BLOG **Primer**

A Global Warming Primer

Jeffrey Bennett

Revised: December 2009

Note: *All figures below are from my textbooks and based on published scientific data.*

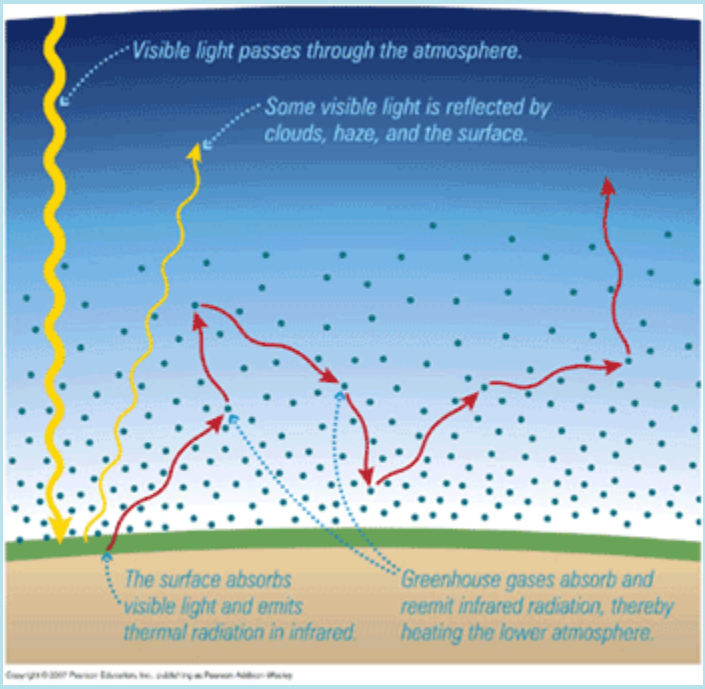
Is global warming real or imagined? Although the news media make this sound like a difficult and contentious question, the basic science is actually quite easy to understand. So for anyone who wonders what to believe, here are five questions and answers that should help you understand the truth behind the headlines:

Question 1: The basic claim of global warming is that a higher atmospheric concentration of carbon dioxide will make Earth warmer. Is there any doubt that, all other things being equal, higher carbon dioxide concentrations do indeed make planets warmer?

Answer: No. The basic mechanism by which carbon dioxide and other "greenhouse gases" (including water vapor and methane) heat planetary atmospheres is called the *greenhouse effect*. This mechanism can be easily demonstrated in the laboratory, and is so well-tested and well-understood that you will not find any scientists who dispute it. (For those who are interested, the figure below shows how the greenhouse effect works.) In fact, the greenhouse effect occurs naturally on Earth, and that turns out to be a very good thing: Without it, Earth would be far too cold for liquid water or life. Studies of other planets show that the greenhouse effect can be even more important in determining a planet's surface temperature than the planet's distance from the Sun. Venus provides the most extreme example: Although Venus is closer to the Sun than Earth, its clouds are so reflective that less sunlight reaches Venus's surface than Earth's surface. As a result, without the greenhouse effect, Venus would be colder than Earth. But because Venus has a thick atmosphere containing far more carbon dioxide than Earth's atmosphere (by a factor of about 170,000), Venus's actual surface temperature is a searing 870°F. Given that the naturally occurring greenhouse effect is a good thing for life on Earth, Venus offers proof that it's possible to have too much of a good thing.

> ***Key point for Question 1***: Scientific understanding of the greenhouse effect is tested and verified, not opinion. Planetary temperatures expected *without* the greenhouse effect can be simply calculated because they depend only on distance from the Sun and the percentage of sunlight that is absorbed rather than reflected; planetary temperatures expected *with* the greenhouse effect can be calculated by also including effects due to the measured amount of greenhouse gases in the atmosphere. The temperatures calculated with the

greenhouse gas contribution match the actual temperatures of the planets, demonstrating that we do indeed understand the greenhouse mechanism very well.



