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Greenhouse Effect

Andrew A. Lacis
NASA Goddard Institute for Space Studies
New York, NY
USA

1. Introduction

The greenhouse effect is the physical warming of the ground surface that arises in semi-transparent planetary atmospheres that are heated by solar radiation. In order for the greenhouse effect to operate, the planet's atmosphere must be sufficiently transparent at visible wavelengths to allow significant amounts of solar radiation to be absorbed by the ground surface. The atmosphere must also be sufficiently opaque at thermal wavelengths to prevent thermal radiation emitted by the ground surface from escaping directly out to space. In such planetary atmospheres, the long-wave opacity for the absorption of radiation at thermal wavelengths is provided by the so-called greenhouse gases (e.g., water vapor, carbon dioxide, methane, nitrous oxide), although absorption by particulate matter such as that due to clouds and aerosols can also make significant contributions to the greenhouse effect. The net effect of the planetary greenhouse effect is to keep the ground surface of the planet at a warmer temperature than it would otherwise be if there were no greenhouse effect. The operation of a greenhouse effect also imparts a temperature gradient in the planet's atmosphere, with the highest temperatures being at the ground, decreasing with height in the atmosphere. This is primarily a radiative effect that is expected to occur in all planetary atmospheres where the ground surface is heated by solar radiation, and there is substantial atmospheric opacity at thermal wavelengths of the spectrum.

2. Planetary comparisons

In our solar system, the greenhouse effect operates on those terrestrial planets that have substantial atmospheres (i.e., Earth, Mars, and Venus), including also on Saturn's moon Titan. Typically, carbon dioxide is the key greenhouse gas that keeps the ground surface temperatures of the terrestrial planets warmer than they would be without the greenhouse effect. The importance of carbon dioxide as a greenhouse gas stems from its very strong absorption bands that cover much of the thermal spectrum, and also because carbon dioxide does not condense and precipitate from the atmosphere at the prevailing temperatures on the terrestrial planets. Being so much farther from the sun, the atmosphere of Titan is much colder than the atmospheres of the terrestrial planets, so much so that carbon dioxide and water vapor cannot be maintained in gaseous form on Titan. Instead, the greenhouse effect on Titan is sustained primarily by pressure-induced

methane, hydrogen, and nitrogen, to keep the surface temperature on Titan some 12°C (22°F) warmer than it would otherwise be if Titan were warmed only by its absorbed solar radiation (McKay et al., 1991). With Saturn being 9.5 times further from the Sun than the Earth, the solar radiation incident on Titan is about 90 times fainter than the solar radiation that is incident on Earth, endowing Titan with a frigid atmosphere and a surface temperature of 82 K (−191°C, −312°F).

Of the terrestrial planets, Venus has by far the strongest greenhouse effect. This is because the atmosphere of Venus is nearly a 100 times more massive and denser than that of Earth, and also because the atmosphere of Venus is composed almost entirely of the prime greenhouse gas, carbon dioxide. The large atmospheric pressure on Venus greatly broadens the carbon dioxide absorption lines to provide strong absorption across the entire thermal spectrum. Only about 1% of the incident solar radiation penetrates to the ground, but the thermal opacity in the atmosphere of Venus is so large as to produce a greenhouse effect that is about 15 times greater than that on Earth. Because of this, the surface temperature on Venus is nearly 460°C (860°F), which is hot enough to melt lead and vaporize mercury. Moreover, this is about 500°C (900°F) hotter than the surface of Venus would be (−40°C, −40°F) if Venus were simply in thermal equilibrium with the global mean solar energy that is absorbed by the Venus atmosphere, without benefit of the greenhouse effect. Interestingly, the non-greenhouse equilibrium temperature of Venus is actually some 12°C (22°F) colder than the corresponding equilibrium temperature of Earth, even though Venus is closer to the Sun and receives twice the terrestrial insolation. This situation arises because the cloud-shrouded atmosphere of Venus is far more reflecting than that of Earth, reflecting more than 70% of the incident sunlight, whereas Earth reflects only about 30%.

On Earth, the strength of the greenhouse warming effect is a more moderate 33°C (60°F). This amount of greenhouse warming makes the global mean surface temperature of the Earth a relatively comfortable 15°C (59°F) instead of an otherwise frigid −18°C (−1°F), which would be the equilibrium temperature for Earth with a planetary albedo of 30% and no greenhouse effect to trap the absorbed solar radiation. Carbon dioxide is also the key greenhouse gas of the terrestrial atmosphere, but with a very important distinction. In the terrestrial atmosphere, most of the greenhouse effect is actually provided by water vapor and by clouds, with only about 20% due to carbon dioxide. This is because Earth is the 'water' planet where water in all of its forms has a central role in defining the properties of the terrestrial climate system. The greenhouse warming provided by carbon dioxide and the other non-condensing greenhouse gases like methane, nitrous oxide, and ozone, allows water vapor to evaporate and remain in the atmosphere. This produces a strong 'feedback effect' which magnifies that part of the greenhouse warming that is uniquely attributable to the non-condensing greenhouse gases. Thus, water vapor with its strong absorption bands in the thermal part of the spectrum, accounts for approximately 50% of the terrestrial greenhouse effect. Long-wave absorption by cloud particles, which absorb radiation at all wavelengths of the thermal spectrum, accounts for about 25% of the total greenhouse effect. The highly interactive atmosphere of Earth serves to produce the uniquely variable climate that exists nowhere else in the solar system.

In contrast to Venus and Earth, the Martian atmosphere is very thin and tenuous, being scarcely 1% of the Earth's atmosphere. Like Venus, the Martian atmosphere is composed

primarily of carbon dioxide. Interestingly, the column amount of carbon dioxide in the Martian atmosphere is actually about fifty times greater than in the atmosphere of Earth. Nevertheless, Mars can only muster a small amount of greenhouse warming (about 5°C, or 9°F). The reason for this is that the atmospheric pressure is a very important factor in determining the efficiency of greenhouse gas performance. Because of the small atmospheric pressure on Mars (less than one hundredth that on Earth), the spectral absorption lines of carbon dioxide on Mars are very narrow, and therefore act like a picket fence that lets most of the thermal radiation emitted by the Martian ground surface to escape directly out to space. This does not happen on Earth because of the atmospheric pressure that is exerted by the radiatively inactive nitrogen and oxygen, causing the spectral absorption lines of carbon dioxide and water vapor to be greatly broadened, making them more effective absorbers of thermal radiation. And, for comparison, it is the extremely high pressure on Venus that makes the carbon dioxide absorption of thermal radiation particularly efficient in the Venus greenhouse effect.

