A VERY LIKELY CAUSE

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The title of my essay is the title of a chapter in the widely-acclaimed book by Richard Muller, a distinguished professor of physics at UC/Berkeley and a MacArthur Fellowship winner, entitled Physics for Future Presidents. The first two sentences of that chapter read:

> "Global warming is real. Since 1957 the average temperature of the globe has risen about 1 degree F, and it is *very likely* that humans are responsible for at least some of that increase." (Italics added)

This statement will probably come as no surprise to many of us. Since 1979, when President Jimmy Carter called for the first rigorous government-level study of global warming, we have witnessed an increasing focus on global warming by governmental agencies and the media—indeed, since 1979 the National Academy of Sciences alone has issued over two hundred reports on climate change (a term which is used interchangeably with global warming).

In 1988 the United Nations established the Intergovernmental Panel on Climate Change (the IPCC), an intergovernmental body charged to evaluate the risk of climate change caused by human activity. The IPCC has now issued four very lengthy and detailed Assessment Reports dealing with climate change. These Assessment Reports are cited in virtually every debate on the subject; they are generally regarded as expressing

the scientific consensus about climate change; and they have been endorsed by the National Academies of Science of virtually all major nations, including Brazil, Canada, China, France, Germany, India, Japan, Russia, the United Kingdom and the United States. In 2007, as you will recall, the IPCC was awarded the Nobel Peace Prize.

So what does the IPCC say about global warming ? Its 2007 Assessment Report states:

> Warming of the climate system is *unequivocal*, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level. (Italics added)

These observations have been widely and frequently reported. But is there any hard evidence of this warming ? The answer is yes. We know—based on instrumental temperature records—that the average surface temperature of the Earth has increased by slightly less than 2 degrees Fahrenheit since 1900. We also know that the warming trend over the 50-year period from 1956 to 2005 was nearly twice that for the 100-year period from 1906 to 2005; and that since 1970, temperatures have gone up at nearly three times the average rate for the 20th century as a whole.

On closer examination, we know that 1990 was the warmest year on record to that date. Almost every subsequent year has been even warmer, with 2005 being the hottest of all. We also know that the warmest 17 years on record have all occurred in the last 20 years. Just last month the World Meteorological Association announced that the decade 2000-2009 was the warmest ever recorded. Taking a longer perspective, the National Academy of Sciences states that the Earth is now warmer than it has been for at least four centuries. Richard Muller calls this fact the "*key fact* of global warming". (Italics added)

So: there appears to be solid evidence of global warming. But what exactly is meant by the term global warming ? When the IPCC and climate scientists talk of global warming, they are referring to this increase in the last 100 years or so in the average surface temperature of the Earth of slightly less than 2 degrees Fahrenheit (with most of that increase coming in the last fifty years); and to the fact that the current temperature of the Earth is at a level that the Earth has not seen for at least four hundred years.

Does this seem a cause for concern ? Here is what Richard Muller says:

> [Two degrees Fahrenheit in a hundred years] doesn't seem like a lot; and in some sense it isn't. *The fear is* that a substantial part of the increase is likely to have been caused by human activity, particularly the burning of fossil fuels. (Italics added)

The IPCC 2007 Assessment Report adds weight to this fear with its conclusion that:

> 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. (Italics added)

What does "very likely" mean ? The IPCC is very careful to define this term. "Very likely" means at least a 90% level of confidence. Obviously, Richard Muller chose the title of his chapter—which I took for the title of my paper—with the IPCC definition of "very likely" in mind.

Yet, not everyone shares the conviction of the IPCC in this regard. As we all recall, President George W. Bush vigorously opposed any form of mandatory limits on carbon emissions from the burning of fossil fuels. Bush said that that any such restrictions are unwarranted because they are not predicated on "sound science". For Bush, global warming was a matter of scientific debate—a theory whose validity was yet to be demonstrated. Just this past summer the United States Chamber of Commerce—an

organization with a membership of over three million US businesses—endorsed the Bush perspective. Indeed, one prominent writer recently opined that the "drumbeat of skepticism about global warming has never been louder".

This, then, is the controversy which led to this paper. Is there in fact solid science establishing that humans are mostly responsible for the current Earthly warming? Or is global warming nothing more than a theory whose validity is yet to be demonstrated ? It is this question which this paper will explore.

