The Scientific Controversy Over Global Warming

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Global warming is a contemporary issue of both general and scientific interest. Concern over global warming has resulted in urgent requests for massive funding and strong legislation to slow the emission of greenhouse gases into the atmosphere. There is consternation around the globe that it may already be too late to ward off catastrophic changes in climate, sea levels, and life as it now exists. Yet, many scientists do not agree that global warming is taking place. Some argue that there is insufficient data to make such a claim; others that the earth is actually cooling. Statistics has a major role to play in this debate and, more importantly, in distinguishing impassioned rhetoric from scientific knowledge.

Global Warming Controversy

The following headlines have been taken from recent news reports in local and national publications:

"Global Warming Exists, Needs Action Now, U.N. Study Says"
"The Heat is On: Chemical Wastes Spewed into the Air Threaten the Earth's Climate"
"1990 Ranks Among the Warmest"
"What's Wrong With Our Weather"
"Global Warming: Can We Avoid the Environmental Crisis"
"5 'Greenhouse Gases' On the Rise, Experts Say"

* This is an invited paper for the American Statistical Association's student magazine **STATS**. It is an introduction to the global warming controversy intended for upper-level undergraduate and graduate students.

before Congress in May 1989 and summarized his comments in an interview in *Science* (2 June 1989, p. 1041): "I said ... I believed the earth was getting warmer and I could say that with 99% confidence." He also stated "... that with a high degree of confidence we could associate the warming and the greenhouse effect." Dr. Hansen's studies and several others have identified an approximate 0.5^{o}C (1°F) rise in average global temperature over the last 100 years, as shown in Figure 1. Since the difference between today's average temperature and that occurring at the depths of the last major ice age was only about 5°C (9°F) and since the age of the dinosaurs, 100-150 million years ago, was only 10-15°C (18-27°F) warmer than today, there appears to be evidence that the earth is on the verge of monumental climatic changes that will seriously affect life on this planet.

The relationship between greenhouse gasses and temperature change is supported by the following two facts. First, physicists have theoretical explanations and empirical evidence for the heating of the planet by certain greenhouse gasses such as carbon dioxide (CO_2). Second, measurements of CO_2 have been rising substantively in recent years. Figure 2 shows measurements on CO_2 taken annually since 1959 at a scientific measuring station in Mauna Loa, Hawaii. The combined evidence of theoretical properties of greenhouse gasses and empirical data similar to Figures 1 and 2 leads Dr. Hansen and other scientists to conclude that a crisis looms.

Are we on the precipice of climatic destruction?

Not all news reports warn of impending catastrophe. Other recent headlines include the following:

> "Clouds of Doubt Hang Over Global-Warming Models"
> "Uncertainties Magnify Greenhouse Concerns"
> "The Greenhouse Effect: Hardly Apocalypse"
> "Climate Science Report Leads to Environmental Confusion"
> "Hansen vs. the World on the Greenhouse Effect"

During the same week in May 1989 that Dr. Hansen was testifying before Congress, a week-long conference titled "Workshop on Greenhouse-Gas-Induced Climate Change," which Dr. Hansen attended for one day, was held in Amherst Massachusetts. It is ironic that the official press release from this conference of scientists includes the following statement (ibid, p. 1043):

> "It is tempting to attribute [0.5^{o}C warming] to the increase in greenhouse gases. Because of the natural variation of temperature, however, such an attribution cannot now be made with any degree of confidence."

This statement is in stark contrast to Dr. Hansen's subjective claim of 99% confidence that global warming is occurring and that the warming is due to the greenhouse gases.

Statistical science is central to this debate. Many individuals who are untrained in the science of statistics read descriptions of this controversy thinking "Here's another example of how you can prove anything with statistics." Perhaps some of you are reminded of the quote often attributed to Mark Twain: "Lies, Damn Lies, and Statistics." A reply to those who have such a view of statistics is that if two people draw opposite conclusions from the same data using the same assumptions, at least one of them is wrong -- often it's both of them.

Why are we in the realm of statistical science? A short definition often used to describe the field of statistics is that

"Statistics is the Science of Collecting, Analyzing, and Interpreting Data."

Many statisticians like to describe the field of statistics as the "language of science". All of you have used statistics, perhaps without being aware of its scientific nature, on every occasion in which you have drawn conclusions based on data. There are correct and incorrect ways of collecting data. There are correct and incorrect ways of analyzing data. There are correct and incorrect ways of interpreting data.

In this article I do not wish to enter into premature conclusions about the adequacy of the data and the correctness of the analysis and interpretation by either proponents or opponents of global warming. I do, however, wish to introduce the issues that several of my colleagues and I are addressing in our current research.

