealing with the science of climate change is over 500 pages long by itself, containing 75 pages of references alone.[1] Documentation from outside the IPCC is equally voluminous.

The terrific complexity of climate change research poses a challenge for the decision-making apparatus in democratic societies, since it is simply unrealistic to expect the public, policymakers or the media to read and understand the full body of climate change literature. Instead, they must rely on publications put out by pressure groups with a position for or against climate change, or on the verbal summation of a small number of high-profile experts. But thirty second sound bites don't leave much room for qualifications, and, just as the devil is in the details, the quality of science is in the qualifications. The first thing to be lost in science-policy discussion is a clear representation of the complexity of the issue which accurately depicts both the certainties and the uncertainties involved.

The importance of having accurate portrayals of the nature, magnitude, certainty and imminence of environmental hazards is hard to overstate. As a society, we have a limited amount of resources with which to address these hazards, whether we address them through environmental improvement programs such as air quality controls, or whether we address them through other public health improvement efforts. Wasting our resources by ranking our problems poorly costs lives, and quality of life, that we could otherwise preserve.

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[1] Intergovernmental Panel on Climate Change (IPCC), *Climate Change 1995, The Science of Climate Change* (Cambridge, MA: Cambridge University Press, 1996). Because neither the executive summary nor the individual chapter summaries do justice to the full detail of the report, the information in this primer will be drawn from the body of the text whenever possible.

The purpose of this guide, then, is to translate the evidence regarding global climate change from the arcane language of science into the mainstream language of English, so that the weighing of evidence can be put back into a public debate that all too often weighs only the sound bites of pundits, politicians, industry representatives and celebrity scientists.

This guide is not intended to be a comprehensive treatment of every facet of global climate change research. Rather, this guide is offered to facilitate independent evaluation of what I hope is an unbiased selection of the relevant evidence in order to enhance the quality of public policy debate.

> *Do not believe in anything simply because you have heard it. Do not believe in anything simply because it is spoken and rumored by many. Do not believe in anything simply because it is found written in your religious books. Do not believe in anything merely on the authority of your teachers and elders. Do not believe in traditions because they have been handed down for many generations. But after observation and analysis, when you find that anything agrees with reason and is conducive to the good and benefit of one and all, then accept it and live up to it.*
>
> *—Gautama Buddha*

Part 1

Global Warming Theory

Global warming theory is really just the planet-wide application of a much more humble theory called the "greenhouse effect." This theory, first quantified by a Swedish chemist named Arrhenius in 1896, is relatively simple, relies on well defined and tested laws of thermodynamics, and has been repeatedly validated by not only laboratory experiments, but by millions of greenhouse owners.[2]

The core greenhouse effect theory is simple: When sunlight reaches the surface of the earth, some of its energy is absorbed by the ground, some of it is reflected back unchanged, and some of the energy absorbed is re-emitted by the ground in the form of heat. Over a bare patch of ground, there would be no net increase in the temperature over time because the heat absorbed during the day is given up overnight. This re-emission of heat is familiar to most people who have ever asked why snakes seek out highways at night: it's to stay warm in the re-radiated heat flowing out of the pavement.

If there is a greenhouse located on the patch of ground discussed above, things are a bit different. The sunlight enters as usual, and some of it is reflected back out as usual, but part of the incoming sunlight that was held by the surface and re-emitted as heat does not pass back out through the glass, and the greenhouse warms up a bit. That warming tends to free some water vapor from the ground and the plants, and that water vapor traps yet more of the re-radiated heat coming up from the surface. In fact, the water vapor traps much more of the retained heat than the glass which started the process. That's the greenhouse effect in a nutshell.

Scientists have known for a long time that the greenhouse effect applies not only to greenhouses, but to the Earth as a whole, with certain "greenhouse" gases playing the role of the glass in the example above. When applied to the whole planet, this relationship between certain gases in the atmosphere and the temperature of the atmosphere is called "global warming theory." The global greenhouse effect is a natural aspect of Earth's environment, crucial for the maintenance of life on Earth. Without Earth's natural greenhouse effect, and the global warming that goes with it, the Earth would be a much colder planet, inhospitable to life as we know it.[3]

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2 Arrhenius, S., "On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground," *Philosophical Magazine*, 41:251, pp. 237–276, April, 1896, as discussed in "Arrhenius and Global Warming, *Science*, Volume 272, May 1996, p. 1122.

3 Stanley E. Manahan, *Environmental Chemistry, Fourth Edition* (Monterey, CA: Brooks/Cole Publishing Company, 1984).

Part 2

Climate Change Theory

Climate change theory is an attempt to understand how global warming might affect the planetary environment as a whole while focusing only on humanity's impact on the Earth's climate.

Concern over climate change is not actually about the warming of the Earth's climate, per se, nor is it about the natural temperature variations that the Earth has shown over its four billion year climate history—which are extensive—as seen in Figure 1.[4]

It is widely acknowledged that the potential temperature changes predicted by global warming theory do not pose a direct threat to human life. Human beings, and a myriad of other organisms, exist quite comfortably in areas with temperature ranges more extreme than those predicted by global warming models.[5] Rather, the major concerns about climate change focus on the second- and third-hand impacts that would theoretically accompany global warming.

Climate change theory suggests that warming of the overall environment could lead to a variety of changes in the patterns of Earth's climate as the natural cycles of air currents, ocean currents, evaporation, plant growth and so on change in response to the increased energy levels in the total system. The most commonly predicted primary impacts of global warming are increased activity in the hydrologic, or water cycle of the Earth, and the possible rise of oceans due to thermal expansion and some melting of sea ice, ice sheets, or polar icecaps. More dynamic activity in the water-cycle could lead to increased rainfall in some areas, or, through increased evaporation rates, could cause more severe droughts in other areas. Rising sea levels could inundate some coastal areas (or low-lying islands), and through salt-water intrusion, could cause harm to various freshwater estuaries, deltas, or groundwater supplies.

Some have also predicted a series of third-hand impact to occur if the climate actually warms and becomes more dynamic.[6] Wildlife populations would be affected (positively and negatively), as would some vegetative growth patterns. The "home-range" of various animal and insect populations might shift, exposing people to diseases that were previously uncommon to their area, and so on.[7]

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4 Figure derived from L.A. Frakes, *Climates Throughout Geologic Time*, (Amsterdam, Netherlands: Elsevier Press, 1979), p. 261.