II.

This exploration starts with the basic physics principle of energy balance. Here—and for much of the following analysis—I am relying on the book Earth's Changing Climate by Richard Wolfson, the Benjamin F. Wissler Professor of Physics at Middlebury College.

The principle of energy balance postulates that the Earth (and, for that matter, every other body in the universe which is hotter than its surroundings) radiates—that is, loses—its heat energy in the form of invisible infrared electromagnetic waves; and it radiates this energy until its rate of heat loss equals the rate at which it receives heat. When this equilibrium is attained, the body will be in energy balance. The rate at which a body loses its heat is dependent on how much hotter the body is than its surroundings—the greater the temperature difference between a body—such as the Earth—and its surroundings—such as the atmosphere, the greater the rate of heat loss. This is the key to understanding the principle of energy balance. When a body reaches a state of energy balance, it will maintain a stable temperature—as long as there are no changes in heat inflow or heat outflow.

For the Earth, the principal heat energy coming in, obviously, is sunlight—a visible form of electromagnetic energy. This energy reaches the Earth's surface at an average rate of about 342 watts per second for every square meter of the Earth's surface. Some 30% of this—about 107 watts per square meter—is immediately reflected back to space by ice, deserts and other features on the surface of the Earth. That leaves about 235 watts of heat energy from the Sun reaching the Earth every second for every square meter of surface area.

Assume, for a moment, that sunlight were the only form of heat energy which the Earth receives. In such a scenario, in order to achieve energy balance, the Earth would have to radiate heat at the same rate as it receives heat from the Sun—235 watts per second for each square meter of the Earth's surface. At that rate of energy loss, the Earth would be in energy balance—and it would have a stable temperature.

We can calculate what that temperature would be because of another law of physics which establishes a mathematical relationship between three variables: the rate at which heat energy is being received by a body, the rate at which heat energy is being lost by that body, and the surface temperature which would be required for that body to be in energy balance. In our scenario where we are assuming that sunlight is the only form of heat energy received by the Earth, and where we know that the Earth is receiving and losing this energy at the same rate of 235 watts per second per square meter of surface area, this law of physics gives us a mathematical equation having only one unknown: the average surface temperature of the Earth; and we can solve this equation.

When we do this calculation, we find that the Earth in this scenario would have an average surface temperature of about *zero degrees Fahrenheit*. But we know that the

average surface temperature of the Earth is much hotter than zero degrees Fahrenheit. It is in fact about 58 degrees Fahrenheit. So what's wrong with our calculation? Simply put, our scenario neglects the Earth's atmosphere—and this brings us to the so-called natural greenhouse effect.

The Earth's atmosphere, as we know, is composed of gases. Two gases make up *almost 99%* of the volume of the atmosphere: nitrogen, which makes up about 78% of its volume, and oxygen, which makes up about 21%. These two gases are largely transparent to incoming sunlight as well as to the outgoing infrared radiation from the Earth. However, the atmosphere also contains very tiny amounts of other gases which are also transparent to sunlight, but which are substantially opaque to the Earth's infrared radiation—in fact, they block and absorb almost all of this radiation. These gases are the greenhouse gases—so-called because they are similar in function to the glass in a greenhouse in keeping heat confined.

The most important of the greenhouse gases are water vapor and carbon dioxide (a gas which, we all know, is formed by the chemical combination of carbon and oxygen). The concentrations of these gases in the atmosphere are minimal to say the least: water vapor constitutes generally slightly less than 1% of the atmospheric volume; while carbon dioxide today constitutes only about .039% (thirty-nine one thousandths of a percent)—or, in the common parlance of climate scientists, only *about 390 parts per million*. Other greenhouse gases include even smaller trace amounts of methane, nitrous oxide and ozone.

The most important fact about the greenhouse gases—at least from the perspective of climate change—is that they not only absorb infrared radiation from the

Earth, but they also re-radiate some of this radiation back to the Earth in the form of heat. This occurs because the Earth's radiation actually heats up the atmosphere. As the atmosphere warms, it radiates this heat in the form of infrared radiation, both upward and downward. In this way the atmosphere sends back to the Earth some of the heat which it receives from the Earth. As a result of receiving this additional heat energy, the surface of the Earth has to be warmer than it would otherwise be in order for the Earth to attain energy balance—and this additional warming is the phenomenon known as the natural greenhouse effect. Because of this phenomenon, the average surface temperature of the Earth today is about 58 degrees Fahrenheit, not zero degrees Fahrenheit which would be temperature if the Earth did not have its atmosphere.