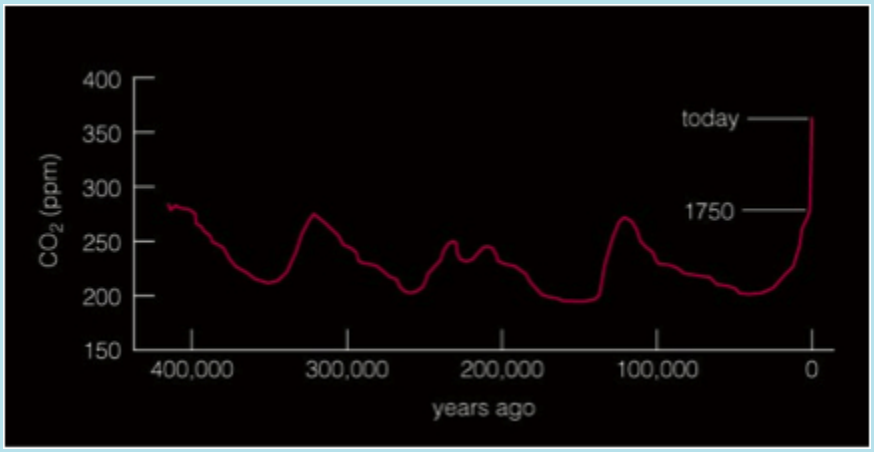
Caption. This diagram shows the basic mechanism of the greenhouse effect. Earth's surface absorbs energy from visible sunlight, and returns this energy to space in the form of infrared light. Greenhouse gases (such as carbon dioxide, methane, and water vapor) slow the escape of the infrared light, thereby keeping the surface and lower atmosphere warmer than it would be otherwise.

Question 2: Is there any doubt that human activity has been raising the concentration of carbon dioxide and other greenhouse gases in Earth's atmosphere?

Answer: No. Scientists have directly measured the atmospheric carbon dioxide concentration since 1958, and in just these past 50 years it has risen steadily from about 315 to 380 parts per million (ppm). Concentrations from longer ago can be measured through records preserved in such things as ice cores (data to a million or more years ago). These data show that the carbon dioxide concentration undergoes substantial natural variations, but until the industrial revolution it had not been above 300 ppm for at least the past million years; the figure below shows data going back 400,000 years. The timing of the rise in carbon dioxide concentration makes it fairly obvious that human activity is responsible for it, but there's additional evidence that makes it even more certain that the rise is due to us: The isotopic composition of the carbon in fossil fuels is slightly different from that from other sources, and careful measurements leave no doubt that the added carbon dioxide is coming largely from the burning of fossil fuels. The same is true for other greenhouse gases, such as methane; carbon dioxide gets the most attention because it is the most common greenhouse gas released by human activity (and because it can remain in the atmosphere for the longest time), but it is important to pay attention to other greenhouse gases as well.

Key point for Question 2: There is no doubt that human activity is adding carbon dioxide and other greenhouse gases to the atmosphere, and data indicate that we've already raised the carbon dioxide concentration to significantly above its natural peak for the past million years. The trend shows that the carbon

dioxide concentration will move rapidly higher unless we do something to dramatically slow the release of carbon dioxide into the atmosphere. The same is also true for other greenhouse gases, such as methane.

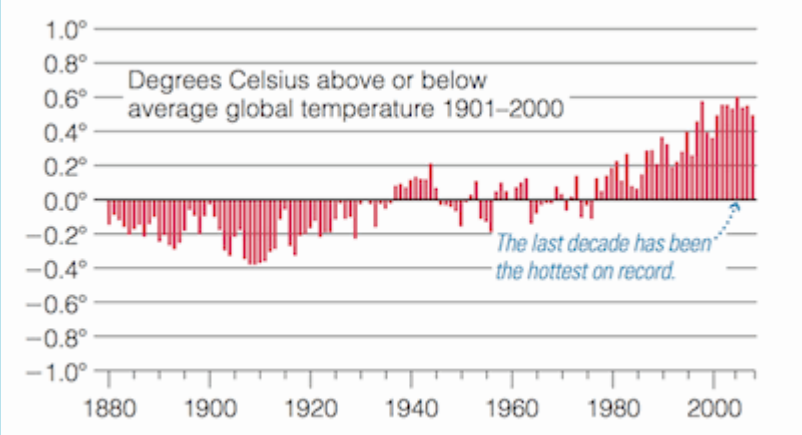


Caption. This diagram shows the atmospheric concentration of carbon dioxide over the past 400,000 years. Data for the past half-century come from direct measurements at Mauna Loa. Earlier data come from sources such as Antarctic ice cores.

Question 3: Is there any doubt that Earth has been warming up during the past century?

Answer: Not any more. For awhile, there were questions concerning whether temperature data were being analyzed correctly, but those doubts have been almost entirely dispelled (see the "postscript" section below). For the past several decades, we've had satellite data from which to make measurements of Earth's global average temperature. Data from earlier times were local rather than global, which means there are greater uncertainties in converting them to a global average. However, by studying a great variety of data sources (ranging from newspaper temperature reports to natural records like those in tree rings), the uncertainties have been reduced enough to make the trend quite clear. The graph below shows the results: The global average temperature has increased about 0.8°C (1.4°F) in the past century.