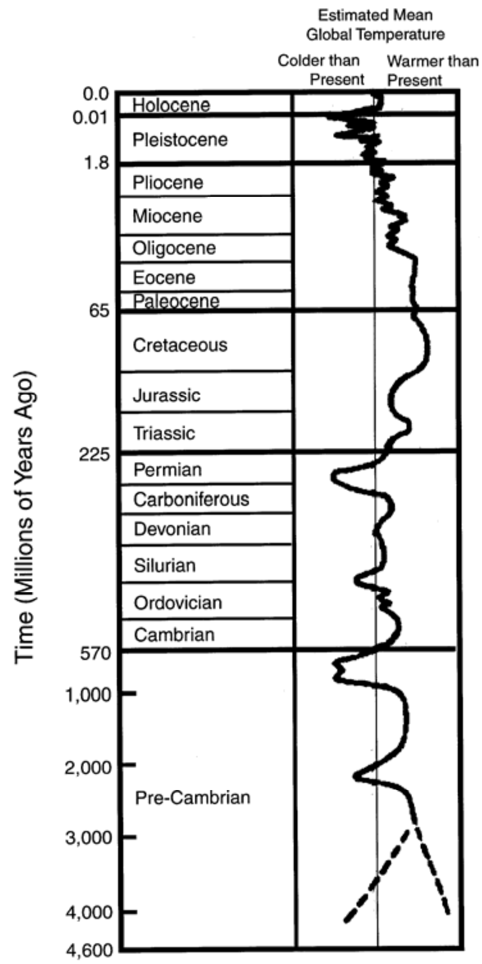
5 Global warming and the potential climate change effects that might accompany such warming, is estimated through the use of complex computer models which simulate with greater or lesser complexity and success, the way that the Earth's climate would change in response to the level of greenhouse gases in the air.

6 Intergovernmental Panel on Climate Change (IPCC), *Climate Change 1995, Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses* (Cambridge, MA: Cambridge University Press), 1996.

7 Richard Stone, "If the Mercury Soars, so May Health Hazards," News and Comment, *Science*, Volume 267, February 1995; Rita R. Colwell, "Global Climate and Infectious Disease: The Cholera Paradigm," Association Affairs, *Science*, Volume 174, December 1996; and Gary Taubes, "Apocalypse Not," News and Comment, *Science*, Volume 278, November 1997.

Finally, the concern over climate change is not about non-human impacts on the climate, but is specifically a concern about human potential to alter the climate through activities such as the emission of fuel combustion by-products, or through land-use decisions that alter the Earth's vegetation patterns. Such human-induced changes in climate are called anthropogenic.[8]

Figure 1: History of the Earth's Temperature



Source: Frakes, 1979.

While greenhouse effect theory is a relatively uncontroversial issue in the scientific sense, the theory of global, human-driven climate change is at a much younger stage of development. Although there are very few articles appearing in science journals that contradict either the overall theory or details of the core greenhouse effect, the same can not be said for the theory of man-made climate change. Indeed, studies jockey back and forth about key elements of anthropogenic climate change nearly every month on the pages of leading science journals including America's premier science journal, *Science.* Even the IPCC report on the Science of Climate Change leaves the question open, saying:

> *Finally, we come to the difficult question of when the detection and attribution of human-induced climate change is likely to occur. The answer to this question must be subjective, particularly in the light of the large signal and noise uncertainties discussed in this chapter. Some scientists maintain that these uncertainties currently preclude any answer to the question posed above. Other scientists would and have claimed, on the basis of the statistical results presented in Section 8.4, that confident detection of a significant anthropogenic climate change has already occurred.*[9]

This is not to say that man-made climate change theory is either right or wrong, proven or not proven, looming catastrophe or massive hoax—only that it is not, as various groups have implied, nearing a final verdict. Indeed, the vigorous flow of publications and the acknowledged controversy within the IPCC documentation of the science of climate change imply that the question is still quite open.

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8 "Anthropogenic" basically means "caused by humans." For the sake of readability, I will most often use other terms, such as man-made, or "caused by humans." No sexism or other discriminatory connotations are intended by the use of such terms, only the clarity that comes with familiarity.

9 "Greenhouse Forecasting Still Cloudy," Research News, *Science*, Vol. 276, May 1997.; K. Hasselmann, "Are We Seeing Global Warming?" Perspectives, *Science*, Vol. 276, May 1997; and IPCC, *Climate Change*, p. 439.

Part 3

Atmospheric Changes

Human activities (as well as non-human biological, chemical, or geological processes) release a variety of chemicals into the atmosphere, some of which, in accordance with climate change theory, could exert a warming effect, and others which, according to the same theory, could exert a cooling effect.

1. Carbon Dioxide

Carbon dioxide, considered a warming gas, comprises about 0.034% of the atmosphere by volume. Carbon dioxide levels have increased as a component of the atmosphere by nearly 30% from the late 18th century to the present.[10] Carbon dioxide is released into the environment by human activities such as fuel burning, cement production and land use. Carbon dioxide in the atmosphere is part of a larger carbon cycle in which carbon is changed from gaseous to non-gaseous forms over the course of time by a variety of organic and inorganic processes. Table 1 shows the tonnage of carbon exchanged between various sources and sinks in the environment, as they are relevant to a potential role for carbon dioxide climate change.[11]

Since highly accurate, direct measurement of carbon dioxide levels only began in the late 1950s, most of our understanding of carbon dioxide's historical patterns of fluctuation come from indirect measurements, such as the analysis of gas bubbles trapped in glaciers and polar ice caps. Though such indirect measure-ments carry greater uncertainty than direct measurements of carbon dioxide levels, they have contributed to rapid growth in our understanding of the Earth's carbon cycle in recent years. Still, significant gaps in our understanding remain, specifically involving questions of time lag, the impact of world

Table 1: Exchangeable Flows of Carbon in the Environment[12]

Natural Sources	Range (Gtons/yr)	Percent of Total (out of 158 Gtons/yr)
• Oceans	90–92	57–58
• Land biota	60–61	36–39
Natural Source Total	***150–153***	***93–97***
Human Sources		
• Burning fossil fuels	5.0–6.0	3.4–3.8
• Deforestation	0.6–2.6	0.01–0.02
Human Source Total	***5.6–8.6***	***3.5–5.4***
Total	***157–160***	***100%***

NOTES: a) A Gton, or gigaton, is a billion metric tons. A Gton/yr is one gigaton of carbon moved from one pool to another over the course of one year.
b) Land biota includes emissions from all plant life on the earth as well as soils and detritus.