Looking more closely, we can observe that only about one-third of the warming attributable to the greenhouse effect is *directly* attributable to carbon dioxide; the rest is the result of *indirect* effects, the most important of which is the so-called "water vapor feedback". This phenomenon occurs because as air warms, it holds more moisture. So as the temperature of the atmosphere warms, the amount of water vapor in the atmosphere increases. Because water vapor itself is a greenhouse gas which absorbs and re-radiates the Earth's infrared radiation, increased water vapor amplifies the greenhouse effect. This in turn causes more warming, which causes further increase in water vapor; and this process goes on in a self-reinforcing cycle. In the natural greenhouse effect, this water vapor feedback *approximately doubles the greenhouse effect* of CO2 alone.

Thus, water vapor is the dominant driver in the *natural greenhouse effect*. But scientists have come to believe that CO2 increasingly plays a much greater role in

bringing about our current global warming. This is because of the differences between the water cycle and the carbon cycle.

We are all familiar with the water cycle. Water evaporates—which means that it turns into water vapor—from the surface waters of the Earth; and as water vapor it rises into the atmosphere. When water vapor reaches the cooler upper atmosphere, it condenses—which means that it turns back into a liquid form—and is precipitated back down to Earth in the form of rain or snow. Then it flows down to the oceans and lakes through rivers and streams; and the cycle is completed.

From the perspective of global warming, the important point is that the water cycle is very fast. In fact, water molecules in the form of water vapor remain in the atmosphere *for only about a week* on the average. This is the key fact. Water vapor clearly contributes to the greenhouse effect—as I mentioned earlier, it has the effect of *doubling* the greenhouse effect of carbon dioxide—but *only during the brief period* that it is in the atmosphere.

The natural carbon cycle is quite different. For starters, it is much more complicated than the water cycle. It involves many different exchanges of carbon occurring on differing time scales through differing interactions among the Earth's atmosphere, soils, surface waters, biosphere—i.e., plants and animals; and, on the longest time scales, through carbon exchanges occurring in the Earth's most basic geological processes.

From the point of view of climate and climate change, we must focus on that part of the natural carbon cycle which involves carbon exchanges between air and water and between air and the biosphere (including the Earth's soils). It is this part of the carbon

cycle—and this pattern of exchanges—which determine our Earth's climate and drive climate change. In this cycle, the atmosphere, the surface waters and the biosphere are all carbon reservoirs from which and to which carbon in the form of carbon dioxide flows quite rapidly back and forth. In the carbon exchange between air and water, atmospheric CO2 dissolves in water on contact, thereby removing CO2 from the air. At the same time, dissolved CO2 in surface waters evaporates into the atmosphere. Quite remarkably, these two processes are nearly in balance in terms of their respective carbon dioxide flows to and from the atmosphere. In the carbon exchange between air and the biosphere, plants remove CO2 from the atmosphere in the process of photosynthesis and simultaneously release oxygen into the atmosphere. Animals, including humans, get involved here, too, through the process of respiration, removing oxygen from the atmosphere and exhaling CO2. Like the carbon exchange between air and water, this exchange between the air and the biosphere is also *almost exactly in balance*: animal respiration—along with the decay of both dead organisms and waste matter—returns to the atmosphere *nearly all* of the CO2 that is removed from the atmosphere by plants in photosynthesis.

Thus, in the flows of carbon dioxide between the atmosphere, the surface waters of the Earth and the biosphere, *there is virtually no net increase or decrease of carbon dioxide in the atmosphere*. This fact is one of the keys, in my judgment, to understanding the stability of the Earth's climate over the past 10,000 years—and to understanding global warming.