On Mercury, there is no tangible atmosphere, and hence there is no opportunity for the greenhouse effect to operate. Accordingly, the surface temperature on Mercury is determined solely as the result of local thermal equilibrium with the absorbed solar radiation, producing scorching hot temperatures on the sunlit side, and being abysmally cold on the dark side.

The strength of the planetary greenhouse effect is something that can, at least in principle, be determined by direct measurement. Perhaps the most basic measurement of a planet's energy balance is the reflected solar energy. Given the planet's distance from the Sun, it is therefore taken for granted that the incident solar radiation is a known quantity. Upon subtracting the reflected solar radiation from the incident solar energy flux, the energy input to the planet is thus defined. Other potential energy sources such as tidal, geothermal, nuclear, etc. are several orders of magnitude smaller than the absorbed solar radiation, and therefore need not be considered. A very natural and logical assumption that is commonly made is that the planet is in global energy balance, meaning that the thermal radiation emitted by the planet is going to be equal to the absorbed solar energy. Accordingly, this determines the outgoing long-wave energy that the planet radiates out to space. The long-wave energy emitted to space then serves to define the effective radiating temperature of the planet by equating the emitted energy to its equivalent Planck, or blackbody radiation, as summarized in equation form by

$$\pi R^2 \, S_o \, (1 - A) = 4\pi R^2 \, \sigma T_E^4 \qquad\qquad (1)$$

where πR^2 is the projected geometrical area of the planet, S_o is the solar constant, A is the planet's bond albedo on the solar side of the equation. On the thermal side $4\pi R^2$ is the total surface area of the planet, σ is the Stefan-Boltzmann constant (5.67×10^{-8} W/m^2 K^{-4}), and T_E is the effective radiating temperature of the planet. The outgoing long-wave flux is also a subject for direct measurement, while the effective temperature is defined numerically from the long-wave flux through the Stefan-Boltzmann law.

$$F_{LW} = \sigma T_E^4 \qquad\qquad (2)$$

and

$$T_E = [S_o (1 - A)/4\sigma]^{1/4} \tag{3}$$

Also needed is the information about the planet's surface temperature and the up-welling thermal flux that is emitted by the ground surface, both of which are measurable quantities. Direct measurements have been made by space probes that landed on the surfaces of Mars and Venus. Space based measurements are also possible by using selected spectral windows in the long-wave spectrum where radiation from the ground surface can escape directly out to space. Such measurements are a topic in remote sensing. They rely on associating the intensity of the measured spectral radiance with the equivalent spectral brightness of Planck radiation. By such means, microwave measurements of Venus were the first indication that the surface temperature of Venus was exceedingly hot, before verification by direct space probe measurements. A summary of planetary greenhouse parameters is listed in Table 1.

Parameter	Mars	Earth	Venus
$T_S(K)$	215	288	730
$T_E(K)$	210	255	230
$\sigma T_S^4 (W/m^2)$	121	390	16,100
$\sigma T_E^4 (W/m^2)$	111	240	157
$G_T(K)$	5	33	500
$G_F(W/m^2)$	10	150	~16,000
$P_S(bar)$	0.01	1	100

Table 1. Planetary greenhouse parameters. (After Lacis et al., 2011).

The greenhouse parameters listed in Table 1 are all measurable quantities so that, at least in principle, the strength of the greenhouse effect of a planet is empirically determinable. As explained above, the effective temperature, $T_E(K)$, is actually a measure of either the emitted long-wave radiation at the top of the atmosphere, or the absorbed solar radiation by the planet, as given by Equation (3). Direct measurements of the globally averaged radiative fluxes at the top of the atmosphere and at the ground surface are actually quite difficult to obtain, particularly in view of the large variability of the solar and thermal radiative fluxes both geographically and with time, and also as a function of wavelength and viewing geometry. In practice, it is a combination of observational data analyses and theoretical modeling that is required to refine our knowledge of the planetary greenhouse parameters.

Basically, it is the long-wave radiative fluxes at the top of the atmosphere and at the ground surface that define the greenhouse effect. The strength of the planetary greenhouse effect is expressed as the difference between the up-welling long-wave flux emitted by the ground surface, and the outgoing long-wave flux at the top of the atmosphere. Thus,

$$G_F = \sigma T_S^4 - \sigma T_E^4 \tag{4}$$

and

$$G_T = T_S - T_E \tag{5}$$

where the greenhouse strength G_F is expressed in flux (W/m^2) units, and G_T is expressed as a temperature (ΔT_K) difference. The two greenhouse expressions are equivalent. G_F expressed in flux units is more directly comparable to radiative modeling results and

observational data. G_T expresses the strength of the greenhouse effect directly in terms of the temperature difference by which the global mean surface temperature would be increased in comparison to the temperature that would exist if there were no greenhouse effect. The numbers given in Table 1 represent annually-averaged global-mean values. Obviously, the strength of the greenhouse effect varies with geographic location and with season. While the well-mixed non-condensing greenhouse gas contribution to the greenhouse effect may tend to be globally uniform and steady in time, the water vapor and the cloud feedback contribution to the greenhouse effect is strongly variable, geographically, seasonally, and even inter-annually.

It is interesting that of the numbers in Table 1, the outgoing long-wave fluxes of the three planets, as represented by the effective temperature, are so similar. More noteworthy are the factors of a 100 difference in the massiveness of the respective atmospheres, as represented by the surface pressure P_S. In all three atmospheres, carbon dioxide is the key greenhouse gas. But the Earth is unique in that its greenhouse effect includes feedback amplification.

3. Geological perspective

It is the combination of solar radiative heating and the strength of the greenhouse effect that determines the surface temperature of a planet. In the early days of the solar system some 4.5 billion years ago, the Sun had only about 75% of its present luminosity. But, as hydrogen in the interior of the Sun gets transformed into heavier elements, this causes the temperature and luminosity of the Sun increase, which in turn produces a slow and steady rise in the energy input to the terrestrial climate system. This is sometimes called the astrophysical climate forcing, and this type of solar radiative forcing will continue unabated. In several billion years time it will make the Earth too hot to be habitable.