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[10] IPCC, *Climate Change 1995, The Science of Climate Change*; Stanley E. Manahan, *Environmental Chemistry, Fourth Edition* (Monterey, CA: Brooks/Cole Publishing Company), p. 311.

[11] Deep ocean reservoirs are not included, for example, though they can exchange carbon with the atmosphere over long periods of time.

[12] Data drawn from IPCC, *Climate Change 1995, The Science of Climate Change*, p. 77.

vegetation on atmospheric carbon dioxide levels, other processes that might lock carbon dioxide away from the atmosphere, and the role of carbon dioxide as a causal agent of climate change.[13]

2. Methane

Methane is a greenhouse gas several times more powerful as a warming agent than carbon dioxide, though with a considerably shorter life-span in the atmosphere. As an atmospheric component, methane is considered a trace gas, comprising approximately 0.00016 percent of the atmosphere by volume. Methane levels in the atmosphere have increased nearly 150 percent since the beginning of the 19th century, with current levels being the highest ever recorded, though the pattern of methane emissions is highly irregular and has actually shown recent downturns for reasons which are not clear.[14]

Methane comes from a variety of sources, only some of which are directly man-made. Table 2 shows the sources of methane found in the atmosphere.

Table 2: Sources of Methane Found in the Atmosphere[15]

Natural Sources	Range (Mtons)	IPCC Value	Percent of IPCC total
• Wetlands	100–200	115	22
• Termites	10–50	20	4
• Ocean/freshwater	6-45	15	3
• Methane hydrates	0–5	5	1
Natural Source Total	***117–325***	***150***	***30***
Human Sources			
• Energy Use	70–120	100	19
• Rice paddies	20–150	60	12
• Enteric fermentation	65–100	80	15
• Human / Animal wastes	20–60	50	10
• Landfills	20–70	30	6
• Biomass burning	20–80	40	8
Human Source Total	***215–580***	***360***	***70***
Total	***332-905***	***515***	***100***

NOTES:
a) An Mton, or megaton, is one million metric tons.
b) Column three shows the values deemed most likely by the IPCC.
c) "Enteric Fermentation" constitutes gaseous emissions from animals. The IPCC considers all animal emissions as being caused by activities of mankind.
d) Calculations of percent contribution by author, using IPCC 1992 data. The 1995 report did not break out the individual contributions, important information for understanding the relative contributors of methane to the atmosphere. Changes in the actual numerical assessment of the methane budget, however, are not substantial in the newer report.

3. Nitrous Oxide

Nitrous oxides are long-lived warming gases with about 200 times the relative warming strength of carbon dioxide.[16] Nitrous oxides are, like methane, considered a trace gas in the atmosphere, but at considerably lower

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13 IPCC, *Climate Change 1995, The Science of Climate Change*, pp. 75–87

14 IPCC, *Climate Change 1995, The Science of Climate Change*, p. 87.

15 Table adapted from R.T. Watson, L.G. Meira Filho, E. Sanhueza, and A. Janetos, "Greenhouse Gases: Sources and Sinks," *Climate Change 1992*, J.T. Houghton, B.A. Callander, and S.K. Varney, eds. (Cambridge, MA: University Press), p. 35.

16 IPCC, *Climate Change 1995, The Science of Climate Change,* p. 88.

levels, between 0.000001 percent and 0.0000000001 percent of the atmosphere by volume. With the exception of a downturn attributed to the eruption of Mt. Pinatubo, nitrous oxide concentrations have increased in recent years, though not beyond the levels seen in previous decade-long averaging periods[17]

Nitrous oxides come from a variety of sources, only some of which are directly man-made. Table 3 shows the sources of nitrous oxides found in the atmosphere.

Table 3: Sources of Nitrous Oxides Found in the Atmosphere[18]

Natural Sources	Range (in Mtons)
• Oceans	1.4–2.6
• Tropical Soils	Uncertain
• Wet forests	2.2–3.7
• Dry savannas	0.5–2.0
• Temperate soils	Uncertain
• Forests	0.5–2.0
• Grasslands	Uncertain
Natural Source Total	***4.6–10.3***
Anthropogenic Sources	
• Cultivated soils	0.3–3.0
• Biomass burning	0.03–1.0
• Combustion	0.1–0.3
• Mobile sources	0.2–0.6
• Acid production	0.5–0.9
Anthropogenic Source Total	***0.13–5.8***
IPCC Total	***5.2–16.1***

NOTES:
a) An Mton, or megaton, is a million metric tons.
b) The IPCC total was deduced using both the magnitude of the sinks and the rate of accumulation in the atmosphere.

4. Chlorofluorocarbons

Chlorofluorocarbons (CFC) are man-made compounds used as cooling agents and propellants in a broad range of applications. Since CFCs are a class of many different long-lived chemicals, some of which have been banned, characterizing their concentration in the atmosphere is difficult. Ozone-depleting CFCs can exert either warming or cooling effects, depending on where they are found. In the lower atmosphere, ozone-depleting CFCs exert a warming effect through the absorption of heat re-radiated from the Earth's surface. In the upper atmosphere, ozone destruction exerts a cooling effect by destroying some of the high-altitude ozone that can either warm or cool the surface in different circumstances. On a net basis, our current understanding is that the ozone-depleting CFCs (now banned by the Montreal Protocol) exerted a cooling effect.[19] Replacement chemicals for the ozone-depleting CFCs are considered pure warming gases, but with a considerably lower warming potential than the chemicals they displaced.[20] Because of the huge complexities of ozone chemistry in the atmosphere and uncertainties regarding the warming or cooling potential of remaining ozone-depleting CFCs and replacement compounds, the ultimate impact of CFCs on climate change is highly uncertain.[21]

5. Aerosols

Aerosols are not gases, but are liquid or solid particles small enough to stay suspended in the air. Aerosols are generated by both man-made and natural processes. Some aerosol particles tend to reflect light, or cause clouds to brighten, exerting a cooling effect on the atmosphere. Other aerosol particles tend to absorb light and can exert a warming effect. Most man-made aerosols exert a cooling effect on the climate. On a global basis, this cooling effect offsets about 20 percent of the predicted warming from the combined greenhouse warming gases,

[17] IPCC, *Climate Change 1995, The Science of Climate Change*, p. 88.

[18] Table adapted from R.T. Watson, L.G. Meira Filho, E. Sanhueza, and A. Janetos, *Greenhouse Gases: Sources and Sinks, Climate Change 1992*, J.T. Houghton, B.A. Callander, and S.K. Varney, eds. (Cambridge, MA: University Press, 1992), pp. 37–38.

