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The Increase in Global Temperature: What it Does and Does Not Tell Us

By Dr. Robert Balling, Director of the Office of Climatology at Arizona State University

Summary

The global temperature record is often used to support the claim that the Earth is warming at a rate that is "reasonably consistent" with predictions for warming due to the buildup of greenhouse gases. This paper examines how the Earth's temperature is taken, examines the reliability of those measurements, and highlights several factors that affect temperature trends and variation.

No matter how many confounding variables are brought to the table, many argue that the rise in greenhouse gases is or soon will dominate all other factors that affect the distribution of energy in the atmosphere, and will drive the global temperature further upward. If reported temperature continues to rise, some scientists will inevitably claim that the empirical evidence is highly supportive of that theory. However, it is important to recognize that association or statistical correlation is not causation.

But major problems remain with the above assessment. The warming rate in the last three decades is not significantly different from the warming rate in the early 20th century (1915-45). Temperature records are far from perfect and contain biases from urbanization, distribution of measurement stations, instrument changes, time-of-observation, assorted problems in measuring temperatures in ocean areas, and so on. These factors could introduce a total bias of 0.2-0.3°C, or about one-third of the observed warming. Even if we accept that the warming as real, there is a strong argument that approximately half of the warming—the portion that took place in the early 20th century—was a natural recovery from the Little Ice Age. There are many non-greenhouse factors at work on temperature, and it is very difficult to isolate the signal related to the buildup of human produced greenhouse gases. Finally, we need to understand why the trends in surface and lower tropospheric temperature differ to be able to explain the roles of the various climate system forcings.

Consequently, strong evidence suggests that there was a systematic under-estimation of temperature. In other words, the Earth was probably warmer in the past than our records indicate and, therefore, the change in temperature that we now observe is not as great as it appears.

This conclusion is important for at least two reasons. First, it provides further evidence that modeled estimates of the CO_2 influence on temperature are overstated, which means that the projections of future temperature increases are as well. Second, it demonstrates the high priority that should be assigned to improving the global observation system. More accurate data are essential for setting wise policy and for developing better models.

Defining the Earth's Temperature

The fact that global temperatures have risen over the past century is often presented as evidence that human emissions of greenhouse gases are changing the

Earth's climate. At first glance, it would seem easy to determine whether the Earth's temperature has been increasing over the past hundred or so years since many weather records extend for more than a century. In theory, we should be able to assemble those records, check for trends, and determine whether or not the world is warming. That exercise has indeed been carried out, and the world is now warming at a rate that is "not inconsistent" with the expectations from current model simulations, i.e., the observed rate of warming is the same order of magnitude as calculated from climate models.

The most popular and widely used temperature record has been developed by Dr. Phil Jones of the Climate Research Unit at the University of East Anglia.[1] His data set is based on the records of several thousand land-based stations and millions of weather observations taken at sea. Jones has assessed the quality of the data in an effort to identify and eliminate erroneous values. He converts monthly average data into 5° latitude by 5° longitude grid data, which are then averaged to estimate global temperature.

A plot of Jones' annual values shows considerable support for global warming predictions (Figure 1). However, when tests are run where only the concentrations of greenhouse gases are allowed to change, the predicted temperature increase is double what was actually observed. Adding estimates of cooling due to the effects of sulfate aerosols brings the computer model results more in line with observed changes in temperature, but adds considerable uncertainty about how accurately these aerosols are characterized.

Over the entire 1900–2002 period, the surface temperatures rose linearly by 0.069°C per decade; warming spurts occurred from the late 1910s to 1945 and from 1970 to the present. Since 1970, the warming rate of the Earth has accelerated to 0.17°C per decade, about three times as fast than the average rate for the past century. However, this comparison (while often made) is somewhat misleading because the actual rate of warming in 1915-1945 was 0.16°C per decade, essentially the same as for 1970 to the present.