I should note that cycling of the carbon in this part of the natural carbon cycle occurs relatively quickly: the average carbon molecule stays in the atmosphere for *only*

about five years. But this fact is misleading. *Roughly one-half* of the carbon which is added to the atmosphere stays—not in the atmosphere per se—but in the rapid carbon cycle for a very long time. The exact length of time is uncertain, but scientific estimates range from a few hundred years to many thousands of years as the typical residence time for carbon in the rapid carbon cycle. That is, even though any particular CO2 molecules remain in the atmosphere only about five years on average, one-half of these molecules are rapidly cycled into and out of the atmosphere for hundreds if not thousands of years. Thus, over time there is a cumulative effect of new carbon added to the rapid carbon cycle. In Professor Wolfson's words:

> That is the big, huge key idea here that you have to understand to realize why *any...[added]* carbon affects the carbon cycle, *and* the atmospheric carbon concentration, *and therefore* the concentration of greenhouse gases, *and therefore* the strength of the greenhouse effect for a long time. (Italics added)

Finally, I might also mention here another part of the carbon cycle which is important to our understanding of the greenhouse effect. Over millions of years a very tiny fraction of the carbon dioxide that has been removed from the atmosphere by plants in photosynthesis has ended up as fossil fuels: coal, oil and natural gas. This occurs when plants (or the animals that have ingested them) die and get buried underground before they decay. This buried organic material is rich in hydrocarbons. Over time these buried carbon compounds undergo certain chemical processes which convert them into fossil fuels. For as long as the fossil fuels remain buried, the carbon stored in them has no effect on climate. However, when we extract the fossil fuels and then burn them to create energy, we thereby release the burnt carbon into the atmosphere—and into the rapid carbon cycle—when it combines with oxygen to form carbon dioxide. In this manner we

have over the last 200 years or so gradually added a significant amount of *new carbon* to the carbon flows circulating in the rapid carbon cycle; and this has altered the historic carbon equilibrium in that cycle. It is this new carbon which we have added to the carbon cycle which most climate scientists believe is bringing about the global warming we are now experiencing.

III.

Admittedly, the greenhouse effect is just a theory. But, as Professor Wolfson points out:

> "In science, *theory* doesn't mean hypothesis or speculation. It means a coherent body of scientific understanding, with a conceptual framework supported by diverse evidence."

So what is the "diverse evidence" that supports the theory of the greenhouse effect ?

Well, for starters, the fact that the average temperature of the Earth is 58 degrees Fahrenheit rather than zero degrees seems to me to be strong and persuasive evidence of the greenhouse effect.

There is also evidence from the laboratory. Obviously, science cannot do laboratory experiments dealing with the Earth's climate. But there are some experiments we can perform which support the theory of the greenhouse effect. We can put CO2 or water vapor in a chamber. We can then beam infrared radiation into the chamber. We then can measure how much of this radiation passes through—or does not pass through—the CO2 or water vapor. In this way we can verify that both CO2 and water vapor are substantially opaque to infrared radiation.

There is also abundant *indirect* evidence of the greenhouse effect. For example, we have unquestioned evidence that there is a remarkable correlation between the Earth's

temperature and the CO2 content in the atmosphere over the past 650,000 years or so. From ice cores drilled into the Antarctic and Greenland ice sheets—some to a depth of almost 10,000 feet—scientists have been to reconstruct the Earth's average global temperature and to measure the CO2 in the Earth's atmosphere in surprising detail over this long period. The records thus obtained show a cyclic and repeated climate pattern of brief (10,000 to 20,000-year) warm spells called interglacials, separated by longer cold periods called ice ages. For the past half million years or so, this cycle has repeated on roughly 100,000-year intervals. As you may know, we are currently in an interglacial warm period which started some 12,000 years ago. Further, we have learned that there was a surprising consistency in the Earth's average temperature during each of the ice ages and also during each of the interglacials; and that the temperature differential between the ice ages—when all of Canada and the northern half of the United States was covered with a mile or two of ice— and the interglacials was probably not more than 10 degrees Fahrenheit. Similarly, the CO2 concentrations in the Earth's atmosphere during the ice ages and the interglacials in the distant past were also surprisingly consistent: they ranged from a low of slightly less than 200 ppm during each of the ice ages to a high of about 300 ppm during each of the interglacials prior to our present interglacial. But my main point here is that during this long period the Earth's temperature and atmospheric CO2 content go up and down every 100,000 years or so in *almost exactly parallel paths*. The warmer the average global temperature, the greater the concentration of CO2 in the atmosphere; the colder the temperature, the lesser the concentration of CO2. Thus, there is definite correlation between the Earth's temperature and the CO2 concentration in the Earth's atmosphere.