[19] IPCC, *Climate Change 1995, The Science of Climate Change*, pp. 90–93, 119–123.

[20] Ibid.

[21] IPCC, *Climate Change 1995, The Science of Climate Change*, p. 122.

but it's not uniform: the offsetting impact varies geographically depending on local aerosol concentrations.[22] Table 4 shows the origin and flow rates of aerosol particulates in the atmosphere.

The omission of aerosol considerations in earlier climate models led to considerable over-prediction of projected global warming and predicted regional impacts, though newer models have done much to internalize the cooling effect of aerosols.[23] Aerosols act as cooling agents through several mechanisms, however, some of which are only poorly understood. Besides directly scattering incoming sunlight, most particulates also increase the reflectivity, formation, and lifetime of clouds, affecting the reflection of incoming solar radiation back to space.[24]

6. Summary of Atmospheric Changes

It is clear that human action affects the level of several atmospheric components, including five of the six constituents considered to be the major greenhouse gases: carbon dioxide, methane, nitrous oxides, ozone, and CFCs. The sixth major greenhouse gas is water vapor, and while it's almost certain that human action influences the amount of water vapor in the atmosphere, the role of water vapor in climate change is still highly uncertain, as will be discussed later.

It is also clear that human action is not the only factor involved in determining the atmospheric concentrations of these gases. For all gases except methane, sulfur-based aerosols, and CFCs, the human contribution is, by far, the smaller part of the total.

Table 4: Aerosol Particulate Types and Flow Rates in the Atmosphere[25]

Natural Sources	Flux (in Mtons/yr)
Primary	
• Soil dust	1,500
• Sea salt	1,300
• Volcanic dust	33
• Biological debris	50
Secondary	
• Sulphates from natural precursors	102
• Organic matter from biogenic VOC	55
• Nitrates from NOx	22
Total from Natural Sources	***3,062***
Anthropogenic Sources	
Primary	
• Industrial dust	100
• Soot (elemental carbon) from fossil fuels	8
• Soot from biomass burning	5
Secondary	
• Sulphates from SO_2	140
• Biomass burning	80
• Nitrates from NOx	36
Total from Anthropogenic Sources	***369***
Combined Total	***3,431***

NOTE:
a) An Mton, or megaton, is one million metric tons.

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22 Total greenhouse gas forcing estimate is 2.45 Wm^{-2}, total aerosol forcing is –0.5 Wm^{-2}. IPCC, *Climate Change 1995, The Science of Climate Change*, p. 118.

23 IPCC, *Climate Change 1995, The Science of Climate Change*, p. 297.

24 IPCC, *Climate Change 1995, The Science of Climate Change*, p. 103.

25 Adapted from IPCC, *Climate Change 1995, The Science of Climate Change*, Table 2.6, p. 104.

Part 4

Climate Changes

Part of the concern about global climate change stems from the human tendency to seek meaning in events which may or may not be more than simply a random event. A particularly cold winter, a particularly hot summer, an especially rainy season, or an especially severe drought will all send people off on a search for the greater meaning of the phenomenon. Is it a pattern, or a one-time event? Must we build a dike, or has the danger passed? Since the summer of 1988, virtually all unusual weather events seem to trigger questions about global climate change.

Our ability to really know what the climate is doing is limited by a short observational record, and by the uncertainties involved in trying to figure out what climate was like in the past, or might be like in the future, for comparison with recent climate changes. While the Earth's climate has been evolving and changing for over four billion years, recordings of the temperature only cover about 150 years, less than 0.000004% of the entire pattern of evolving climate. In fact, temperature records are spotty before about 40 years ago and only cover a tiny portion of the globe, mostly over land. In addition to that 150-year conventional surface temperature record, temperature readings taken from weather balloons cover the last 30 years, and satellite temperature readings cover the last 18 years. Modern, reliable measurements of greenhouse gases are an even newer source of data, beginning with carbon dioxide measurements at the South Pole in 1957, at Mauna Loa in 1958, and later for methane, nitrous oxides and chlorofluorocarbons.[26]

Aside from temperature readings, other climate trends proposed as secondary effects of global warming carry information about the state of the climate. Changes in absolute humidity, rainfall levels, snowfall levels, the extent of snowfall, the depth of snowfall, changes in ice caps, ice sheets, sea ice, and the intensity or variability of storms have all been proposed as secondary effects of global warming. But because the history of recording such climate trends is extremely short, most evidence regarding non-temperature-related changes in Earth's climate and atmospheric composition prior to the recent history of direct measurements is gathered from indirect sources such as air bubbles trapped in polar ice, or the study of fossils. This evidence, while interesting as a potential "reality check" for global anthropogenic climate change models, is considered far less reliable than direct observational data.[27]

These limitations in our evidence make it difficult to draw hard and fast conclusions regarding what changes have actually occurred recently in comparison to past climate conditions. More importantly, these limitations make it difficult to determine whether those changes are beyond the range of previous climate trends, happening at a faster rate than previous climate trends, or are being sustained for longer than previous climate trends, all critical questions when evaluating whether humanity is causing changes to Earth's normal climate patterns.[28]

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26 IPCC, *Climate Change 1995, The Science of Climate Change,* p. 78.

27 This type of evidence is what was used to compile the temperature record for prehistoric times shown in Figure 1. Discussion of the relative reliability of such data with regard to evaluating current change is from K. Hasselmann, "Climate Change Enhanced: Are We Seeing Global Warming?," Perspectives, *Science*, Volume 276, May 1997, p. 915.

28 Ibid.

Nevertheless, we do have evidence at hand regarding recent changes in both atmospheric composition and global climate trends that suggest that humanity has at least changed the Earth's atmospheric composition in regard to greenhouse gases and other pollutants, which may, or may not, be contributing to recently observed changes in global warmth. A quick review of the climate changes which are suggested by the available evidence follows.

