An Astrophysicist Looks at Global Warming

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Absent in much of the public debate on climate change has been discussion of the basic science behind it. This perspective discusses that science by comparison with the well-known laws of motion and gravitation. The basic science behind global warming is firmly established. The connection between observed temperature and atmospheric CO_2 increase is much more than sheer supposition.

A great deal of confusion is present within the general public on the role of greenhouse gases in causing global warming. Even within the scientific community there sometimes seems to be a lack of understanding of the physics of greenhouse gas warming, especially among scientists who are not familiar with molecular physics. It is often assumed, especially within the general public, that global warming can be understood by supposition only. The reported correlation between the increase in global temperature and the increase in atmospheric greenhouse gases is taken to represent the basis of the science.

There has been little public discussion of the actual scientific basis of greenhouse gas warming. In this note, I present the case from the viewpoint of an astrophysicist. Geologists are probably most familiar with the role of orbital insolation variations (Milankovitch cycles) as a major contribution of astronomy to geosciences. But astrophysicists have long appreciated the important contribution of greenhouse gases in the warming of planetary atmospheres and that the scientific basis for this warming is firmly established in the science of molecular physics. Here, a parallel is drawn between the relatively simple application of Newtonian physics to problems in mechanics and the more complex enterprise of applying molecular physics to greenhouse warming.

The scientific basis, in theory and experiment, underlying greenhouse gas warming is as robust as any aspect of modern science. A good analogy can be found in our understanding and application of the laws of motion and the law of gravity. Few would question the efficacy of the basic mathematical laws of motion and the inverse square law of gravitation in computing the trajectories of artillery shells, orbiting satellites, and interplanetary spacecraft. Classical Newtonian laws can be used to determine the trajectory of an artillery shell to a high degree of accuracy. Given the velocity of the artillery projectile, wind, and the effects of gravity, the point of impact can be located with great precision. Of course, there are uncertainties that must be considered. But "uncertainty" or "error" is not meant to imply that the laws of physics are incorrect. Unfortunately, the latter seems to be the interpretation of "uncertainty" held by much of the general public in the context of global warming discussions.

Uncertainty in the context of global warming models refers to the numerical uncertainties for the input information that must be factored into calculations. In the case of the trajectory of the artillery projectile, it might be computed for given wind conditions that the projectile has a 98% probability of hitting within 10 feet of the intended target position if fired from a distance of one mile. The point is that the laws of motion and gravitation permit highly accurate calculations of the trajectory of a projectile, but that in the real world there are many factors that can slightly perturb the trajectory. To reach an estimate of the actual trajectory, one must include these perturbing factors.

The scientific basis and calculations for greenhouse gas warming of the atmosphere have many parallels to the problem of computing projectile trajectories ("greenhouse warming" is a misnomer; in a greenhouse, warming is due to confinement of air warmed by sunlight, whereas in "greenhouse gas" warming, gases confine more heat in the atmosphere).

What is the physical theory behind the greenhouse gas effect, and can it be computed from the laws of physics? The answer is a resounding yes! The effects of heat trapping by greenhouse gases was first noted over a century ago and understood from the viewpoint of classical physics involving the absorption and emission of electromagnetic radiation by matter and the thermodynamics of gas. The mathematical and physical laws of the interaction of electromagnetic radiation and matter underlie our understanding of greenhouse gas warming.

This understanding gained a firm basis with the development of quantum mechanics in the 1920s. This development enabled detailed calculations of the physics of absorption, scattering, and emission of electromagnetic radiation by atoms and molecules that make up Earth's atmosphere. Highly sophisticated radiation transfer codes have been perfected to calculate the energy balance in an atmosphere as energy is transferred through atmospheric layers. Trace polyatomic molecules such as water vapor, CO_2, and methane have rotation, bending, and vibration degrees of freedom, and are quite effective at intercepting infrared radiation radiated by Earth's surface and the atmosphere.

When a greenhouse molecule absorbs an infrared photon, the molecule rotates or vibrates faster and is said to be in an "excited" state. At low gas densities, an excited greenhouse gas molecule will

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spontaneously (by the rules of quantum mechanics) reradiate an infrared photon, which may escape the atmosphere into space and produce no net warming.

At the higher densities of Earth's atmosphere, the excited molecule will bump into (collide with) another molecule (any molecule in the atmosphere). In the collision, the energized greenhouse gas molecule loses its rotational energy, which is transferred to the kinetic energy of the molecule it collides with (this is called collisional de-excitation). The increased kinetic energies of the colliding molecules means that the molecules are moving faster than they were prior to the collision, and the increased velocities of such molecules represents a direct measure of increased atmospheric temperature.