Key point for Question 3: You will no longer find any serious disagreement about the fact that Earth's global average temperature has warmed about 0.8°C (1.4°F) in the past century. ***What about the claim that the warming trend has stopped during the past decade?*** A look at the graph shows that the warming has indeed slowed or stopped during this period — but you can also see that 10 years on a graph like this are not enough to establish a trend, and that the past decade has still been the hottest on record. Indeed, the fact that the warming slowed or stopped during this time fits well within the expected range of variability that can occur due to natural effects. The well-understood theory of the greenhouse effect clearly predicts that the warming trend will resume, and at this point there is nothing in the data that suggests otherwise.

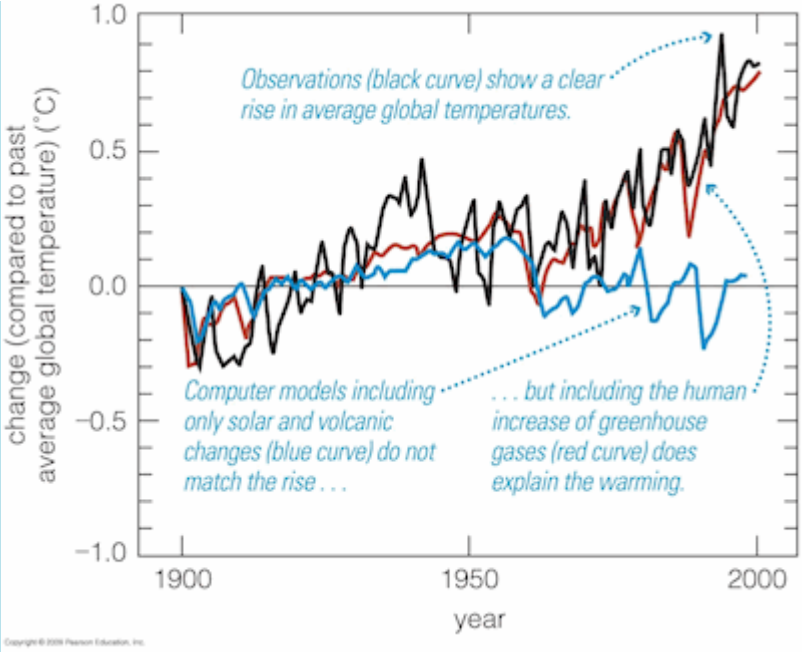


Caption. This graph shows changes in Earth's global average temperature (in Celsius degrees) since about 1880; the zero line is the average for 20th century. Uncertainties are not shown, but range from about 0.3°C for the earliest years (left) to less than 0.1°C for recent years. Based on data from NOAA.

Question 4: OK, so there's no doubt that carbon dioxide raises a planet's temperature, that we're increasing Earth's carbon dioxide concentration, and that Earth is already showing signs of warming. Still, couldn't the recent rise in temperature be due to natural variability, rather than human activity?

Answer: The only way to know for sure whether the temperature rise is natural or due to human activity is to perform experiments in which we compare what would happen on Earth with natural factors alone to what would happen when humans are included in the equation. Of course, we don't have two Earths to compare, so we use computer models to make "simulated Earths." Modeling inevitably involves uncertainties, but if a model fits data well, then we can have confidence that it is on the right track. The figure below shows actual temperature measurements in black. The blue curve shows model predictions based only on natural factors, while the red curve includes the human contribution to the greenhouse gas concentration. Note that both models match the actual data reasonably well before about 1950. But for the past few decades, the models that include only natural factors fail quite miserably, while the models that include the human contribution continue to match the actual data.

> ***Key point for Question 4***: Climate models offer strong evidence in support of the claim that human activity is the primary cause of recent global warming. When you couple this evidence with the rock-solid foundation of the theory of the greenhouse effect (Question 1 above) and the observed fact that human activity has added carbon dioxide and other greenhouse gases to the atmosphere (Question 2 above), it becomes difficult to imagine any other explanation for the observed warming (Question 3 above).



Caption. This graph compares observed temperature changes (black) with the predictions of climate models that include only natural factors (blue) and models that also include the human contribution (red). Only the models that include the human contribution to the greenhouse gas concentration match observations well.

Question 5: So what *is* uncertain about the science of global warming?