1. Temperature Trends

Besides readings of Earth's surface temperatures taken with standard glass thermometers, direct readings of atmospheric temperatures have been taken with satellites and weather balloons. In addition to the direct measurements of the Earth's recent temperatures, proxy measurements of temperatures from farther in the past can be derived from bore-hole temperature measurements, from historical and physical evidence regarding the extent and mass of land and sea ice, and from the bleaching of coral reefs.[29]

This information is in relatively good agreement regarding what seems to be happening to global temperatures, at least in the recent periods of change spanning the last few hundred years, though there are discrepancies between some of the data sets. According to the IPCC, temperatures recorded at ground-based measuring stations reveal a mean warming trend ranging from 0.3 °C to 0.6 °C since about 1850, with 0.2 – 0.3 °C of this warming occurring over the last 40 years. The warming is not uniform, either in chronology or distribution. More of the change occurs over land than over water. More of the warming happens at night, resulting in warmer night-time temperatures, rather than hotter daytime temperatures. More of the warming is noticeable as a moderation of wintertime low temperatures, rather than as an increase in summertime high temperatures. Temperatures taken from weather balloons (also called radiosondes) and from satellites span a much shorter period of time (though arguably, a more rigorously standardized measuring technique), and there is controversy over what they indicate, and how much weight should be given to such a short data set. Some analysts contend that the satellite and balloon recordings show a slight cooling trend in the tropics (about 0.10 °C/decade) over the last 18 years, while others contend that the discrepancy is only an artifact caused by a limited data set, and the recent, unrelated increase in the strength of the El Niño Southern Oscillation.[30]

And even here, taking the simplest of physical measurements, uncertainties are present. Temperature readings (satellite or ground station) were not taken specifically for the sake of evaluating the climate patterns of the entire Earth. Consequently, the readings were taken from a variety of locations, cover only selected parts of the atmosphere, and are not necessarily well-placed to be most informative about the climate as a whole.[31] Further, measurement techniques and stations varied over the course of the temperature record, with data adjustments of a full degree occasionally needed to make the different sets of data compatible with each other.[32] Satellites and balloons measure a different part of the atmosphere than ground stations do, making the comparability of such records questionable, and the shortness of the satellite data record, punctuated as it has been by impacts of volcanic eruptions and the El Niño Southern Oscillation further complicate the evaluation of temperature data.

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[29] Bleaching of coral reefs marks a variety of environmental disturbances, from high-heat episodes, to high-pollution episodes such as the eruption of Mount Pinatubo in June 1991.

[30] R.W. Spencer and J.R. Christy, "Precision and radiosonde validation of satellite gridpoint temperature anomalies, Part II: A tropospheric retrieval and trends during 1979-90," *J. Climate*, Volume 5, 1992, pp. 858–866.

[31] IPCC, *Climate Change 1995, The Science of Climate Change*, p. 181.

[32] Michael L. Parsons, Ph.D., *Global Warming, the Truth Behind the Myth* (New York: Insight Books, Plenum Press, 1995), Ch. 5.

Some people interpret the observed changes of temperature as being evidence supporting the theory that human action has caused changes in the global climate.[33] Others find the evidence regarding observed changes in temperature insufficient to allow a sound conclusion regarding the validity of that theory because of the historical volatility of climate variations.[34] While the last 10,000 years have been abnormally placid as far as climate fluctuations go, evidence of prior climate changes show an Earth that is anything but placid, climatically.[35] Some 11,500 years ago, for example, there is evidence that temperatures rose sharply over short periods of time. In Greenland, temperatures increased by as much as 7 °C over only a few decades, while sea surface temperatures in the Norwegian Sea warmed by as much as 5 °C in less than 40 years.[36] There is also evidence of about 20 rapid temperature fluctuations during the last glaciation period in the central Greenland records. Rapid warmings of between 5 and 7 °C were followed by slow returns to glacial conditions over the course of 500 to 2000 years.[37] In interpreting current climate changes, the broadest view of past climate changes lends important perspective.

2. Precipitation Trends

Changes in precipitation trends are, potentially, a form of indirect evidence reflecting whether the Earth is currently experiencing man-made climate change. As the IPCC report observes, "an enhanced greenhouse effect may lead to changes in the hydrologic cycle, such as increased evaporation, drought, and precipitation."[38] But the section on precipitation changes as an indirect measure warns that "our ability to determine the current state of the global hydrologic cycle, let alone changes in it, is hampered by inadequate spatial coverage, incomplete records, poor data quality, and short record lengths."[39]

According to the IPCC, the global trend in rainfall has shown a slight increase (about 1 percent) during the 20th century, though the distribution of this change is not uniform either geographically or over time. Rainfall has increased over land in high latitudes of the Northern Hemisphere, most notably in the fall. Rainfall has decreased since the 1960s over the subtropics and tropics from Africa to Indonesia. In addition, some evidence suggests increased rainfall over the Pacific Ocean (near the equator and the dateline) in recent decades, while rainfall farther from the equator has declined slightly.[40]

Global warming would also be expected to influence things like snowfall, snow depth, and snow coverage (or extent), but studies examining changes in such aspects of the climate are quite mixed. Consistent with the indications of slight warming of the global climate, snow cover has declined in recent years, with a higher percentage of precipitation in cold areas coming down as rain, rather than snow. But while the annual mean extent of snow cover over the Northern Hemisphere has declined by about 10 percent over the past 21 years of study, snowfall levels have actually increased by about 20 percent over northern Canada, and by about 11 percent over Alaska. Between 1950 and 1990, snowfall over China decreased during the 1950s, but increased during the 1960s

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33 Richard A. Kerr, "Studies Say—Tentatively—That Greenhouse Warming is Here," Research News, *Science*, Volume 268, June 1995.

34 Michael L. Parsons, Ph.D., *Global Warming, the Truth Behind the Myth*, Insight Books, Plenum Press, New York, 1995, Ch. 5.

35 IPCC, *Climate Change 1995, The Science of Climate Change*, p. 179.

36 IPCC, *Climate Change 1995, The Science of Climate Change,* p. 178.

37 Ibid.

38 IPCC, *Climate Change 1995, The Science of Climate Change,* pp. 151–152.

39 Ibid.

40 IPCC, *Climate Change 1995, The Science of Climate Change,* pp. 152–154.

and 1970s. Snowfall over the 45–55 degree latitude belt has declined slightly.[41] Snow depth levels, which respond both to atmospheric temperature and to the ratio of rainfall to snowfall show equally mixed changes. Snow-depth measurements of the former Soviet Union over the 20th century show decreased snow depth of about 14 percent during the Soviet winter, mostly in the European portion of the ex-Union, while snow depth in the Asian sectors of the former Soviet Union has increased since the 1960s.