While changes in solar insolation act to regulate the inflow of energy to the atmosphere and ground, it is the strength of the greenhouse effect that exerts its influence on the terrestrial climate system by regulating the energy outflow, and by generating additional heating of the ground surface by down-welling long-wave radiation. Here, carbon dioxide plays the leading role. In the early days of the Earth when the Sun was much less luminous, high concentrations of carbon dioxide where able to keep the temperature habitable for life forms to get established and to take root.

Over million-year time scales, volcanoes are the principal source of atmospheric carbon dioxide, and weathering of rocks is the principal sink (Berner, 2004), with the biosphere of the Earth also participating both as a source and as a sink. Because the principal sources operate independently of each other, the atmospheric level of carbon dioxide can fluctuate unchecked. There is geological evidence that shows glaciation was taking place at tropical latitudes 650 to 750 million years ago (Kirschvink, 1992), suggesting that snowball Earth conditions might have existed at that time. If, over millions of years, rock weathering were to exceed volcanic replenishment, atmospheric carbon dioxide could fall below its critical value, thus sending the Earth to snowball conditions. Eventually, with the ocean covered by ice, and thus prevented from taking up carbon dioxide, sufficient buildup of atmospheric carbon dioxide from volcanic eruptions would gradually bring the Earth out of its snowball state climate.

The Cenozoic era, comprising the past 65.5 million years, marks the Cretaceous extinction of dinosaurs and the auspicious rise of mammals. During this era, the level of atmospheric concentration of carbon dioxide peaked near 3000 parts per million roughly 50 million years ago (Royer, 2006). This coincided with peak global warming when the global mean ocean temperature was some 12°C warmer than present (Hansen et al., 2008). The information on carbon dioxide concentrations comes from carbon isotope analysis obtained from ocean core data (Fletcher, 2008), and temperature information is deduced from oxygen-18 variations in the ocean core data. It so happens that about two tenths of one percent of atmospheric oxygen is oxygen-18, or heavy oxygen with ten neutrons instead of the nominal eight. Since oxygen-18 concentration relative to oxygen-16 is systematically temperature dependent, this ratio can therefore be used as a geological thermometer to estimate global temperature changes in the geological record.

It is generally believed that it was enhanced weathering of rocks associated with the formation of the Himalayas that brought the atmospheric carbon dioxide down to a critical 450 ppm level, at which point the Antarctic polar ice cap began to form about 34 million years ago. The geological record clearly shows the close coupling between the level of atmospheric carbon dioxide and the global temperature of Earth, suggesting a thermostat-type control by atmospheric carbon dioxide in regulating the surface temperature of Earth. All along, the terrestrial biosphere has also played a very critical role in the time evolution of the global carbon cycle by having sequestered most of Earth's carbon in the form of limestone, and not allowed it to accumulate in the atmosphere as was apparently the case on Venus.

On thousand-year time scales, both the Antarctic and Greenland ice core data show that atmospheric carbon dioxide has fluctuated between 180 to 300 ppm over the glacial-interglacial cycles during the past 650,000 years (Jansen et al., 2007), with close coupling between the carbon dioxide concentration, ice volume, sea level, and global temperature. The relevant physical processes that control atmospheric carbon dioxide on thousand-year timescales between the glacial and interglacial extremes are not yet fully under-stood, but appear to involve the biosphere, ocean chemistry, and ocean circulation, with a significant role for Milankovitch variations in the Earth-orbital parameters which alter the seasonal distribution of incident solar radiation in the polar regions. While in the context of current climate, carbon dioxide is clearly an externally imposed radiative forcing on the climate system (as the direct result of fossil fuel burning) in the context of recorded human history, within the longer geological record, carbon dioxide is seen to be a variable quantity, albeit on a very slow time scale.

In some ways Venus is the twin sister of Earth. Both planets have similar mass and size, similar composition, similar amounts of carbon, an a generally similar location within the solar system, Based on this, there is well-grounded speculation, supported by isotope evidence, that originally Venus may have supported an ocean and an atmosphere similar to that of Earth. The suggestion is that for some reason Venus was not able to sequester its store of carbon in the form of limestone as Earth was able to accomplish. In this scenario, carbon dioxide arising from volcanic eruptions continued to accumulate within the Venusian atmosphere, increasing its greenhouse effect to the point where eventually all ocean water was vaporized. Water vapor then was carried high into the atmosphere where

it was photolyzed by the intense sunlight and the liberated hydrogen was lost to space. There is thus the lingering suspicion that the current climate on Venus might well be attributed to the absence of having had appropriate life forms that could have prevented the critical buildup of carbon dioxide and thus prevented the runaway greenhouse effect that has rendered Venus inhospitable to life.

4. Historical understanding

The basic understanding of the greenhouse effect mechanism was first described in 1824 by the French mathematician and physicist Joseph Fourier (Fourier, 1824). This was also that period in time when conservation of energy, the most basic and fundamental concept of physics, was being formulated and quantified. Solar energy from the Sun is absorbed, and warms the Earth. An equal amount of thermal energy must then be radiated to space by the Earth in order to maintain its equilibrium energy balance. Otherwise the temperature of Earth would either keep rising indefinitely, or decrease indefinitely. In this spirit, Fourier performed experiments on atmospheric heat flow and pondered the question of how the Earth stays warm enough for plant and animal life to thrive. Fourier realized that much of the thermal radiation emitted by the Earth's surface was being absorbed within the Earth's atmosphere, and that some of this absorbed radiation was then being re-emitted downward, providing additional warming of the ground surface over and above that attributable just to the direct absorption of solar energy.

In 1863, the Irish physicist John Tyndall (Fleming, 1998) provided experimental support for Fourier's greenhouse idea, demonstrating by means of quantitative spectroscopy that the common atmospheric trace gases, such as water vapor, ozone, and carbon dioxide, are strong absorbers and emitters of thermal radiant energy, but are essentially transparent to visible sunlight. It was clear to Tyndall from his measurements that water vapor was the strongest absorber of thermal radiation, and therefore, the most influential atmospheric gas controlling the Earth's surface temperature. Meanwhile on the other hand, the principal components of the atmosphere, nitrogen and oxygen, were found to be radiatively inactive, providing only the atmospheric framework and temperature structure within which water vapor and carbon dioxide can exert their radiative influence. With this understanding of the radiative properties of the absorbing gases in the atmosphere, Tyndall speculated in 1861 that a reduction in atmospheric carbon dioxide could in fact induce an ice-age climate.