Global Warming and the Greenhouse Effect

The term "global warming," as it is used today, refers to increases in the temperature of the earth due to intervention by humankind. Climatologists refer to this as "climate forcing."

The natural warming of the earth comes primarily from solar radiation, i.e., radiation from the sun. Solar radiation reaching the earth is mostly short wavelength radiation, radiation at the

violet end of the color spectrum. When this radiation reaches the earth, some of it is absorbed, resulting in some warming of the earth. Some of the incoming radiation is reflected back toward space as long wavelength radiation, radiation at the red end of the color spectrum. If all the reflected long wavelength radiation were emitted back into space, the earth would be a frozen planet like Mars. The greenhouse effect prevents much of the long wavelength radiation from escaping the earth's atmosphere, contributing further to the warming of the earth.

The greenhouse effect is not something to be feared; in fact, it is necessary for life on earth. In the troposphere, which is roughly the 10 miles of atmosphere closest to the earth, there are many gases. Some of these gases, the so-called "greenhouse gases," act like the transparent roof on a greenhouse. A greenhouse permits short wavelength solar radiation to enter but it traps reflected long wavelength radiation. So too, greenhouse gases in the troposphere permit much of the short wavelength solar radiation to reach the earth but they trap much of the long wavelength reflected radiation. The trapping of this long wavelength radiation warms the troposphere and the earth.

The primary greenhouse gases are water vapor, carbon dioxide, methane, and chlorofluorocarbons. Water vapor occurs naturally and is not the focus of the current concern over climate forcing. The most important of the greenhouse gases from a climate forcing perspective is carbon dioxide. Carbon dioxide, methane, and chlorofluorcarbons do occur naturally, but their amounts in the atmosphere have been greatly increased due to

human intervention. Carbon dioxide, for example, is being introduced into the atmosphere by the burning of fossil fuels and as a result of the clearing of forests. Some scientists contend that carbon dioxide accounts for roughly half of the global warming that is due to human intervention.

Data Collection

Historical data on surface global temperature dates from the middle 1870's. In this context I am not referring to surrogate archaeological or geological data, rather to actual temperature records that are considered reliable and extensive enough to permit calculations of global temperatures. Temperatures have been recorded both at sea and on land.

For navigational reasons, temperatures have been recorded in ship logs throughout the last 200 years. The procedures for doing so are not uniform. For example, up until the middle part of this century "sea surface temperature" was obtained by collecting water in canvas buckets and recording the temperature of the water in the buckets. Tremendous difficulties arise because of this method of measuring temperature. First, the canvas buckets were not insulated, so their temperature could change in a short period of time depending on whether the air is warmer or cooler than the sea water, on whether the buckets were exposed to heating or cooling because of where on the ship the temperature was measured, and simply on how long after the water was collected that the temperature was taken. In addition, the ship's

locations varied, as did the time of day at which the measurements were taken.

Scientifically, these are problems of serious consequence. Recall that the proponents of global warming assert a 0.5°C change in temperature over the last century. Far greater variations than this can occur with the bucket method of measuring sea surface temperature. Today, scientific advances enable great improvements in the measurement of temperature. Sea surface temperatures are now taken on the inlet sea water ships use to cool their engines. While this is regarded as a much better way to determine sea surface temperature, it also typically results in warmer temperature readings than the bucket method. Estimates range from 0.3°C to 0.7°C warmer. Changes in the size and speed of ships, notably the transition from sail to steam, also affect the temperature measurements. Part of the apparent warming could be due to these technological improvements.

Dr. Hansen's analyses of mean global temperature utilizes only land surface data. He states that doing so removes much of the uncertainty and scientific concerns related to the recording of sea surface temperature. Even so, the land-based stations do not account for approximately two-thirds of the surface of the earth. Even though there have been combined analyses of land and sea surface temperatures, and the results have been regarded as consistent with the land-based station analyses, there are serious concerns about the quality of land-based data.

Two of the major criticisms of the use of temperatures from land-based stations are the number and locations of the stations. There have been substantial changes in the number and locations of temperature stations over the last 150 years. For example, in 1850 there were fewer than 100 land-based temperature stations throughout the world. In 1960, there were approximately 1,800 land-based temperature stations. Today there are about 600. In 1850, land-based temperature stations were overwhelmingly in the northern hemisphere, primarily in Europe. The first permanent temperature station in the Antarctic was not set up until about 1945.

The location of temperature stations has an important impact on global temperature trends over the last 100 years. High latitudes receive more solar radiation than lower ones due to the tilt of the earth on its axis. This should cause the northern hemisphere to be warmer than the southern hemisphere. In addition, the northern hemisphere has less ocean area than the southern hemisphere, which again should result in warmer overall temperatures. Thus, the imbalance in the location of temperature stations from 1850 to today could induce a temperature trend without any warming of the globe.