3. Ice and Sea Level Trends

Changes in sea level and the extent of ice sheets, sea ice, and polar ice caps are still another form of indirect evidence reflecting whether the Earth is currently undergoing anthropogenic climate change. Climate change theory would suggest that rising global temperatures would cause sea levels to rise due to a combination of the thermal expansion of water and melting of glaciers, ice sheets, ice caps, and sea ice.

Recent studies of sea levels alone indicate a rise of 18 cm over the last 100 years, with a range of uncertainty of 10–25 cm, though there is little evidence that the rate of sea level rise has actually sped up during that time period, in theory, the rate of warming has been accelerating.[42]

But thermal expansion of water is only one contributor to sea level changes. Glaciers, ice sheets, and land water storage all play a role—a highly uncertain role.

The IPCC sums up the changes in water level trends this way: "The current estimates of changes in surface water and ground water storage are very uncertain and speculative. There is no compelling recent evidence to alter the conclusion of IPCC (1990) that the most likely net contribution during the past 100 years has been near zero or perhaps slightly positive, with an uncertainty of about +/- 6 cm."

With regard to glaciers and ice caps, the state of knowledge is even more limited: Glaciers and ice caps may have accounted for 2-5 cm of the observed sea level rise, but the range of uncertainty is high.[43] Finally, with regard to ice sheets, data are contradictory: there is not enough evidence to know whether the Greenland and Antarctic ice sheets are shrinking, hence contributing to sea level rise, or growing, and hence retarding sea level rise. They may even be doing both, growing on top, and shrinking at the margins.[44]

The IPCC report sums up the situation thus: "In total, based on models and observations, the combined range of uncertainty regarding the contributions of thermal expansion, glaciers, ice sheets and land water storage to past sea level change is about –19 cm to +37 cm."[45]

4. Extreme Weather Intensity or Variability Trends

Finally, increases in the intensity or variability of weather is considered another form of indirect evidence reflecting whether the Earth is currently undergoing anthropogenic climate change.

Predictions of increased incidences of extreme temperatures, tornadoes, thunderstorms, dust storms and fire weather have been drawn from basic global anthropogenic climate change theory.

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41 IPCC, *Climate Change 1995, The Science of Climate Change,* p. 157.

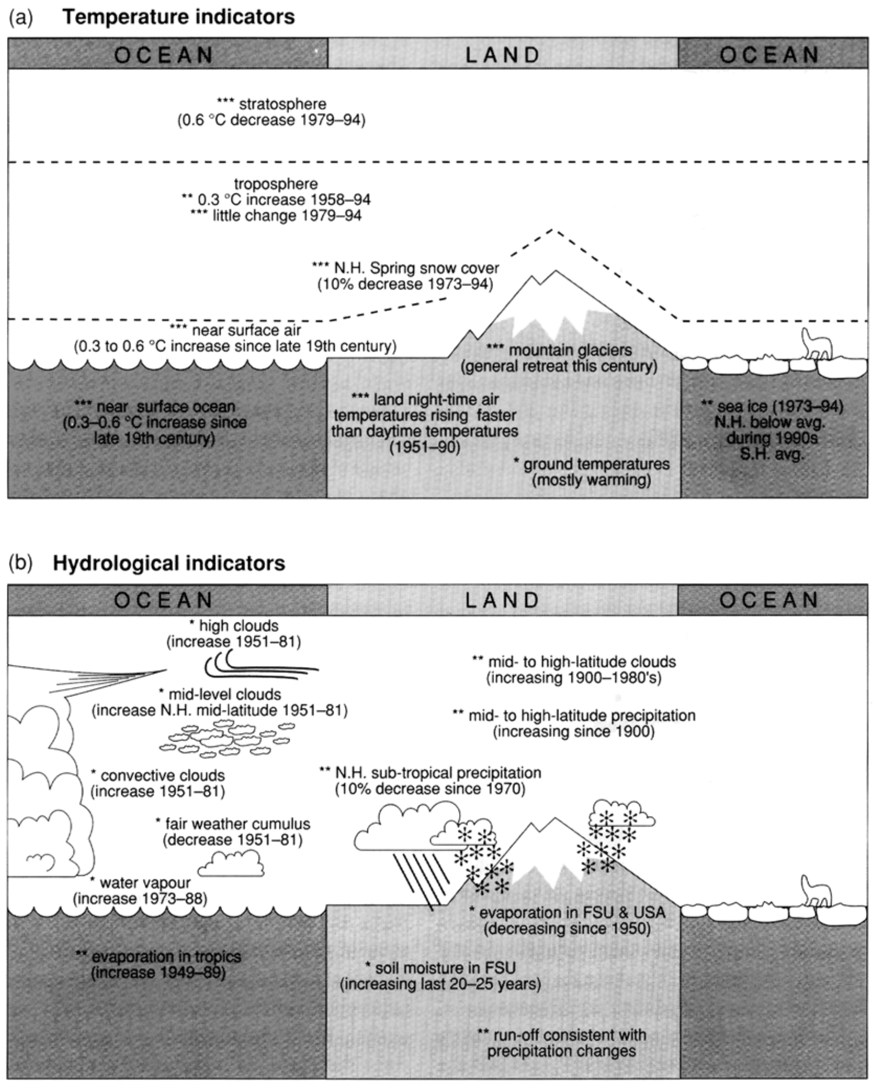
42 IPCC, *Climate Change 1995, The Science of Climate Change,* p. 368.

43 IPCC, *Climate Change 1995, The Science of Climate Change,* p. 381.

44 Ibid.

45 Ibid.

Figure 2: Summary of Temperature and Hydrological Changes



Asterisk indicates confidence level (i.e., assessment): *** high, ** medium, * low

Source: IPCC, Figure 3.22, p. 180.

But evidence has not, so far, borne out these predictions on a global scale. The IPCC concludes that:

> *…overall, there is no evidence that extreme weather events, or climate variability, has increased, in a global sense, through the 20th century, although data and analyses are poor and not comprehensive. On regional scales, there is clear evidence of changes in some extremes and climate variability indicators. Some of these changes have been toward greater variability; some have been toward lower variability.*[46]

[46] IPCC, *Climate Change 1995, The Science of Climate Change,* Cambridge University Press, p. 173.

5. Summary of Climate Changes

As Figure 2 indicates, evidence regarding changes in Earth's climate in the 20th century is mixed, and encompasses a range of uncertainties.