Utilizing the work of Tyndall and the careful measurements of heat transmission through the atmosphere compiled by the American astronomer Samuel Langley, the Swedish chemist and physicist Svante Arrhenius was the first to develop a quantitative mathematical framework of the terrestrial greenhouse effect (Arrhenius, 1896). Arrhenius published his heat-balance calculations of the Earth's sensitivity to carbon dioxide change in 1896. His radiative modeling results were remarkably similar to our current understanding of how the terrestrial greenhouse effect keeps the surface temperature some 33°C (or 60°F) warmer than it otherwise would be. Given that Arrhenius' basic interest was to explain the likely causes of ice-age climate, his greenhouse model was quite successful. He showed that reducing atmospheric carbon dioxide by a third would cool the global surface temperatures by −3°C (−5.5°F), and that doubling carbon dioxide would cause the tropical latitudes to warm by 5°C (9°F), with somewhat larger warming in polar regions, results that are in surprisingly

close agreement with current climate modeling simulations for the expected change in global surface temperature in response to the doubling of carbon dioxide forcing.

In 1905, the American geologist Thomas Chamberlin made the important finding that the greenhouse contribution by atmospheric water vapor behaved as a positive feedback mechanism (Christianson, 1999). In his thinking, Chamberlin noted that surface heating by solar radiation, or surface heating due to other agents such as carbon dioxide, raises the atmospheric temperature and leads to evaporation of more water vapor. This extra amount of water vapor produces additional heating and the further evaporation of additional water vapor. When the added heat source is taken away, any water vapor that is in excess of its equilibrium amount will precipitate from the atmosphere. Clearly, this is not a runaway situation. Rather, the change in the externally applied heating simply results in the establishment of a new equilibrium for the amount of water vapor that the atmosphere can hold. Since water vapor is an efficient greenhouse gas, the net effect of this interaction produces a significantly larger temperature change than would otherwise be the case if the amount of atmospheric water vapor did not change, demonstrating that it is carbon dioxide (and the other non-condensing greenhouse gases) that are the controlling factor of the terrestrial greenhouse effect. As a result, atmospheric water vapor and clouds act as feedback effects that magnify the greenhouse heating that is initially supplied by the non-condensing greenhouse gases, or by other radiative forcings.

5. Terrestrial greenhouse effect

In the terrestrial greenhouse, carbon dioxide accounts for approximately 7°C (13°F) of the total 33°C (60°F) greenhouse effect. The other non-condensing greenhouse gases, i.e., ozone, methane, nitrous oxide, and anthropogenic chlorofluorocarbons, add another 3–4°C (5–7°F) to the overall global greenhouse strength. Because clouds absorb thermal radiation at all wavelengths of the thermal spectrum, this makes clouds into important contributors to the terrestrial greenhouse effect. Even aerosols, in particular the larger sized desert dust particles, with their substantial absorption and scattering at thermal wavelengths, make a small but non-negligible, contribution to the terrestrial greenhouse effect. Also, the cooling efficiency of volcanic aerosols is reduced by about 10% because of their non-negligible greenhouse effect (Lacis and Mishchenko, 1995).

The greenhouse effect is intimately an integral part of the global energy balance within the climate system. Basically, it is the greenhouse effect that determines how the long-wave thermal energy is transformed from its initial emission from the ground surface to its final destination out to space from the top of the atmosphere. In the process, this effectively defines the strength of the terrestrial greenhouse effect and determines the magnitude of the greenhouse warming over and above what the surface temperature would be if the ground surface were determined by simply being in equilibrium with the absorbed sunlight. In general terms, the nominal global mean surface temperature of the Earth is about 288 K (15°C, 59°F). The corresponding thermal radiation emitted by the ground surface is very closely described by the 'black body', or Planck emission, which is proportional to the fourth power of the surface temperature. This yields 390 W/m^2 for the up-welling long-wave flux emitted by the ground surface. However, the long-wave flux to space leaving the top of the atmosphere is about 240 W/m^2, which has been verified by satellite-based long-wave

radiative flux measurements of the Earth's energy balance. The flux difference of 150 W/m² between the up-welling surface flux and the long-wave flux at the top of the atmosphere that is emitted out to space, is a simple measure of the strength of the terrestrial greenhouse effect. As a further point, in terms of black body Planck radiation, the 240 W/m² that is radiated out to space corresponds to a Planck temperature of 255 K (−18°C, −1°F), which is sometimes referred to as the effective temperature of the Earth. Thus, the temperature difference between the surface temperature and the effective temperature (33 K, 33°C, 60°F) provides another equivalent measure of the strength of the terrestrial greenhouse, one that is expressed in terms of temperature.

The relative efficacy of any particular atmospheric greenhouse contributor is determined by how strongly it will absorb thermal radiation, and on how weakly the absorbed thermal radiation is re-emitted to space. According to the principles of radiative physics, the emissivity of a substance must be equal to its absorptivity. It is notable that the absorptivity of most absorbing materials has very little dependence on temperature, while the emission of thermal radiation is very strongly dependent on the temperature of the emitting body (varying approximately as the fourth power of the temperature of the radiating substance). As a result, clouds that are near the ground are poor contributors to the greenhouse effect because they absorb and re-emit thermal radiation at nearly the same temperature. Cirrus clouds, on the other hand, are very strong greenhouse contributors because they absorb the relatively high-temperature radiation emitted from the ground surface, but because they are located at a cold temperature, they emit to space only a small fraction of the radiation they have absorbed. This is the basic principle of efficient radiative operation of the greenhouse effect: absorb the up-welling high-temperature radiation, and emit radiation at a much colder temperature. This kind of radiative interaction makes for efficient trapping of heat within the atmosphere below.

5.1 Modeling realism

The modern approach to the study of Earth's climate and of the human impact on climate began in the 1930s with the work of Guy Callendar (Fleming, 1998), a British engineer who very systematically documented the time trend of anthropogenic fossil fuel use and was able to make the connection between fossil fuel burning and the corresponding increase in atmospheric carbon dioxide. However, realistic modeling of the Earth's climate system did not become feasible until the 1960s and 1970s when the availability of high-speed large-memory computing systems began to be applied to the analysis of what is really a very complex problem in atmospheric physics. At present time, capable climate models are being run at dozens of climate centers worldwide. Their modeling task is to simulate the workings of current climate system in great detail. The model generated climate is represented by the global maps and vertical profiles of evolving atmospheric temperature, wind, water vapor, clouds, aerosols, and greenhouse gases. The objective of the modeling effort is to understand how the climate system works. By demonstrating the ability to model the geographic and seasonal patterns and variability of temperature, winds, cloudiness and precipitation, this will establish confidence to model the changes in global climate that are occurring as the result of global warming due to the increase in atmospheric greenhouse gases produced by human industrial activity.