Answer: The uncertainty lies in the timing and precise nature of the consequences of global warming. Earth's climate has numerous complexities and feedbacks that, in principle, could either reduce or exacerbate the magnitude of global warming over the next few decades. It is this uncertainty that explains why a small number of scientists (and a larger number of non-scientists) question the general consensus that we should be taking immediate steps to reduce global warming. Remember, however, that even among the scientists who count themselves as "global warming skeptics," there is still no dispute that significant warming would *eventually occur*. It's just that they think we can safely wait it out for a while rather than taking expensive action now. While it's possible that these "skeptics" might be correct, the vast majority of scientists think otherwise. To make your own decision about whether action is needed, you need to understand the potential consequences of inaction. A good resource for lots of details is the IPCC web site, but here's my quick summary:

- The same models that successfully match past temperatures predict that, if we do nothing to slow our emissions of carbon dioxide and other greenhouse gases, the warming trend of the past century will accelerate; by the end of this century, the global average temperature will be 6°F to 10°F (3°C to 5°C) higher than it is now.
- Although a temperature increase of a few degrees might not sound so bad, regional changes in climate patterns can be much more dramatic. Polar regions will generally warm more than equatorial regions, leading to increased melting of polar ice. The amount and distribution of global rainfall will change, with the potential for major disruptions of our agricultural systems, as well as further limitations on the supply of fresh water. And the fact that warming means more total energy in the atmosphere means we should expect more frequent and more severe storms; note that this can mean more severe blizzards in the winter as well as more severe hurricanes in the summer.
- Rising temperatures will cause sea level will rise. Even without ice melting, the fact that water expands slightly as it warms

may make sea level rise up to about a meter (3 feet) by the end of this century. The added effect of melting ice could increase sea level much more. For example, some recent data suggest that the Greenland ice sheet is melting much more rapidly than models have predicted. If this is the case and if it continues, sea level could rise as much as several meters by the end of this century—enough to flood regions populated by hundreds of millions of people worldwide. And while it's highly unlikely that all the polar ice could melt in less than several centuries, remember this fact: Complete melting of the polar ice caps would increase sea level by some 70 meters (more than 200 feet). Are you willing to risk keeping our planet on a course that would mean future generations will need deep-sea diving gear to visit places like New York City and San Diego?

- As the oceans absorb more carbon dioxide (an effect that is actually helpful in that it prevents all of our carbon dioxide emissions from remaining in the atmosphere), the pH of ocean water becomes more acidic. The overall effects of this *ocean acidification* are not yet well-understood, but some studies suggest that they could have devastating consequences not only to ocean species but to the commercial fisheries that are an important part of the global food supply. **Note**: Ocean acidification is independent of temperature; it occurs as long as we keep adding carbon dioxide to the atmosphere, even if the temperature does not go up. This means it throws a major wrench into proposed "geoengineering" schemes that suggest counteracting global warming with such things as spraying sunlight-blocking chemicals into the stratosphere or deploying giant sunshades in space; while these schemes could possibly slow the warming, they would do nothing about ocean acidification.
- And if all that is not enough to spur you to action, many scientists are concerned that continued global warming could lead to "tipping points" that might have even more severe consequences. For example, changes in regional climates might lead to sudden loss of forests that could amplify other climate effects, and changes in ocean temperature might cause major changes to currents (including the gulf stream) that regulate much of the world's climate.

> ***Key point for Question 5***: Although there are indeed uncertainties in the short-term (decades) consequences of global warming, there is no doubt about the basic underlying science. If we keep pumping carbon dioxide and other greenhouse gases into the atmosphere, Earth will eventually warm up significantly, with all the attending consequences listed above.

Bottom Line. So there you have it. There's really very little uncertainty surrounding the entire global warming issue, and what little there is concerns only whether we need to worry immediately or if we can afford to wait a few decades. In essence, the "global warming skeptics" (at least the ones who are serious scientists) are arguing that we should bet on the bad consequences taking longer to occur than current models predict, generally in hopes that future technologies might make it cheaper and easier for us to solve the problems in the future than to address them now. My opinion is that the risks of waiting are too great, and that the skeptics argument is rather like having a doctor tell you not to worry about quitting smoking, since we may find a cure for lung cancer before you die from it. To help you make up your own mind, I suggest that you take the "**letter to your grandchildren test**": Imagine writing (or actually write one!) a letter that will be placed in a time capsule for your children or grandchildren to read in 50 years, telling them what you did to help alleviate global warming, or why you decided that no action was required. Then ask yourself: How will they feel about the decisions you made?