While the IPCC report holds that there is a discernible human influence on climate, this conclusion is not dependent on the evidence of actual changes in the Earth's climate as shown in this Figure. On that note, the IPCC says, "Despite this consistency [in the pattern of change], it should be clear from the earlier parts of this chapter that current data and systems are inadequate for the complete description of climate change."[47] Rather, this conclusion is based on mathematical modeling exercises and "reality checked" with what hard evidence we have.[48] The IPCC sums up the question of attributing observed climate changes to human action, thus: "Although these global mean results suggest that there is some anthropogenic component in the observed temperature record, they cannot be considered as compelling evidence of a clear cause-and-effect link between anthropogenic forcing and changes in the Earth's surface temperature."[49]

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[47] IPCC, *Climate Change 1995, The Science of Climate Change*, p. 411.

[48] Something which really is not a particularly huge logical leap, since virtually all organisms impact their ecosystem, with humankind as no exception.

[49] Ibid.

Part 5

Uncertainty and Future Research Needs

While recent studies of climate have contributed a great deal to our understanding of climate dynamics, there is still much to learn. The process of searching for evidence of man-made climate change, in fact, is both a search for new discoveries about how climate works, and continuing refinement of our understanding of the underlying theories we already have.

Many areas of uncertainty remain. Current climate change models have acknowledged weaknesses in their handling of changes in the sun's output, volcanic aerosols, oceanic processes, and land processes which can influence climate change.

Some of those uncertainties are large enough, by themselves, to potentially become the tail which wags the dog of climate change theory. Three of the major uncertainties which remain are discussed below.

1. The Natural Variability of Climate

Despite the extensive discussion of climate modeling and knowledge of past climate cycles, only the last 1000 years of climate variation are included in the two state-of-the-art climate models referred to by the IPCC.[50] As discussed earlier, however, the framework in which we view climate variability makes a significant difference in the conclusions we draw regarding either the comparative magnitude or rate of climate changes, or the interpretation of those changes as being either inside or outside of the envelope of normal climate change variations. The IPCC report summarizes the situation succinctly:

> *Large and rapid climatic changes occurred during the last ice age and during the transition towards the present Holocene period. Some of these changes may have occurred on time-scales of a few decades, at least in the North Atlantic where they are best documented. They affected atmospheric and oceanic circulation and temperature, and the hydrologic cycle. There are suggestions that similar rapid changes may have also occurred during the last interglacial period (the Eemian), but this requires confirmation. The recent (20th century) warming needs to be considered in the light of evidence that rapid climatic changes can occur naturally in the climate. However, temperatures have been far less variable during the last 10,000 years (i.e., during the Holocene).*

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50 IPCC, *Climate Change 1995, The Science of Climate Change,* p. 416.

Until we know which perspective is more reflective of Earth's climate as a whole—the last 10,000 years, or a longer period of time—it will be difficult to put recent warming trends in perspective, or to relate those trends to potential impacts on the climate, and on the Earth's flora and fauna.

2. The Role of Solar Activity

At the front end of the climate cycle is the single largest source of energy which is put into the system, namely, the sun. And while great attention has been paid to most other aspects of climate, little attention has been paid to the sun's role in the heating or cooling of the Earth. Several recent studies have highlighted this uncertainty, showing that solar variability may play a far larger role in the Earth's climate than it was previously given credit for by the IPCC.[51] If the sun has been heating up in recent times, researchers observe, the increased solar radiation could be responsible for up to half of the observed climate warming of the past century.[52] Astrophysicist Sallie L. Baliunas attributes up to 71 percent of the observed climate warming of the past century to increased solar irradiance.[53] Other researchers such as climatologist T.M.L. Wigley, however, rank the influence of solar activity on climate warming much lower, at "somewhere between 10 percent and 30 percent of the past warming."[54] But as with satellite measurements of Earth's temperature, the short time line of satellite measurements of solar irradiance introduces significant uncertainty into the picture. Most researchers believe that at least another decade of solar radiation measurement will be needed to clearly define the influence of solar input on the global climate.[55]

3. Clouds and Water Vapor

Between the emission of greenhouse gases and change in the climate are a range of climate and biological cycles that can influence the end-result. Such outcome-modifier effects are called "feedbacks" or "indirect effects" in the climate change literature.

One such feedback is the influence of clouds, and water vapor. As the climate warms, more water vapor enters the atmosphere, but how much? And, which parts of the atmosphere, high or low? And how does the increased humidity affect cloud formation? While the relationship between clouds, water vapor, and global climate is complicated in and of itself, the situation is further complicated by the fact that aerosols exert a poorly understood influence on clouds. Earlier computer models, which omitted the recently validated cooling effect of aerosols, overestimated the global warming that we would have expected to see by now, based only on the levels of greenhouse gases which have been emitted. As discussed earlier, aerosols themselves may offset 20 percent of the expected impact of warming gases. In addition, though direct cooling impacts of aerosols are now being taken into account by climate models, aerosol impact on clouds remains a poorly defined effect with broad implications, given a range of additional cooling potential of up to 61 percent of the expected warming impact from the warming greenhouse gases.[56]

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51 Richard C. Willson, "Total Solar Irradiance Trend During Solar Cycles 21 and 22," Reports, *Science*, Volume 277, September 1997; and IPCC, *Climate Change 1995, The Science of Climate Change*, p. 117.

52 Richard A. Kerr, "A New Dawn for Sun-Climate Links?," Research News, *Science*, Volume 271, March 1996.

53 William J. Broad, "Another Possible Climate Culprit: The Sun," *New York Times*, September 1997.

54 Richard A. Kerr, "A New Dawn for Sun-Climate Links?," Research News, *Science*, Volume 271, March 1996.

55 Richard A. Kerr, "Did Satellites Spot a Brightening Sun?," News, *Science*, Volume 277, September 1977.

56 Potential aerosol impacts on clouds are given a value range from 0-1.5 Wm^{-2}, compared to the total warming potential of the well-mixed greenhouse gases of 2.45 Wm^{-2}. IPCC, *Climate Change 1995, The Science of Climate Change*, p. 118.