Since the greenhouse problem is largely radiative in nature, it follows that effective radiative modeling is the key. Unfortunately, the spectral absorption properties of greenhouse gases is very complex, consisting of many thousands of individual spectral lines of widely varying strengths, grouped in different sized often overlapping bunches, spread across the entire long-wave spectrum. Moreover, the width of each line is strongly pressure dependent, and there is a temperature dependence of the absorption strength as well. Before the advent of large computers, it was common practice then to rely on empirical formulas and statistical band models to represent the spectral absorption properties of the different atmospheric gases. The atmospheric temperature profile is the one additional, and absolutely essential factor that is required in order to perform the radiative calculations. Given a multi-layered model of the atmosphere, the radiative calculations yield heating rate profiles of solar radiation and cooling rate profiles of thermal radiation. By means of brute force time marching, the results of the heating and cooling rate calculations are applied over a short time interval to recalculate the atmospheric temperature profile until the radiative heating and cooling rates balance each other. Such atmospheric heat balancing calculation (Manabe and Moller, 1961) produce an atmospheric temperature profile that is in radiative equilibrium.

Radiative equilibrium might be adequate to represent the Martian atmosphere, but not that of Earth. The atmospheric lapse rate, or the rate that the atmospheric temperature decreases with height, has a defining role in determining the strength of the terrestrial greenhouse effect. The temperature structure of the atmosphere becomes established as the direct result of radiative heating and cooling, including also the effects of atmospheric dynamics and thermodynamics. If radiation were the only means of energy transport in the atmosphere, given the large thermal opacity of the atmosphere, the resulting temperature gradient needs to be very steep in order to export all of the energy radiated by the ground surface out to space. The greenhouse effect corresponding to such a 'radiation only' atmosphere would be about 66°C (120°F), or about twice its actual value of 33°C (60°F). But such a purely radiative temperature gradient would be dynamically unstable against convection. Convection would set in, and heat energy would be transported upward by a newly enabled parallel means of energy transport to establish a less-steep temperature gradient that would be stable against further convection. This problem was resolved by including a 'convective adjustment' to the atmospheric temperature gradient (Manabe and Strickler, 1964) to produce a realistic profile for the atmospheric temperature, and thus provide a realistic atmospheric structure for the calculation of the radiative fluxes.

5.2 Temperature lapse rate

In the Earth's atmosphere, water vapor plays a very important role in energy transport by convection. This is because water vapor contains latent heat energy which is released to the atmosphere when water vapor condenses, thus making energy transport by convection that much more energetic than by dry gas alone. The net effect of including water vapor in the convective energy transport establishes what is called the 'moist adiabatic' temperature gradient, a very persistent characteristic of the terrestrial atmosphere. It had been noticed from meteorological observations that as temperatures changed, the moisture content in the atmosphere changed by large amounts, but that the relative humidity profile tended to be more stable. By imposing a condition of 'fixed relative humidity' when calculating the

thermal equilibrium of the atmosphere, more realistic temperature profiles could be obtained (Manabe and Wetherald, 1967).

The need to have a realistic atmospheric structure in order to be able to calculate accurate radiative fluxes is self-evident. It is also clear that the terrestrial atmosphere is very complex in both the radiative properties of the atmospheric constituents as well as the atmospheric dynamics and thermodynamics that are involved in producing the resultant temperature structure. In the early models, improvisation and approximation were the rule, primarily because the computer resources to do better were not available. In current state-of-the-art climate models the problems of determining the atmospheric structure, including as well the vertical distribution of water vapor, clouds, greenhouse gases, and temperature, all of which vary geographically and with time, are gradually beginning to be addressed in realistic fashion.

5.3 Current climate models

A rather full description of our current climate modeling capabilities, including the success in our ability to model the terrestrial climate system, and our ability to address the looming problems of global warming and climate change that confront the future of humanity is contained in the *IPCC AR4 (2007) Report of the Intergovernmental Panel on Climate Change* (Solomon et al, 2007). The overall objective is to be able to simulate the basic behavior of the climate system in terms of fundamental physics principles. This means that the evaporation and condensation of water vapor is computed based on local temperature, pressure, wind speed, relative humidity, and surface conditions. Atmospheric winds are calculated from hydrodynamics principles and include dependence on pressure, temperature, topography, and surface roughness. The incident solar radiation is calculated at each geographic point depending on its latitude and longitude, and also includes the effects of changing Earth-Sun distance and variation in orbital parameters. All this is being done with the highest spatial, vertical and time resolution that is supported by current computer speed and memory. This typically means that current climate models might employ a horizontal resolution of 50-500 km, support 20-100 vertical layers, and employ an 0.5-3 hour time resolution. Such climate models generate a lot of simulated 'climate' data which then can be compared to similarly voluminous observational data of spatial and seasonal maps of temperature, water vapor, cloud, and precipitation variations to critically evaluate the climate modeling performance. If a climate model can reproduce the observational data with reasonable fidelity, there is then reason to believe that such a model might be useful for analyzing past trends of climate change, and also in making prediction for the future.

One example of such a model is the GISS ModelE climate model (Schmidt et al., 2006). This climate model can be operated at different resolutions for the horizontal, vertical, and time dimensions. It is coupled to a fully interacting ocean model to provide an accurate rendering of the temporal response of the climate system to changes in radiative forcing. The model produces realistic simulations of current climate temperature, precipitation, water vapor, and clouds. More specifically, the GISS ModelE produces realistic atmospheric temperature profiles, and realistic horizontal and vertical distributions of water vapor and clouds – all the information that is necessary to calculate accurate radiative fluxes and atmospheric heating and cooling rates.