Another problem is that a larger proportion of temperature stations are currently located in large cities or near major metropolitan areas (e.g., at airports) than there were in 1850. Urban areas are known to be warmer than rural areas, suggesting the possibility that a warming trend might exist due to the different locations of stations in 1850 and today.

Obviously there is great scientific concern over the quality of the data used in drawing conclusions about temperature trends over the last 100 years. In the face of these concerns, one must question the degree of confidence that Dr. Hansen places in the existence of global warming. The lesson to all scientists from these concerns is that the credibility of any scientific conclusion rests in large part on the quality of the data.

Estimation of Mean Global Temperature

A second major issue concerning the establishment of temperature trends over the last century concerns the use of the term "mean global temperature." What specifically is "mean global temperature?" In my review of the literature on this subject, I find no definition of mean global temperature. This is important because the statistics used to determine temperature trends should be estimating the quantity referred to as "mean global temperature." The adequacy of these statistics can only be gauged relative to their ability to estimate this quantity.

An analogy will help clarify this issue. In most studies of income, median income rather than mean income is the quantity of interest. This is because income data tends to be skewed. Very few employees in a company earn salaries in the $100,000 or $1,000,000 range. Yet, if these few employees, usually the President and Vice Presidents, are included in a summary of salaries for the company, the average salary will appear disproportionately high. In an extreme situation, the President and the Vice Presidents of a company may be the only ones who

earn salaries that are larger than the average. In such situations, the average salary is not representative of the company.

The median salary is the salary that divides the company salaries in half. Half of the employees make more than the median, half make less. For salary data, the median is a better statistic to use to estimate a representative salary than is the mean.

The situation for global temperature data is similar but more complex. To date, the de facto definitions of mean global temperature must be inferred from the statistics used to calculate the temperature averages. The methodology causes concern for two reasons. First, if simple averages are used to estimate mean global temperature, no account is taken of the fact that some temperature stations are located close to one another and others are separated by great distances. In statistical terms, the closer stations should give highly correlated measurements while the stations located great distances from one another should give temperature readings that are relatively uncorrelated. At best, very crude use of station locations is currently used in the averaging process.

A second issue in the estimation methodology is that an adequate account of the uncertainty in the temperature measurements rarely accompanies analysis of the temperature trends. In any scientific measurement there is uncertainty. Some measurement processes result in measurements for which the uncertainty is so small it can be ignored and the data can be

treated as exact or error-free. In most scientific measurements, the uncertainty cannot be ignored and must be accommodated in the interpretation of the data. Temperature measurements at different stations throughout the world are subject to a variety of measurement errors that are not accounted for in the analysis of the temperature data.

The scientific lesson from this discussion of methodology is that even if the data are of very high quality, inferences drawn from the data can be compromised by the use of incorrect data analysis methods. In particular, one must be careful in the arbitrary use of any statistic, including a simple average.

Milankovitch Cycles

Throughout this discussion of global warming, the inference that the earth is warming and that this global warming is due to an enhanced greenhouse effect caused by human intervention has been presented as though the conclusion is inevitable, provided the data are of high quality and the methodology used is correct. A major concern by some scientists about conclusions drawn from the temperature records of the last 100 years is that these data may be almost irrelevant to the issue of global warming. An opposing theory is that the earth is not heading toward a period of rapidly rising temperatures, but that it is on an inexorable path toward the next ice age.

Milutin Milankovitch was a Serbian mathematician who in the 1920's and 1930's published a series of works describing how the

earth's orbital changes affect the amount of solar radiation reaching the earth. He postulated that it is these orbital changes, which occur in regular cycles, that determine the occurrence and severity of ice ages.

The "Milankovitch Cycles" describe three components to the earth's orbit. One cycle is the earth's elliptical path around the sun, first described by Kepler. Milankovitch determined that the elliptical path around the sun narrows and widens until it is almost circular in regular intervals of about 100,000 years. Milankovitch's second cycle is that the earth's tilt from the vertical varies from about 22 to 24.5 degrees approximately every 41,000 years. The third cycle is the precession of the equinoxes. Milankovitch determined that the earth, while currently closest to the sun in December, will in 11,000 years be closest to the sun in June. Approximately 22,000 years from now the earth will again be closest to the sun in December.

According to the Milankovitch theory, the coldest ice ages occur when the earth's orbit is most elliptical, when it is most tilted on its axis, and when the northern hemisphere is farthest away from the sun in summer. Adherents to this theory contend that the earth is just entering a phase when these three features of the Milankovitch cycles will line up; hence, that the earth in entering its next ice age. If so, the natural cooling of the earth will compensate for any increase in global temperatures caused by an enhanced greenhouse effect.