As the IPCC report acknowledges: "the single largest uncertainty in determining the climate sensitivity to either natural or anthropogenic changes are clouds and their effects on radiation and their role in the hydrological cycle…At the present time, weaknesses in the parameterization of cloud formation and dissipation are probably the main impediment to improvements in the simulation of cloud effects on climate."[57]

4. The Impacts of Climate Change

As discussed earlier, the crux of the debate over climate change is not the question of direct changes in average global temperatures, but centers on the second- and third-hand effects of that change. One need not wade far into the IPCC's 880-page volume on the potential impacts of climate change, however, before encountering an admission that uncertainty dominates any discussion of such potential impacts.[58]

> *Impacts are difficult to quantify, and existing studies are limited in scope. While our knowledge has increased significantly during the last decade and qualitative estimates can be developed, quantitative projections of the impacts of climate change on any particular system at any particular location are difficult because regional scale climate change projections are uncertain; our current understanding of many critical processes is limited; and systems are subject to multiple climatic and non-climatic stresses, the interactions of which are not always linear or additive. Most impact studies have assessed how systems would respond to climate changes resulting from an arbitrary doubling of equivalent atmospheric carbon dioxide concentrations. Furthermore, very few studies have considered greenhouse gas concentrations; fewer still have examined the consequences of increases beyond a doubling of equivalent atmospheric carbon dioxide concentrations, or assessed the implications of multiple stress factors.*

The IPCC report goes on to point out that this extreme uncertainty is likely to persist for some time, since unambiguous detection of man-made climate change hinges on resolving many difficult problems.[59]

> *Detection will be difficult and unexpected changes cannot be ruled out. Unambiguous detection of climate-induced changes in most ecological and social systems will prove extremely difficult in the coming decades. This is because of the complexity of these systems, their many non-linear feedbacks, and their sensitivity to a large number of climatic and non-climatic factors, all of which are expected to continue to change simultaneously. The development of a base-line projecting future conditions without climate change is crucial, for it is this baseline against which all projected impacts are measured. The more that future climate extends beyond the boundaries of empirical knowledge (i.e., the documented impacts of climate variation in the past), the more likely that actual outcomes will include surprises and unanticipated rapid changes.*

Uncertainties of this scale do not imply, as some analysts have asserted, that there is no reason to fear negative change, nor does it imply that we must fear drastic impacts. Rather, uncertainties of this scale indicate the need for a sustained research program aimed at clarifying our understanding of Earth's climate, and how human activities might or might not translate into negative environmental impacts.

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[57] IPCC, *Climate Change 1995, The Science of Climate Change*, p. 346.

[58] Intergovernmental Panel on Climate Change (IPCC), *Climate Change 1995, Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses* (Cambridge, MA: Cambridge University Press, 1996), p. 24.

[59] Ibid.

Part 6

The Role of Consensus and Evidence in Science and Public Policy

The debate over national climate change policy exemplifies an increasingly frequent rhetorical approach of media and political figures involved in the handling of scientific issues in public policy debate: the inappropriate assertion that scientific issues can be resolved by reference to lists of scientists—not necessarily trained in the subject at hand, or involved in research about that subject—who are willing to attest to their belief one way or another regarding the certainty of a scientific theory.[60]

The argument of EPA administrator Carol Browner, for example, comes down to: I'm not a scientist, but we have a list of 2,500 scientists who say this is a serious problem.[61] In the meantime, those arguing against urgent action wave their own list of 4,000 scientists in opposition.[62]

But both approaches are inappropriate for evaluating evidence in a scientific framework. The degree of certainty surrounding a scientific issue is not decided by the number of scientists willing to make broad statements of their belief, nor by celebrity endorsements, nor by the repeated sound-bites of politicians or political appointees. It's decided by the weight of evidence, issue by issue, and nothing more.

While politics might be a numbers game, science is not. As commentator Ted Koppel put it so eloquently: "The measure of good science is neither the politics of the scientist nor the people with whom the scientist associates. It is the immersion of hypothesis into the acid of truth."[63] The rightness or wrongness of a scientific theory is not determined by the speaker's fame, majority rule, or celebrity endorsement, but by the ability of an idea to withstand challenges in an open process of inquiry in which validation is based on the weight of evidence interpreted according to the rules of inquiry that we call Science.

Violating this process of inquiry with inappropriate use of "consensus" to stifle debate can lead to some torturous justifications for drastic actions. Earlier in this century, for example, Italian philosopher Benedetto Croce used the same "decision by consensus" reasoning to defend the Inquisition, saying: "The inquisition

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60 This same reasoning was used in the debate over the adoption of new National Ambient Air Quality Standards in 1997.

61 Even as international discussions on the future of climate change policy were beginning in Kyoto Japan, this was the only substantiation that Ms. Browner raised in support of her Administration's position in a debate over the science of climate change with IPCC member Dr. Patrick Michaels on *Crossfire*, CNN, December 1, 1997.

62 Fred Singer, "A Heated Debate Over Global Warming," *The Washington Times*, July 5, 1996. The Heidelberg Appeal was released at the 1992 Earth Summit in Rio de Janeiro with 425 signatories. The current list holds over 4,000 signatories, including 70 nobel prize winners.

63 *USA Today Magazine*, March 1997, referencing a 1993 *Nightline* episode featuring a global warming discussion with Vice President Gore.

must have been justified and beneficial, if whole peoples invoked and defended it, if men of the loftiest souls founded and created it severally and impartially."[64] Such a rationale was wrong then, and it's wrong now.

While the consensus of high-profile scientists can give an issue a certain cachet, we should remember that before each new theory emerges, the majority of scientists or experts believe something else, and that belief is wrong. Before Copernicus gave us a sun-centered solar system, most scientists thought we had an earth-centered solar system. Before the Wright brothers flew at Kittyhawk, most aeronautic experts thought that heavier-than-air craft would never fly. Before Darwin defined evolution, most biologists believed in the inheritance of acquired characteristics. This is, in fact, the heroism of science—that individual scientists go on to make new discoveries precisely because they are unwilling to accept what "most scientists" think is the end of the story.

In the climate change discussion, the process of inquiry is still, in many respects, in its infancy. While we know some things, many relevant questions still remain unanswered. Our best tool for the resolution of these questions is science and a scientific evaluation of evidence. These tools may not rest well with those in a policy process that wants fast answers to complex questions, but they are the tools we have.

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[64] S. Morris Engel, *With Good Reason, An Introduction to Informal Fallacies* (New York, NY: St. Martin's Press, 1976).

Part 7

About the Author

Dr. Kenneth Green is Director of Environmental Studies and Senior Policy Analyst at the Reason Public Policy Institute. Dr. Green has published five previous studies on air quality policy: *Looking Beyond ECO, Defending Automobility, Checking Up on Smog Check, Rethinking EPA's Proposed Ozone and Particulate Standards*, and *Estimating Fatalities Induced by Economic Impacts of EPA's Proposed Ozone and Particulate Standards* (co-authored). Green received his doctorate in environmental science and engineering (D.Env.) from UCLA in 1994.

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