5.4 Radiative transfer modeling

The GISS ModelE radiative transfer model has been specifically designed to render accurate results for the radiative fluxes and the radiative heating and cooling rates throughout the atmosphere for any specified atmospheric temperature structure and absorbing gas and cloud distribution. The starting point for modeling the absorption by atmospheric gases is the HITRAN line atlas (Rothman et al., 2009) which contains absorption line strengths, line positions, widths, and energy levels for several hundred thousand lines for water vapor, carbon dioxide, ozone, and other atmospheric gases. This information is used in line-by-line models to calculate the spectral transmission and absorption by the different greenhouse gases, including the effects of overlapping absorption, with very high precision. The line-by-line results are time consuming, but they serve as the standard of reference to which much faster methods of calculation can be compared and validated for use in climate modeling applications. The correlated *k*-distribution method (Lacis and Oinas, 1991) is a widely used approach for reproducing the line-by-line accuracy to well within 1% for all the greenhouse gases, including an accurate rendering of the non-linearities due to pressure broadening and the overlapping absorption for widely varying absorber amounts. For thermal radiation the effects of multiple scattering are accounted for as parameterized corrections, but they are modeled explicitly for solar radiation. All in all, the GISS modelE radiative transfer modeling is performed with high accuracy, as verified by a wide range of line-byline calculations.

The ModelE radiation treatment has been designed to be both comprehensive and flexible. At each grid point of ModelE, accurate radiative fluxes are calculated at each model time step in response to ever changing temperature profiles, clouds, aerosols, and greenhouse gases. These calculations are performed globally at thousands of grid points, and thousands of times annually. In this way, accurate values of globally and annually averaged fluxes at the ground surface and at the top of the atmosphere are obtained for a more convenient analysis of the terrestrial greenhouse effect and of the global energy balance, results that include a detailed and realistic rendering of the climate system and its seasonal variability. Moreover, with the current computer speed and memory capabilities, all of this data can be stored and reprocessed over and over again. This is where the radiation model flexibility comes into play. All of the different greenhouse gases, clouds, and aerosols can individually be selected or zeroed out, and the radiative calculations repeated to obtain a quantitative measure of the non-linear effects of overlapping absorption by different combinations of greenhouse gases.

5.5 Greenhouse warming attribution

While it is important to have an accurate measure of the total greenhouse strength for our current-climate atmosphere, it is equally important to have a clear understanding of the relative contribution that each of the atmospheric constituents makes to the total strength of the greenhouse effect. This task was performed with the GISS ModelE (Schmidt, et al., 2010) whereby the radiative effects of the different atmospheric constituents were evaluated individually one by one, so as to determine their relative importance. The results of these calculations are summarized in Table 2.

LW absorber	single-addition		single-subtraction		normalized average	
	W/m²	fraction	W/m²	fraction	W/m²	fraction
H_2O	94.7	.458	59.8	.534	74.7	.490
cloud	56.2	.272	23.2	.207	37.3	.244
CO_2	40.3	.195	24.0	.214	31.0	.203
O_3	4.0	.019	1.7	.015	2.7	.018
N_2O	4.1	.020	1.5	.013	2.6	.017
CH_4	3.5	.017	1.2	.011	2.2	.014
CFCs	1.0	.005	0.2	.002	0.6	.004
aerosol	3.0	.014	0.4	.004	1.5	.010
sum	206.8	1.000	112.0	1.000	152.6	1.000

Table 2. Single-addition & single-subtraction LW flux changes. (After Lacis et al., 2010)

The results in Table 2 were obtained by starting with a one-year's worth of ModelE climate data which had been run to equilibrium for 1980 atmospheric conditions. For this model, the globally averaged annual-mean long-wave up-welling flux at the ground surface was 393.9 W/m² (T_S = 288.7 K), and the long-wave flux at the top of the atmosphere emitted to space was 241.3 W/m² (T_E = 255.4 K), with the total strength of the greenhouse effect G_F = 152.6 W/m² (G_T = 33.3 K). Upon zeroing out all atmospheric absorbers, the outgoing long-wave flux to space was that emitted by the ground surface, 393.9 W/m². The absorbers were then added in individually one at a time, and the reduction in outgoing flux re-evaluated. These are the global annual mean flux changes listed in the left hand single-addition column. Thus, water vapor by itself reduced the outgoing flux by 94.7 W/m², cloud alone by 56.2 W/m², carbon dioxide alone by 40.3 W/m², with smaller amounts for the minor greenhouse gases. The sum of these single-addition contributions adds up to 206.8 W/m², indicative of the substantial effect of non-linear overlapping absorption since the sum total flux reduction with all greenhouse gases acting together is 152.6 W/m². In the second column these fractional single-addition contributions have been normalized to unity.

Similarly, the single-subtraction columns were obtained by subtracting each individual atmospheric absorber one at a time from the full compliment of absorbers. In this case, the reference top of the atmosphere outgoing long-wave flux was 241.3 W/m². By removing water vapor alone, the flux emitted to space increased by 59.8 W/m², 23.2 W/m² for cloud alone, 24.0 W/m² for carbon dioxide alone, with smaller amounts for the minor contributors. Again, because of non-linear overlapping absorption effects, the individual flux changes only sum to 112.0 W/m², instead of 152.6 W/m². The single-subtraction results are similarly normalized to unity.

The single-addition and single-subtraction results are then weighted by their closeness to the equilibrium G_F value. Thus, by taking 0.572 times the group-subtraction values plus 0.428 times the single-addition values, we arrive at the normalized average results for the radiative flux and corresponding fractional contributions to the total greenhouse effect by

the individual greenhouse contributors. In round numbers, of the total greenhouse effect for the current climate atmosphere, about 50% is directly attributable to water vapor, 25% to clouds, 20% to carbon dioxide, and the remaining 5% due to the minor greenhouse gases, i.e., methane, nitrous oxide, ozone, and chlorofluorocarbons.

5.6 Forcing/feedback significance

The most important conclusion to be drawn from this greenhouse attribution is that the individual radiative flux contributions to the total greenhouse effect can be gainfully subdivided into two separate groups: (1) the thermodynamically inactive non-condensing greenhouse gases (carbon dioxide and the other minor trace gases), which basically remain in the atmosphere once they enter there; and (2) the thermodynamically active condensing species (water vapor and clouds), which evaporate, condense, and precipitate, and thus respond quickly to changes in local temperature and other meteorological conditions. To be sure, the non-condensing greenhouse gases do interact chemically, but these chemical reactions are slow acting processes that result in atmospheric life times ranging from a decade to longer than several centuries. Because of this, the non-condensing greenhouse gases effectively behave as permanent fixtures of the atmosphere, and as such, provide a steady amount of radiative heating that is largely independent of varying meteorological conditions. The condensing species, on the other hand, adjust rapidly to changes in meteorological conditions, behaving as feedback effects that seek to establish the maximum allowable equilibrium concentration in accordance with the background atmospheric temperature structure that is provided by the non-condensing greenhouse gases.