The geographic pattern of the recent warming is broadly consistent with model

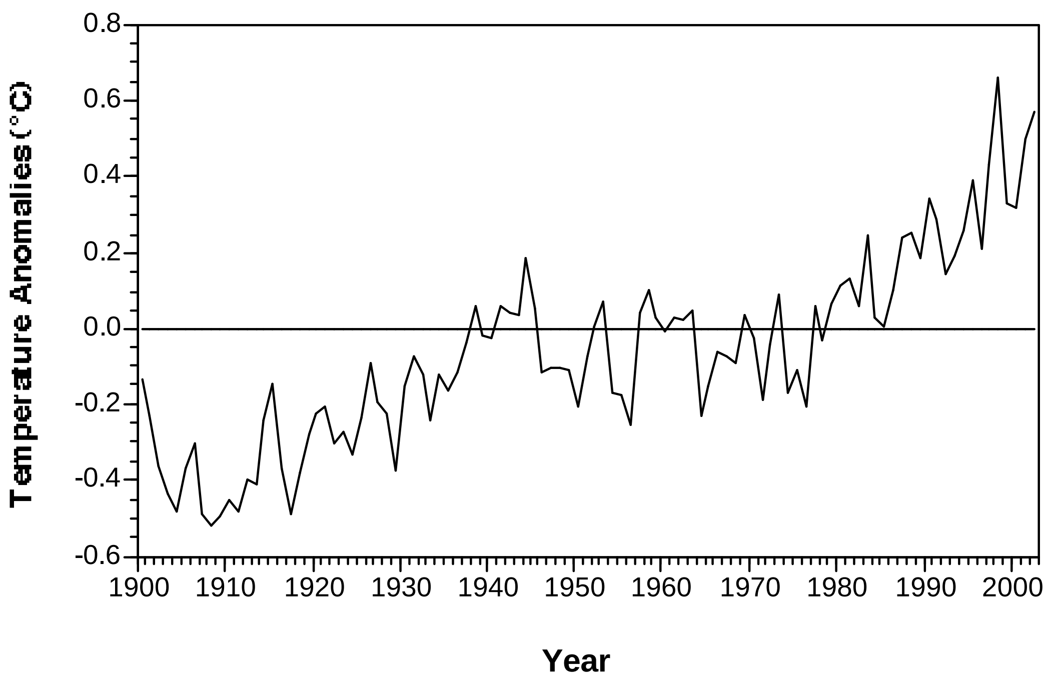

Figure. 1. Plot of annual near-surface global temperature anomalies over the period 1900-2002.

simulations as well. One consistent prediction from the models is that the cold and dry air of the high latitude northern hemispheric locations will be particularly responsive to the increase in greenhouse gases. In lower latitudes, the higher levels of atmospheric moisture produce such a strong natural greenhouse effect that additional concentrations of carbon dioxide have less of an effect compared with the drier air masses. Temperature data show that the high latitudes of the Northern Hemisphere have warmed more than any other location on the planet, even though the warming rate is far less than what has been predicted by numerical models. Is there a seasonal fit as well? Apparently so. Models consistently predicted the greatest warming in the winter season (December–February in the Northern Hemisphere and June–August in the Southern Hemisphere) and the least warming in the summer season.

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Scientists also have conducted analyses of daily maximum and minimum temperature data, and even hourly temperature data, and have identified a clear global signal of greatest warming at night and least warming during the day. This diurnal pattern in the warming rates is evident in many numerical models used to simulate the effect of increasing concentrations of greenhouse gases.

When added together, temperature measurements evidence appears to support the conclusion that the planet is responding to the buildup of greenhouse gases. While the global trend is lower than the model-generated, greenhouse-only response; both the regionality and seasonality of the warming are broadly consistent with the model simulations; and the diurnal pattern of the warming is broadly consistent with expectations given the models' output. We could stop here and declare, as so many others have, that the observations are consistent with the theory, and therefore the science is settled. But there is a lot more to this story.

How Reliable Are the Records?

Missing Data. One of the problems with the surface temperature record is that substantial parts of the globe lack the measurements needed to generate monthly temperature records for various 5° latitude by 5° longitude grid cells. Ocean areas off major shipping lanes, ice-covered areas, and many desert and mountainous areas often lack temperature records. And not surprisingly, the area of the Earth without valid data increases further back in time and also during periods of global strife. Less than 30 percent of the planet had temperature records at various times in the 20th century, and even today, fully 20 percent of Earth is not covered by the Jones database (Figure 2). While missing data poses substantial problems for generating an accurate trend over the past 100-plus years, it is noteworthy that global temperature has increased during the past three decades, a period when coverage has hovered near 80 percent. Still, the amount of bias resulting from missing data is unknown.