Curiously, despite this close correlation, there is *not* a clear scientific consensus that there is a *cause and effect relationship* between CO2 and temperature in the distant past. In fact, it appears that in the distant past warmer temperatures were *followed* by increases in the CO2 concentration in the atmosphere—with a lag time of about 800 years. Scientists believe that this lag time is the length of time for the CO2 in the deep oceans to rise to the surface as the oceans warm where it is released into the atmosphere through evaporation. Skeptics about global warming have seized upon this evidence to discredit the claim that increased CO2 concentration in the atmosphere drives our current global warming.

Perhaps the most interesting indirect evidence supporting the greenhouse effect is found in a comparison of the average surface temperatures and atmospheric CO2 concentrations of our sister planets, Mars and Venus. Doing the mathematical calculation to establish what the average surface temperature for these planets would have to be for these planets to be in energy balance—disregarding the effect of their respective atmospheres— yields the following temperatures: for Mars, *minus* 58 degrees Fahrenheit, and for Venus, 131 degrees Fahrenheit.

Now let's look at the actual measured average surface temperatures of these planets. For Mars, it's *minus* 81 degrees Fahrenheit, which is not substantially different from what its temperature would be if it had no atmosphere of *minus* 58 degrees Fahrenheit. For Venus, on the contrary, the average measured surface temperature is 932 degrees Fahrenheit, which is obviously *far above* its hypothetical temperature absent an atmosphere of 131 degrees Fahrenheit.

How is this inconsistency between Mars and Venus explained ? Most climate scientists believe that this inconsistency is due to the role that the atmospheres of the two planets play in determining their actual temperatures. Mars' atmosphere has only a negligible amount of greenhouse gases. So the atmosphere of Mars has *almost no greenhouse effect* in determining the temperature of Mars. Venus, on the other hand, has an atmosphere which is 96% CO2. This fact is seen to be the cause of Venus' actual average surface temperature of 932 degrees Fahrenheit. Venus' actual surface temperature is all the more remarkable because very little sunlight reaches the surface of Venus: it's atmosphere is so dense that it reflects back into space nearly all the sunlight which it receives. This is seen as further evidence that the very high temperature of Venus is determined almost solely by the greenhouse effect of its atmosphere.

This, then, is the evidence in support of the theory of the greenhouse effect. Because of this evidence, Richard Muller speaks for the IPCC and most climate scientists in saying:

> The greenhouse effect is one of the fundamental facts of atmospheric science. It is real; that fact is beyond dispute. Without it the entire surface of the ocean would be frozen solid. Life—at least the kind that depends on liquid water and warmth—could not survive. We owe our existence to the greenhouse effect.

So why are we worried about the greenhouse effect ?

IV.

That question brings us to the *enhanced* greenhouse effect.

Like the natural greenhouse effect, the enhanced greenhouse effect is—in theory—uncontroversial. If greenhouse gas levels in the atmosphere increase, all other things being equal, the Earth's temperature will rise.

Why will this happen ? To help us understand the answer, Richard Muller asks us to think of the Earth's atmosphere as a blanket with holes in it. This seems an apt metaphor. For, in fact, not *all* of the infrared radiation which is emitted by the Earth is blocked and absorbed by the greenhouse gases. Some of it passes through the atmosphere to outer space because there is not enough water vapor, CO2 and other greenhouse gases to absorb it all. When we add CO2 to the atmosphere from fossil fuels, we are plugging the holes in our leaky atmospheric blanket. This is the phenomenon we call the enhanced greenhouse effect. In Professor Muller's words:

> We are making the atmosphere into a better blanket—by pumping in carbon dioxide and other greenhouse gases. *That's the reason we are worried about the greenhouse effect...If we make the greenhouse effect stronger, the surface temperature of the Earth will rise.*

The IPCC concurs. In its 2007 Report, the IPCC states that the *main reason* for concern about global warming is the indisputable increase in the concentration of greenhouse gases, especially CO2, in the atmosphere.