"Greenhouse gas" warming occurs because the collisional de-excitation time for greenhouse molecules in Earth's lower atmosphere is much shorter than the radiation lifetime of excited molecular states. This is the basic science of greenhouse gas warming, and can be computed from the laws of physics and demonstrated and measured in laboratory experiments. There is no doubt about the efficacy of the science behind greenhouse gas warming (see www.youtube.com/watch?v=SeYfl45X1wo).

Although there are parallels between computing projectile trajectories and computing global warming, there are also differences. In the case of trajectories, one can repeat an experiment many times and measure the uncertainty. In the case of global warming, there is only one Earth's atmosphere with which to "experiment." One arrives at formal uncertainties in the models by varying the input parameters (for example, the rate of CO_2 input into the atmosphere from fossil fuel burning) and computing many such models.

Modeling global warming is more complex than the relatively simple modeling of the trajectory of a projectile. A great many uncertainties, including the effects of clouds, solar variation, volcanism, and the complex coupling of atmosphere, oceans, land, and the carbon cycle, must be incorporated into models.

There are other planets, however, for which greenhouse gas warming is important, and for which modeling can test the importance of the process. In particular, both Mars and Venus have predominantly CO_2 atmospheres. If the Martian atmosphere consists of 95% CO_2, why is it not much warmer? The basic answer is that the very low gas pressure (0.01 earth atmosphere) of the Martian atmosphere allows most excited CO_2 molecules to radiate away their energy before they have a chance to collide with another molecule and deposit heat in the atmosphere. Even so, there is enough warming to raise the temperature by ~6 °C over what the case would be if the Martian atmosphere consisted of nitrogen rather than CO_2.

In the case of Venus, not only is the atmosphere dominated by CO_2 (98%), but the pressure is ~90 earth atmospheres (because Venus and Earth are of comparable size, and outgassing accounts for the CO_2, the total carbon in the Venusian atmosphere is approximately the same as in Earth's atmosphere, ocean, and crust). This means that excited CO_2 molecules will collide with one another so frequently that few will have a chance to lose energy through radiation to outer space. Therefore a much higher fraction of the infrared radiation from the surface and the atmosphere is trapped within the lower atmosphere, leading to a very high (nearly 900 °F [460 °C]) atmospheric temperature.

In the case of Earth's atmosphere, it has been known for some time that the most important greenhouse gas is water vapor, contributing ~75% of the total atmospheric greenhouse gas warming of some 33 °C. CO_2 and other trace greenhouse gases are responsible for the remaining 25% of heating. Without these greenhouse gases, Earth would be in a frozen state.

Most contrarians fail to recognize the great importance of carbon dioxide in producing the warming of Venus and Mars. The fundamental physics of the important feedback of increasing water vapor (another important greenhouse gas) in response to carbon dioxide warming (i.e., warmer air holds more water vapor) has been applied in thermodynamics for more than 150 years. These two powerful concepts provide a very firm foundation for the fundamental soundness of global warming physics.

Even a cursory reading of international climate assessments (IPCC, Intergovernmental Panel for Climate Change) indicates inclusion of quantitative estimates of many factors that influence radiation forcing and their uncertainties. Scientists may disagree with the uncertainties associated with, for example, the net effect of clouds on radiation forcing. But those disagreements must be weighed in the context of a mountain of published evidence that supports the conclusions and uncertainties reported by the IPCC.

In summary, many criticisms of global warming models are specious and fail to reflect an understanding of the basic science behind the models and the extensive history of the development of radiation transfer codes in modeling planetary and stellar atmospheres. Some contrarians engage in arguments that the warming observed is due to "natural" mechanisms that have been in play for millions of years. *Such proposals should be required not only to identify the specific natural mechanisms in question, but quantify them and present observational or experimental evidence that the mechanisms play a role on a time scale of the past 150 years.* Such proposals also ignore the fact that proxy geochemical data show strong support for the conclusion that CO_2 increases have played the largest role in explaining these past intervals of global warmth!

Most important, contrarians *must* show why the scientific basis of greenhouse gas warming is incorrect. It remains unfortunate that the opinions of a handful of contrarians should be given the same weight in the press and the popular media as the studied conclusions of thousands of scientists. This reinforces the general perception that the "science" of global warming is uncertain, and provides fodder for some (but by no means all) business and political factions to question the reality of anthropogenic global warming.

RECOMMENDED READING

Pierrehumbert, R.T., 2011, Infrared radiation and planetary temperature: Physics Today, v. 64, p. 33–38.

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