Urban Heat Island. Many weather stations are located in growing urban areas where the climatic effects of the urbanization process may overwhelm the effects of the buildup of greenhouse gases. Energy reaching the Earth's surface can be either reflected or absorbed. Some of the energy that is absorbed heats the Earth and air, and evaporates surface water; the rest is re-radiated. Urbanization affects these processes in several ways. The most important is the waterproofing of the urban surface. In many cities, the natural vegetation is largely removed, and the surface covered by nearly impervious materials. Precipitation quickly runs off the urban surface into

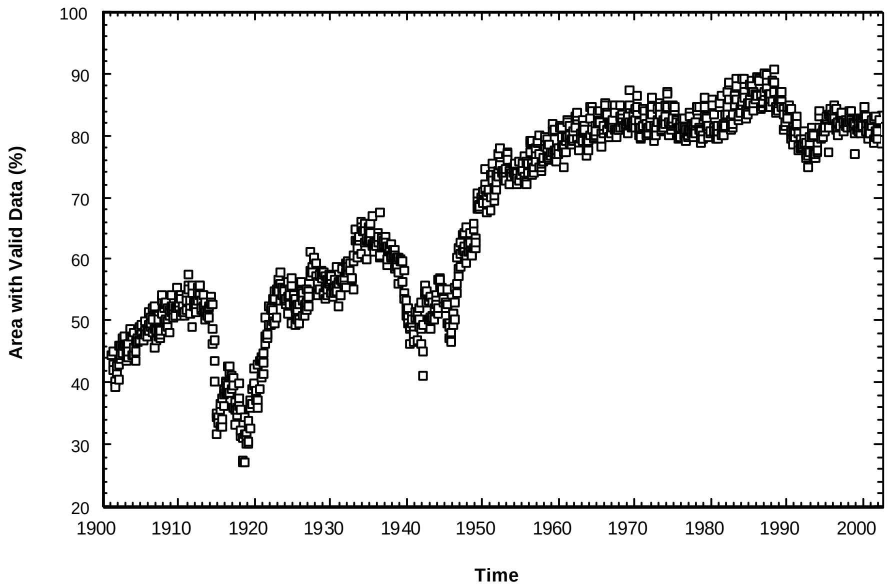

Figure 2. Plot of area of the Earth with valid near-surface air temperature data from 1900 to 2002.

underground storm sewers, minimizing surface moisture in the city. As a result, some of the climate system energy that would have been used to evaporate water is used to heat the surface and air. Other effects of urbanization include heat storage by concrete, asphalt, and other building materials; urban canyons that reduce the re-radiation of climate system energy; release of heat from a variety of anthropogenic activities within the city; and the trapping of re-radiated energy by soot and other low-level atmospheric aerosols.

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There is no doubt that urbanization leads to warming. In its latest assessment, the Intergovernmental Panel on Climate Change (IPCC) estimated that urbanization has added 0.006°C per decade to global warming, about nine percent of the global warming rate of 0.069°C per decade over the 1900 - 2002 time period.

Instrument Problems and Adjustments. Traditional mercury-in-glass thermometers are being replaced worldwide by thermistors, electronic instruments capable of continuous temperature monitoring. The change in instruments may be introducing a warming bias into the record for three reasons.

1. During the summer season, turbulent eddies of air pass by instrument shelters. In the past, the warm eddies would have passed by the glass thermometers too quickly to heat the glass and mercury. But the new, highly sensitive electronic sensors immediately recognize and record the temperature of each turbulent eddy, and as a result increase daily temperature readings.
2. The shelter itself introduces yet another warming trend; its fresh white paint, which deteriorates over time, changes the shelter's reflectivity ultimately the temperature within the shelter.
3. The use of continuous temperature monitors also removes the cooling bias that was introduced by reading temperatures early in the morning, formerly standard practice, which has been shown to contribute over 0.05°C per decade to reported temperatures in the U.S.

Because the spread of thermistors has occurred primarily in the last three decades and mainly in the industrialized and developed world, a reasonable upper limit for its effect on overall global warming is about 0.10-0.15°C.

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Finally, many weather stations have been moved from colder river valleys to warmer airport sites, leading to a warming bias in the temperature record. Clearly, such inadvertent, but very real, warming biases can and do affect temperature records on local, regional, hemispheric, and global scales. In combination, they could artificially inflate the observed warming by 0.2 to 0.3°C.

With 71 percent of the earth covered by ocean, any discussion of temperature bias must acknowledge the special problems of measurements over the water. Many marine "surface" temperatures are measurements of the temperature of the ocean, not the air adjacent to its surface; the assumption being that the surface water temperatures would be close to air temperature, particularly at night. Some vessels had weather stations on board to measure actual air temperature; of course, the accuracy of a weather station on the deck of the ship would be impacted by its position and the actual height of the deck above the sea surface. In 2001, Christy et al.[2] concluded that trends in sea-surface temperatures are not the same as trends in air temperature and that using sea-surface temperature measurements for air temperature measurements may compromise the depiction of temperatures through time.