How precise can we be about this increased CO2 concentration? For starters, we know that for over 10,000 years—from the end of the last ice age through the late 1800's—the concentration of CO2 in the atmosphere remained constant at about 280 ppm. Beginning just before 1900, the atmospheric CO2 level began to rise rapidly. By 1930, the level had reached 330 ppm. In just the decade from 1995 to 2005, CO2 levels rose as much—twenty ppm—as they had risen during the entire 10,000 years prior to the late 1800's. Today, the level of CO2 concentration in the atmosphere is almost 390 ppm, *an increase of some 39%* since the late 1800's—and most of this increase has come since 1970. The current level, most climate scientists believe, is higher than at any time in the

last twenty million years—*perhaps as much as 30% higher*. In fact many believe that the last time the atmospheric CO2 concentration was 390 ppm was during the period known as the Eocene, some 50 million years ago. In the Eocene, may I remind you, the Earth's temperature was very warm; palm trees grew in the Arctic; crocodiles roamed Colorado; and sea levels were nearly 300 feet higher than they are today.

I should also point out that the *rate* of increase in the atmospheric CO2 concentration in the past century is unprecedented. To put this rate of increase in perspective, the increase in the CO2 concentrations during the each of the interglacial warmings after the four most recent ice ages was in each instance only about 90 ppm—and these increases occurred in each instance over a period of more than *ten thousand years*. Our current increase of 110 ppm in the CO2 concentration in our atmosphere has occurred in less than 150 years.

At this point I should note that our increased CO2 concentration reflects not only increased fossil fuel combustion, but also the effect of deforestation. Deforestation is responsible for the equivalent of about 30% of the current annual carbon emissions from fossil fuels. Fossil fuels and deforestation together account for about 77% of the annual CO2-equivalent emissions into the atmosphere resulting from human activities.

I should also note that the atmospheric concentrations of the other primary greenhouse gases have also increased markedly—mostly as a result of human activities—since 1750; and they now far exceed pre-industrial values. Methane is a greenhouse gas which has both natural and anthropogenic sources including mining, agriculture, natural gas distribution, sewage treatment plants and landfills. On a per molecule basis, methane is about twenty-six times more effective than CO2 in blocking and absorbing infrared

radiation. Since 1750, *the concentration of methane in the atmosphere has increased by some 150%.* As a result of this increase, methane now contributes about 15% as much as CO2 to global warming. However, there is a lot less methane in the atmosphere—its level of concentration is expressed in parts per billion—and it remains in the atmosphere for only about twelve years before chemical reactions remove it permanently. Similarly, the concentration in the atmosphere of nitrous oxide (N2O)—a gas which is also emitted by both natural processes and by human activities—has also significantly increased since 1750. Even though it's concentration in the atmosphere is also expressed in parts per billion, it now contributes about 10 % as much as CO2 to global warming

So. The evidence seems clear that the concentrations of CO2 and the other greenhouse gases are at levels which the Earth has not experienced for hundreds of thousands if not millions of years; and they have *increased at unprecedented rate* during the last 150 years.

V.

What is driving this change ? The consensus of climate scientists is that this change can almost certainly be attributed to human activities. In the words (which I will quote again) from the IPCC 2007 Assessment Report:

> 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.

"Very likely", we know, means that the IPCC has concluded that there is a level of certainty *greater than 90%* that human activities are responsible for *most* of the global warming which we are experiencing.

What is the evidence for this conclusion ?

First, we can quantify the amount of carbon we have been emitting to the atmosphere during the past 150 years or so from the burning of fossil fuels. We can do this because fossil fuels are commercial commodities for which increasingly reliable records have been kept relating to extraction, processing and consumption. During this same period we can also quantify the carbon equivalents which we have been adding to the atmosphere from deforestation. Because we know that about one-half of the carbon which goes into the atmosphere gets into the rapidly revolving atmosphere-biosphere-ocean carbon cycle and, thus, remains in the atmosphere in effect for hundreds if not thousands of years, we can correlate the increase in the concentration of CO2 in the atmosphere with the quantities of carbon we humans have been putting into the atmosphere; and we find a strong correlation. This is solid evidence that the increased CO2 concentration in the atmosphere in the last 150 years is anthropogenic in origin.