Accordingly, the amount of water vapor that the atmosphere can sustain is temperature dependent, as dictated by the Clausius-Clapeyron equation. Basically, this means that a warmer atmosphere can sustain more water vapor, and a colder atmosphere less. Possession of strong long-wave absorption bands by water vapor make water vapor a strong positive feedback in response to radiative forcing produced by the non-condensing greenhouse gases. Since clouds are closely dependent on the amount of available water vapor, clouds are likewise classified as part of the fast feedback processes, with the added complication that clouds also reflect solar radiation, a cooling effect that offsets the cloud greenhouse effect. From these climate modeling analyses it is clear that the non-condensing greenhouse gases provide the sustaining radiative forcing for the terrestrial greenhouse effect, but that water vapor and clouds, in their role as climate feedbacks, act as amplifiers (by about a factor of four) of the radiative forcing provided by the non-condensing gases.

As further evidence to emphasize this very point, recent climate modeling experiments were performed to demonstrate even more clearly the feedback role of water vapor and clouds in the current climate system (Lacis et al., 2010). In these experiments all of the non-condensing greenhouse gases were set to zero. Without the radiative forcing temperature support by the non-condensing greenhouse gases, excess atmospheric water vapor rapidly condensed and precipitated from the atmosphere, plunging the Earth inevitably toward an ice bound state. This was a clear-cut demonstration that the non-condensing greenhouse gases do indeed control the magnitude of the terrestrial greenhouse effect. Since carbon dioxide is by far the

strongest of the non-condensing greenhouse gases in the atmosphere, the argument can be effectively made that carbon dioxide is indeed the principal control knob that governs the temperature of Earth. This has important consequences and bearing on our understanding of current climate change as well as the changes in climate that have taken place over geological time scales.

5.7 Present-day perspective

It is illuminating to examine the historically recent change in atmospheric carbon dioxide in the broader geological context. The ice core record shows that during the last ice age, when the global temperature was roughly 5°C (9°F) colder than current climate, the atmospheric carbon dioxide was at levels near 180 ppm. In fact, the Vostoc ice core data show four major ice-age cycles during the 420,000 year time span with the carbon dioxide level peaking near 280 ppm during the relatively brief interglacial warm interludes when global temperatures were similar to present day conditions. During the coldest extremes of the ice-age cycle, the carbon dioxide level is seen to drop to its lowest levels near 180 ppm. Hansen has used this geological data to establish an empirically based sensitivity to radiative forcings for the fast-feedback processes of the climate system. In his ice-core data analysis, Hansen finds the terrestrial climate sensitivity to be such that the global surface temperature warms about 3°C per 4 W/m^2 of radiative forcing.

The significance of all this information is becoming ever more clear, pointing to a growing global warming climate crisis. The geological record and climate modeling analyses show that carbon dioxide is indeed the principal control knob, or thermostat, that is instrumental in governing the temperature of Earth through its controlling influence on the terrestrial greenhouse effect.

The inescapable conclusion is that the anthropogenic forcings continue to add onto the growing strength of the terrestrial greenhouse effect. The continuing high rate of increase in atmospheric carbon dioxide is particularly worrisome because the present levels are near 390 ppm, far in excess of the more typical 280 ppm for the interglacial maxima. This raises concern of an approaching a 'tipping point', thought to be about 450 ppm, beyond which the radiative equilibrium of the Earth would no longer be capable of sustaining polar icecaps (Hansen et al., 2007). Moreover, since the atmospheric residence time of carbon dioxide is very long, and measured in centuries, this makes the reduction of atmospheric carbon dioxide a difficult undertaking once a decision is eventually reached to limit or reverse the growth of carbon dioxide emissions.

The present biosphere has not experienced climate under such levels of atmospheric carbon dioxide, so there is cause for concern regarding the survival rate of many species under the impending changes in Earth's climate that are being forced by human industrial activity. Because of the very large heat capacity of the ocean, full impact of these radiative forcings is slow to materialize, raising the false hope that climate change is not serious, and may not even be happening. Such opinions stem from the significant uncertainties in modeling the rate at which the climate is changing. Because of the non-linearities in feedback interactions, there is additional uncertainty in regard to sensitivity of the climate feedbacks that act to determine the magnitude of the eventual change in climate. Still

larger uncertainties abound in modeling the space-time response of the climate system because horizontal energy transports tend to be several orders of magnitude larger than corresponding greenhouse gas radiative forcings that are the ultimate instigators of global climate change.

While there remain legitimate uncertainties regarding the details of time specific, local, and regional global climate change, these uncertainties should not be projected onto the solid evidence that human industrial activity is busy driving Earth's climate into uncharted territory. The atmospheric carbon dioxide control knob is currently being turned at a much faster rate than ever before.

In view of the pivotal role that carbon dioxide plays in governing the global temperature of Earth, a great deal of attention has being focused on obtaining accurate measurements of atmospheric carbon dioxide, and how carbon dioxide has been changing with time. In 1958, Charles Keeling, a research chemist at Scripps Institute in California, began making such high-precision measurements of carbon dioxide and of the other greenhouse gases such as methane and nitrous oxide. These very high precision measurement techniques have been subsequently applied to measuring the gaseous composition of air bubbles trapped in glacial ice, thereby extending knowledge of atmospheric composition over time scales that go back more than 420,000 years, as in the Antarctic Vostoc ice-core data. These ice-core measurements show that the atmospheric concentration of carbon dioxide has increased from its pre-industrial level of 280 parts per million in 1850 to the present value near 390 ppm, and exhibits a steady rate of increase by about 2 ppm per year.

5.8 Future prospects

The problem that we face today, has been described by James Hansen in his book *Storms of my Grandchildren*. The problem is that carbon dioxide is not only the principal thermostat that governs the global temperature of Earth, carbon is also the principal fuel that powers the human civilization. It is expected that at the current rate of fossil fuel use, the critical level of 450 ppm for carbon dioxide will be reached in about thirty years. Clearly, the thermal inertia of the ocean and the polar ice caps is very large, and it would take many centuries for the polar ice to melt. But upon reaching 450 ppm for atmospheric carbon dioxide, the terrestrial climate will be set on a collision course where the Earth will no longer be able to support polar ice caps. And the obvious implication of this is the eventual rise in sea level by some 70 meters, which would inundate most of the land areas where civilization resides.