The problems with the historical temperature records notwithstanding, it is very likely that the recent upward trend in Figure 1 is very real and that the upward signal is greater than any noise introduced from uncertainties in the record. However, the general error is most likely to be in the warming direction, with a maximum possible (though unlikely) value of 0.3°C. The indicated rise of 0.7°C is likely to be an overestimate.

However, the retreat of mountain glaciers, decrease in spring snow cover and sea ice, and the increase in water vapor are all consistent with surface warming in recent decades. It is tempting to conclude that the warming in the historical temperature record is a response to the buildup of greenhouse gases, but many other possible explanations exist.

Alternative Explanations for Temperature Trends and Variations

Little Ice Age. The warming of 0.16°C per decade that occurred in the 1915-1945 period is difficult to ascribe to human emissions of greenhouse gases. Its magnitude is the same as the warming of the last three decades, yet the human greenhouse "forcing" was much smaller—approximately 10% of the current levels in 1915 and about 35% by 1945. The Earth's temperature has risen and fallen many

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times in the past when humans had no chance to alter the climate. Given the massive swings in global temperature approaching 10°C from coldest periods to warmest periods, the approximately 0.7°C temperature rise since 1900 is not unusual when viewed over long periods of Earth's history.

The last Ice Age ended approximately 12,000 years ago, and we remain in an interglacial warm period that could last another 4–5,000 years. However, within warm interglacial periods, the global climate system periodically endures substantially cooler times. In about 1450, European and global temperature fell by a few degrees, leaving the Earth in the "Little Ice Age," a period that ended in the mid-19th century. A comprehensive study of paleoclimatic indicators by Soon et al.[3] appears to have confirmed the global extent of the phenomenon. The warming evident in the surface temperatures in the first part of the 20th century may be little more than a natural recovery from the Little Ice Age.

Solar Variability. Over the past few decades, scientists have determined that the sun is far from a constant star, and that its output varies at many time scales. Indeed, solar output has increased by approximately 2.0 watts per square meter (Wm^{-2})over the period 1900 to 2002 (Figure 3). An increase in solar irradiance should translate into warmer Earth temperatures. From 1900 to 1969, solar irradiance appeared to explain more than 50 percent of the variance in global temperature. However, from 1970–2002, other factors dominated. The consensus view, as articulated in the IPCC's most recent assessment, is that the global climate was strongly controlled by solar variability until approximately 1970, but that sometime after that date, the buildup of greenhouse gases overcame the solar-climate connection.

Despite the obvious physical linkage between solar output and Earth's temperature, there is considerable debate about how small variations in incoming radiation cause relatively large variations in global temperature. Most numerical climate models fail to reproduce the statistical association shown in Figure 3. There must be a positive feedback

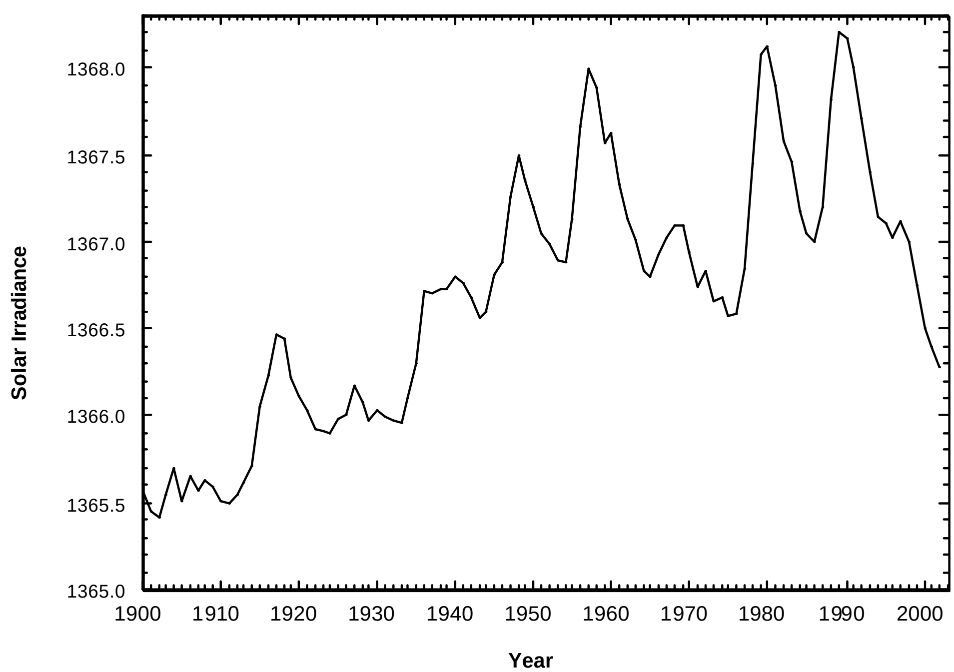

Figure 3. Plot of solar irradiance (W m-2) over the period 1900-2002.

mechanism that enhances the temperature response to the small changes in radiation.