Even more persuasive, I find, is the evidence from a chemical analysis of the CO2 in the atmosphere over time. Atmospheric CO2 is a mix of the carbon isotopes carbon-12, carbon-13 and carbon-14. We find that there has been a fixed ratio of these three carbon isotopes in atmospheric CO2 for at least 12,000 years. However, from about 1750—the beginning of the industrial era—and coming down to the present, this ratio has exhibited a gradual, but increasingly dramatic, change. Today, the CO2 in the atmosphere is substantially depleted in carbon-14 and carbon -13.

Why does today's atmosphere contain so little carbon-14 ? Climate scientists have a simple answer: since carbon-14 only lasts for about 5,000 years before its decays, and since the carbon in fossil fuels has been buried in the ground for many millions of

years, any carbon-14 which was initially in that carbon has long since decayed. When fossil fuels with this carbon -14 deficiency are burned, the resulting CO2 which is added to the atmosphere is likewise depleted in carbon-14.

Climate scientists have an equally simple answer as to why today's atmosphere is also deficient in carbon -13. Science has established that plants, in taking CO2 from the atmosphere during photosynthesis, have a genetic preference for carbon-12 (the lightest of the three carbon isotopes in the atmosphere). Thus, when the plants that became fossil fuels died and decayed, they were deficient in carbon-13. It follows that this same deficiency is found in fossil fuels and in the CO2 which comes from the burning of fossil fuels. So, when we look at the ratio of the three carbon isotopes in the CO2 in the atmosphere, we find that over the last 250 years or so the carbon content of the CO2 has become more and more depleted in carbon-13 and carbon-14. Most climate scientists believe that this change is best explained as the result of the addition to the atmosphere during this period of CO2 from the burning of fossil fuels.

Perhaps the most persuasive evidence that humans have very likely caused the current global warming is the *virtual absence of any natural phenomena* during the past 250 years or so which could account for the warming. Climate scientists agree that there are only three natural phenomena which are known to have an effect on the Earth's energy balance—and, thus, on the Earth's climate: volcanic eruptions, solar irradiance variations (including changes in the Earth's orbit and axis) and changes in greenhouse gas concentrations. When climate scientists examine the Earth's climate changes occurring prior to the 20th century, there is a strong correlation between temperature changes and the occurrence of volcanic eruptions or solar radiation changes. Beginning

about 1750, however, and coming down to the present, *these natural phenomena have been largely absent*. Indeed, the IPCC's 2007 Assessment Report confirms that the only natural phenomenon occurring between 1750 and 2005 which could have altered the Earth's energy balance was a slight increase in solar irradiance; and that this change accounted for an increase in the rate of heat energy reaching the Earth of about 0.12 (twelve one-hundredths) watts per square meter. By comparison, the increase during this period in the rate of heat energy reaching the Earth as a result of the increase in the atmospheric concentration of greenhouse gases is more than 2.5 watts per square meter. It is this comparison which causes the IPCC to conclude that "the human influence on climate very likely (i.e., at least a 90% certainty) dominates over all other causes of the present global warming."

In support of this conclusion the IPCC cites the numerous experiments that have been conducted using climate models to determine the causes of the 20th-century climate change. These climate models are computer runs created by teams of supercomputers. These experiments indicate that the climate models cannot reproduce the rapid warming observed in the latter half of the 20th century if they take into account *only the natural factors* affecting climate which occurred during the 20th century—that is, variations in solar irradiance and volcanic activity. However, these models are remarkably accurate in simulating the 20th-century change in temperature when they are programmed to include, in addition to the natural climate-affecting factors, the increase in greenhouse gases caused by human activities which occurred during the 20th century.

Why isn't the IPCC 100% certain of its conclusion that the cause of the 20th-century warming is anthropogenic ? The answer is: we simply don't understand how

clouds behave when the temperature rises. It is this uncertainty that led the IPCC to conclude that there may be a 10% chance that humans are not responsible for the present global warming. It is possible that increased water vapor from warmer temperatures *might* increase cloud cover, which would increase the reflection of sunlight and thereby reduce the heat energy from the sun which reaches the Earth. In this scenario, increased cloud cover would have the effect of canceling the greenhouse effect; and the Earth's present warming would thus be attributable to an unknown natural effect, perhaps the continuance of the warming of our current interglacial period. The IPCC acknowledges that this scenario is possible, but very unlikely. For the American Geophysical Union, one of the nation's largest and most respected scientific organizations, this scenario is even less credible. In 2003 that organization declared, "Natural influences *cannot* explain the rapid increase in global near-surface temperatures."