Postscript

As I write this update in December 2009, the news is filled with stories about "climate-gate": e-mails from scientists that are said to show a concerted effort to distort data and prevent skeptic arguments from being heard. Some of the e-mails do indeed seem to suggest ethical lapses, and many more suggest a level of arrogance that is sad to see from anyone, and especially tragic coming from people whose work should be held to the highest standards of both science and ethics. Keep in mind, however, that the failings of these individual scientists do not change the laws of physics. Earth is still livable only thanks to the

naturally occurring greenhouse effect, Venus is still unlivable because of its far stronger natural greenhouse effect, and denying the basic science of global warming still falls into the same camp as denial of the Moon landings or claims that the Grand Canyon proves Earth is only 6,000 years old. Nevertheless, the e-mails will probably provide fuel to the "global warming is a hoax" camp for years to come, so I suppose I'd better address a few of the claims you are likely to hear from this camp. I can't possibly cover everything, but here are the facts behind some of the most common claims:

- A basic claim in the hoax camp (and one that is fueled by the "climate-gate" e-mails) is that "science is not done by consensus." While it is true that science must be based on evidence rather than on votes, it is also still the case that science progresses only when the evidence becomes strong enough to lead to widespread acceptance in the scientific community. For example, Einstein's theories might have died a quick death if not for the fact that evidence in support of them soon convinced the vast majority of scientists. Indeed, when people ask me for a brief statement on the purpose of science, I like to say that *science is a way of examining evidence so that people can come to agreement*. The so-called "consensus" view of global warming is nothing more sinister than this principle in action: The basic science and the available data are now so strong that the vast majority of scientists who have examined the issue in detail have become convinced that global warming presents a serious threat to our future.
- Many in the hoax camp say that the scientists are ignoring the fact that water vapor is a more important greenhouse gas than carbon dioxide or any of the other gases released by human activity. This claim starts with a grain of truth: water vapor is indeed the most important greenhouse gas in our atmosphere. However, the amount of water vapor in the atmosphere is self-regulated by the ocean and atmospheric temperatures. As a result, water vapor actually has the effect of *amplifying* any climate changes caused by changes in the concentration of carbon dioxide or other greenhouse gases: If the addition of other greenhouse gases raises the temperature, ocean evaporation increases, leading to more water vapor and even higher temperatures. Conversely, if the concentration of other greenhouse gases falls, the temperature drops, leading to less evaporation, less water vapor, and an amplified cooling cycle.
- A related claim has to do with the correlation in ice core data between past temperatures and carbon dioxide concentration. These data show clearly that the temperature and the carbon dioxide concentration have risen and fallen together over the past million years. However, close examination of the data shows that the temperature changes tend to begin *first* — seemingly the opposite of what you'd expect if carbon dioxide changes cause temperature changes. But once you understand the water vapor feedback cycle, it's easy to realize what's really going on: Over tens to hundreds of thousands of years, Earth's climate goes through cycles of ice ages and warm periods governed largely by small, cyclical changes in Earth's orbital and rotational properties. Once a rise or fall in temperature is initiated through these natural cycles, the temperature change leads to changes both in the water vapor concentration and in the ocean's ability to hold carbon dioxide. The positive feedback that occurs between water vapor and carbon dioxide then causes both temperature and carbon dioxide concentration to rise or fall rapidly. In other words, the past data actually provide strong evidence for the amplification process, which makes global warming a greater threat, not a less severe one.
- Another claim that begins with a grain of truth is that Earth has been much warmer in the past than it is now (we are still in an ice age by long-term standards of millions of years), and that this therefore proves both that Earth will be fine if it is warmer and that there are natural ways by which the temperature will eventually come back down. True enough, but irrelevant to the current situation. The fact that Earth has been much warmer in the past does not alter the fact that the warming process will mean great changes in sea level, local climates, and ecosystems — changes that could have severe consequences for our civilization. And while it is true that Earth has a natural cycle that self-regulates the climate (it is usually called the *carbon dioxide cycle*, and you'll find it explained in my book *Beyond UFOs*, Chapter 6), this cycle operates over a time scale of hundreds of thousands of years. In other words, even if we completely wreck the planet through global warming, the planet will recover on its own -- a few hundred thousand years from now. Nice to know, but irrelevant to the time scales that matter to our current civilization.