Conclusion

Statistics is the science of collecting, analyzing, and interpreting data. This article focuses on three statistical aspects of the global warming controversy that are germane to any scientific investigation: the quality of the data, the correctness of the analytic methodology, and the possibility of alternative inferences. Much additional scientific work, including high quality statistical research, is needed to resolve the global warming controversy. Criticism of existing data and analyses serves an important purpose: highlighting the exact state of scientific knowledge and deficiencies in methodology and interpretation. Mere criticism does little, however, to improve the state of knowledge of global warming and its relation to climate forcing. Better statistical approaches to the collection and analysis of global warming data lend credibility not only to statistics as a science but also to the need for competent statistical input.

Figure 1. Global Average Temperature Change: Hansen and Lebedeff (Degrees Centigrade Difference from 1951–1980 Average Temperature)

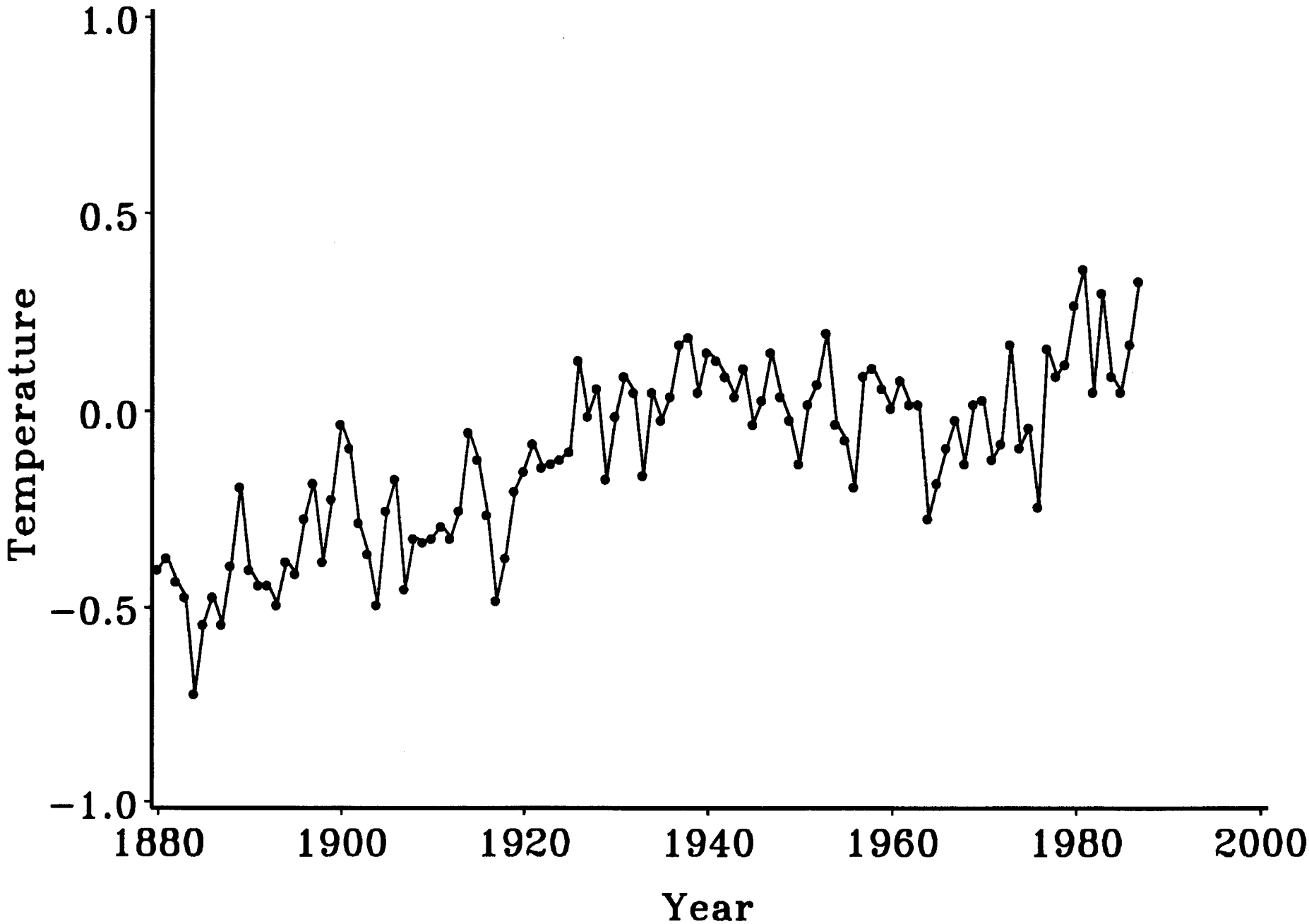

Figure 2. Mauna Loa Carbon Dioxide Concentrations