One candidate for the enhancing feedback involves cosmic rays that may alter cloudiness in the upper or lower levels of the troposphere. During times when there are a large number of sunspots, the Earth's magnetic field weakens and cosmic rays from the sun and from outside the solar system penetrate into the troposphere. A series of complex microphysical processes may then take place that may stimulate the growth of high cloudiness. Cosmic ray feedbacks may help explain the strong correlation known to exist between the solar sunspot cycle length and surface temperatures. Many other mechanisms also may be at work creating a positive feedback between solar output and the Earth's temperature, and this area of research should remain active for years to come.

Volcanic Eruptions. Some volcanic eruptions pump enormous amounts of dust into the stratosphere that can remain suspended in for several years. This stratospheric dust blocks incoming radiation from the sun, thereby cooling surface temperatures. The IPCC has shown that a combination of solar variability with periodic volcanic eruptions explains substantial amounts of the variance in global temperature up to 1970, but not thereafter. Once again, the warming from 1970 to present is difficult to reconcile with only known variations in solar and volcanic activity.

Sulfate Aerosols. It is well known that burning fossil fuels produces not only CO_2 but also SO_2. The SO_2 enters the atmosphere and quickly becomes an aerosol capable of reflecting incoming radiation, making clouds last longer, and brightening clouds, all of which have a cooling effect on the planet. Given the short lifetime of sulfate aerosols in the atmosphere, their effect on surface temperature should be highly regional. Since the Northern Hemisphere has much higher atmospheric sulfate concentrations than the Southern Hemisphere, more warming should be evident in the Southern Hemisphere than the Northern Hemisphere over the past 100 years. Yet there is no indication of the Southern Hemisphere warming faster than the Northern Hemisphere. While there is little doubt that SO_2 is having an effect on air temperature trends at regional scales, the effect on global temperature has been difficult to isolate.

Other Forcings. With increased research to understand the climate system, the number of forcing that need to be considered has risen faster than the temperature. In addition to greenhouse gases, stratospheric and tropospheric ozone, sulfates, fossil fuel soot, biomass burning, mineral aerosols, solar variability, aviation-induced contrails and cirrus clouds, and land-use changes need to be considered. Even if we had accurate temperature data from throughout the world and highly accurate numerical models of climate, we would still be unable to forecast future near-surface air temperature levels given the uncertainties regarding the forcings of climate in the next fifty to one hundred years.

Lower- and Mid-Troposphere Temperatures

The evidence is overwhelming that surface temperatures have increased in the past three decades. However, the climate system involves far more that what happens at the surface. The same models that predict warming near the surface also predict even more warming *above* the surface; yet the lower troposphere does not appear to be warming at a rate consistent with the models. Satellite-based and weather balloon-based measurements of lower-atmosphere temperature are not consistent with surface trends. The National Research Council's 2000 report[4] acknowledged that "if global warming is caused by the buildup of greenhouse gases in the atmosphere, it should be evident not only at the earth's surface, but also in the lower to mid-troposphere." Warming near the surface with little to no warming in the lower to mid-troposphere is *not* a clear greenhouse signal!

Conclusions

The history of the earth is marked by significant fluctuations in global temperatures. The modern science of climatology was concerned about global cooling in the 1970s and global warming since the late 1980s. As time goes forward, we will undoubtedly assemble more accurate temperature records and a greater understanding of the causal mechanisms of the variations and trends. But at this moment in time we know only that:

- Global surface temperatures have risen in recent decades.
- Mid-tropospheric temperatures have warmed little over the same period.
- This difference is not consistent with predictions from numerical climate models.

Endnotes

1. Jones, P.D. (1994): Hemispheric surface temperature variations: A reanalysis and an update to 1993. *Journal of Climate*, **7**, 1794-1802.

2. Christy, J.R., *et al.* (2001): Differential trends in tropical sea surface and atmospheric temperatures since 1979. *Geophysical Research Letters*, **28**, 1240-1248.

3. Soon, W., *et al.* (2003): Reconstructing Climatic and Environmental Changes of the Past 1000 Years: A Reappraisal. *Energy and Environment*, **14**, No. 2-3.

4. Wallace, J.M., *et al.* (2000): *Reconciling Observations of Global Temperature Change.* Washington, DC: National Academy Press.