  Additional note: Based on some questions I've received, I should clarify the difference between global warming as a threat to our *species* and as a threat to our *civilization*. As a species, the question is whether global warming poses a threat of extinction, and the answer is almost certainly no; Homo sapiens have surived much warmer climates in the past, and

presumably could do so again. But most of us care not just about the survival of our species, but of the survival of our own families, our nations, and our civilization. Our civilization today is a deeply interconnected system supporting some 7 billion people -- far more than Earth could support without technology, trade, and other aspects of what we call "civilization." We have developed this civilization in the climate that exists today. Could we adapt in principle to a much warmer world? Sure -- but we'd have to move and rebuild all the coastal cities, change the places and ways in which we do agriculture, and reshuffle the geopolitical map to accommodate the new reality. Moreover, if the projections are correct, we'd have to do all this in less than about a century or two. I don't think we could pull it off without plunging into wars and other terrible problems. And even if we could pull it off, it would be far more expensive than simply dealing with the problem of carbon dioxide emissions, which we could solve right now with a little political willpower.

- Numerous other claims of the hoax camp are not quite so grounded in kernels of truth. A few examples that you may hear:
  - The claim that back in the 1970's, the scientific consensus was that we were headed for global cooling and an ice age - a "fact" the hoax camp uses to support their claim that you can't trust the scientific consensus today, either. However, this "fact" simply isn't true. Perhaps the people stating this untrue "fact" are just confused, since by the '70s we had learned that we are currently in an "interglacial" period following the last ice age (suggesting that we might be "due" for another ice age) and data showed (and still do) a slight global cooling during the mid-20th century. But with a few exceptions, scientists already recognized this cooling as an aberration, unrelated to long-term ice age cycles, and that the real issue for the future would be global warming. I know this from my own experience, since my '70s science classes were already discussing global warming as the serious concern. If you want more proof, just look back at scientific publications from the 1970s. There are many examples, but here's one to start with: The summary of an article published in Science Magazine, 8 August 1975, p. 460, states: "...the exponential rise in the atmospheric carbon dioxide content will tend to become a significant factor and by early in the next century will have driven the mean planetary temperature beyond the limits experienced during the last 1000 years."
  - The claim that the "hockey stick graph" - a graph of data showing that global temperatures are now higher than at any time in the past thousand years - has been discredited. However, while the original methodology that led to this graph was indeed criticized by some scientists, its basic data and conclusions have since been validated. Indeed, based on a request from Congress, the National Research Council (NRC) investigated the "hockey stick" graph. The NRC report on the issue, published in 2006, came out in strong support of the methodologies used to look at past climate data and of the conclusion that temperatures now are certainly higher than at any time in the past 400 years and likely higher than anytime in the past 1,000 years. (You can read the NRC report summary or order the full report here; these data are also discussed in light of the new e-mails in this article from the New York Times.)
  - The claim that satellite data about atmospheric temperatures contradict data showing that Earth is warming. Again, there was once some controversy over these data, but the apparent discrepancy has now been resolved (in essence, the discrepancy was traced to errors in the data calibration, and once those were understood the discrepancy went away). For a summary of how both scientific sides came to agreement this issue, see Science Magazine, 12 May 2006, p. 825.
  - For an extreme example of the lengths to which some people will go to dispute something that is really indisputable, here's a quote from Rush Limbaugh: "I'm not a scientist - in my common man way, I explained to this caller why I do not believe in global warming. I gave as my primary belief that I believe in God.... I'm saying as a believer of a loving God and a God of Creation, that there is a complexity to all this that makes it work; that we cannot understand; that we cannot really control; that we cannot destroy, and that we really can't alter in its massive complexity." So there you have it: If you believe that God has set things up so that it's impossible for us to do anything bad to our planet, then you have nothing at all to worry about. But if you believe that God gave us free choice and helps those who help themselves, then we'd better get to work.
- For other claims that you might hear, check out this well-researched web site that goes through a long list of skeptic claims. If you want more information in general about global warming, a couple of my personal favorite web sites include

realclimate.org and the IPCC web site.

Finally, just for fun, here is what planetary scientist (and co-author of my astronomy texts) Nick Schneider calls "the four levels of denial" for global warming:

Level 1: "The Earth is not warming up." (denying the data)
Level 2: "It's warming up, but it's natural." (denying the cause)
Level 3: "It's warming up, humans are causing it, but it's actually beneficial." (denying the consequences)
Level 4: "It's warming up, humans are causing it, it's harmful, but it's too expensive to solve." (denying responsibility)

Don't you think it's time to get out of denial?

---Jeffrey Bennett