VI.

This, then, is the solid science in support of the thinking that global warming is anthropogenic. For most of the scientific world, this evidence is persuasive. Jared Diamond spoke for those who have been persuaded in a recent Op-Ed piece in the New York Times where he opined:

> Today, virtually every climatologist agrees that average global temperatures, warming rates and atmospheric carbon dioxide levels are higher than at any time in the earth's recent past, and that the main cause is greenhouse gas emissions by humans.

So where is the science of global warming not solid ?

There are several major uncertainties. I have already mentioned the uncertainty about the role of clouds in global warming. Perhaps the greatest uncertainty is what's called the sensitivity of the climate system—including global surface temperature—to increased greenhouse gas emissions. We do know that for every added increment of carbon to the atmosphere, the Earth will experience a rise in surface temperature—but we can't quantify that rise with precision. But credible projections are not lacking. The IPCC tells us that it is *likely*—which means a level of certainty of at least 66%--that if we continue to increase the burning of fossil fuels at the same rate as during the last few decades, greenhouse gas emissions will increase by 90% between the year 2000 and the year 2030; and at an even faster rate during the balance of the 21st century. In this scenario the IPCC projects that the global average temperature will *likely*—again, a level of certainty of at least 66%--increase in this century by at least 4.3 degrees Fahrenheit and by as much as 11.5 degrees, with a *best estimate* of 7.2 degrees. Other projections are more drastic. MIT's Center for Global Change Science warns that, without rapid and massive action to curtail the growth of greenhouse gas emissions, there is a *median* probability of surface warming in this century of 9.4 degrees Fahrenheit, with a 90% probability range of 6.3 to 13.3 degrees.

Even if we stabilize greenhouse gas emissions at a level of 30% over current levels, CO2 levels will almost certainly reach 550 ppm—double the pre-industrial level—within fifty years or so. At that level, the IPCC's *best estimate* is that that the Earth's average surface temperature will be warmer than it is now by 5.4 degrees Fahrenheit—with a 75% probability that our temperature would be even warmer than that.

These, of course, are simply projections made by climate models; and they are not by any means universally accepted. But virtually everyone agrees that *if* the global surface temperature goes up by 8 to 10 degrees Fahrenheit, the habitability of the Earth will be drastically altered—with large-scale economic disruption and human displacement around the world. To put an 8 to10 degree increase in context, the current average global temperature is only about 10 degrees Fahrenheit warmer than during the most recent ice ages—when most of North America and Northern Europe were covered with thousands of feet of ice.

Yet it seems that the world is simply not persuaded by these projections. Last July, the Group of 8 industrial nations pledged to try to limit global warming to 2 degrees Fahrenheit beyond the planet's current temperature; but they failed to embrace the emissions reductions that the IPCC says would be needed to keep that promise. Similarly, the Copenhagen Accord, the only significant agreement reached at the international meeting last December, adopted the same temperature goal and set a target date of 2050 for temperature stabilization, but there was no agreement on how to achieve the deep cuts in CO2 emissions which would be required to reach this goal.

So. Clearly, there uncertainties about climate change. Not concerning the role of human actions in bringing about global warming, as I hope this paper has shown, but about how best to deal with the consequences of our actions—and about how quickly we have to act to avoid disaster. Richard Muller describes our uncertainty—and our worry—with these words:

> The real reason we are worried… is that simple physics calculations of the greenhouse effect show that *we are entering an unprecedented regime of climate uncertainty* in which human emissions *could* soon cause disruptive changes. (Italics added)

Elizabeth Kolbert echoes this concern with these words:

> A possible consequence of even a four- or five- degree temperature rise—on the low end of the projections for doubled CO2—is that *the world will enter a completely new climate regime*, one with which modern humans have no prior experience. (Italics added)

Facing these uncharted waters, I find myself tending to agree with the perspective of John Holdren, a Harvard physicist who is the chief science adviser to President Obama, that *not* acting on climate change would be like being "in a car with bad brakes driving toward a cliff in the fog."

Thank you.