Fortunately, because of the very large heat capacity of the ocean, there is still some time for humans to react and bring the global warming problem under control. While the radiative forcing attributable to the carbon dioxide that is being added to the atmosphere is felt instantaneously, the surface temperature change associated with this increase in radiative forcing materializes more slowly. Thus, about 40% of the global equilibrium temperature response materializes in about 5 years as the ocean mixed layer warms in response to the applied forcing. As the heat begins to diffuse downward into the deep ocean, about 60% of the total temperature response is reached in about 100 years, with approach to the 100% level taking several thousand years. It should also be noted that the

enhancement of the greenhouse effect by water vapor and cloud feedbacks (the fast feedback processes) is not directly in response to the amount of carbon dioxide in the atmosphere per se, but rather to the change in temperature that is generated by the carbon dioxide increase.

There is also substantial natural variability within the climate system that produces global temperature fluctuations by several tenths of a degree on inter-annual and decadal time scales, including climate system response to the 11-year sunspot cycle. However, all of these temperature fluctuations are relative to a zero reference point, while the steady increase in the strength of the terrestrial greenhouse effect continues unabated. These fluctuations produce random looking changes in global temperature that tend to mask and obscure the steadily increasing global warming signal of carbon dioxide. Perhaps of more immediate concern are the likely prospects for an increase in the weather extremes such as more severe droughts and more severe floods, all fueled by the greater energy that is being added to the hydrological cycle as the global temperature rises and atmospheric water vapor increases. The more menacing future concern is the inevitable rise in sea level.

There is no mistaking the fact that the level of atmospheric carbon dioxide is increasing, and this continued increase causes the strength of the terrestrial greenhouse effect to keep on increasing. Accordingly, there is no viable alternative to counteract the impending effects of global warming except through direct human action to reduce the level of atmospheric carbon dioxide, to control the strength of the terrestrial greenhouse effect which ultimately determines the surface temperature of Earth and the global climate that results therefrom.

5.9 Public perception

Assessing the real cause and the perceived reality of global climate change has become a heated topic in the public discourse, particularly in the United States. Global warming has been denounced as the "greatest hoax ever" by prominent Senators and Congressmen. There are well organized efforts funded by fossil fuel interests to discredit climate science and to promote discord and mistrust in the public mind. The presumed rationale for this anti-climate science crusade by fossil fuel interests is perhaps similar to the reaction of the tobacco industry in response to the linking of deleterious health impacts to smoking. In their thinking, if global warming is determined to be harmful to human interests, the pressure to limit carbon dioxide emissions will be harmful to fossil fuel financial interests. On the other hand, there are environmental groups who already perceive global warming as a brewing environmental disaster that is already happening. They are demanding immediate action to curtail the use of fossil fuels. This brawling has attracted the attention of a broad spectrum of individuals from many different disciplines weighing in with opinions and suggestions as to how best understand what is really happening with global climate.

The terrestrial climate system however is very complex, and is not really amenable to simple analyses and interpretations. So, for example, performing a 'more sophisticated' statistical analysis of the global temperature record will not yield quantitative attribution as the cause of global warming because the existing temperature record is much too short, and there are too many causative factors that are not adequately accounted for that impact the global

temperature. Also, sufficiently precise measurements that would definitively describe what is happening in the climate system are not available. And, there are aspects of the climate system, particularly interactions of the atmosphere with ocean dynamics that give rise to the so-called natural variability that is still not fully understood. All of this provides plenty of room for rampant skepticism to flourish.

There are, nevertheless, some important aspects of the ongoing global climate change that are understandable in fairly simple basic physics terms. Global warming, the steadily increasing component of global climate change, is specifically linked to the growing strength of the greenhouse effect. Thus, it is the greenhouse effect that is at the very center of the global warming controversy, and it is also the component that is most readily understandable in basic physics terms.

6. Conclusion

There is a close analogy to be drawn between the way an ordinary thermostat maintains the temperature of a house, and the way that atmospheric carbon dioxide (and the other minor non-condensing greenhouse gases) control the global temperature of Earth. Atmospheric carbon dioxide performs a role that is similar to that of the house thermostat in setting the equilibrium temperature of the Earth. It differs from the house thermostat in that carbon dioxide itself is a potent greenhouse gas, warming the ground surface by means of the greenhouse effect. It is this sustained warming that enables water vapor and clouds to maintain their atmospheric distributions as the so-called feedback effects that amplify the initial warming provided by the non-condensing greenhouse gases. It is also important to keep in mind that the house thermostat merely turns the furnace on and off, and that the heat capacity of the house requires minutes before the house temperature responds to the thermostat setting. The climate system similarly has a delayed response to forcing.

Within only the past century, the carbon dioxide control knob has been turned sharply upward toward a much hotter global climate. The pre-industrial level of atmospheric carbon dioxide was about 280 ppm, which is representative of the inter-glacial maximum level of atmospheric carbon dioxide. During ice age extremes, the level of carbon dioxide drops to near 180 ppm, for which the global temperature is about 5 °C colder. The rapid recent increase of atmospheric carbon dioxide has been attributed to human industrial activity, primarily due to the burning of fossil fuels has pushed the carbon dioxide level to near the 390 ppm, far beyond the inter-glacial maximum. The climate system is trying to respond to the new setting of the global thermostat, and this response has been the rise in global surface temperature by about 0.2 °C per decade for the past three decades.

It has been suggested that we are well past the 300 to 350 ppm target level for atmospheric carbon dioxide beyond which dangerous anthropogenic interference in the climate system would be expected to exceed the 25% risk tolerance for impending degradation of land and ocean ecosystems, sea level rise, and inevitable disruption of the socio-economic and food-producing infrastructure (Hansen et al., 2008). This prospect of a rising risk of triggering unacceptable environmental consequences makes reduction and control of atmospheric carbon dioxide a serious and pressing issue for humanity, one that is worthy of real-time attention.

The bottom line is that atmospheric carbon dioxide has been a thermostat in regulating the temperature of Earth throughout the entire geological history of Earth. The present-day exceedingly rapid increase in atmospheric carbon dioxide due to human industrial activity is unprecedented in the geological record. It is setting the course for continued inevitable global warming that will eventually melt the polar ice caps to produce a catastrophic sea level rise if left unchecked. The large heat capacity of the ocean provides ample time for humans to forestall a climate disaster. Since humans have been responsible for changing the level of atmospheric carbon dioxide, they are then also in control over the thermostat that controls the global temperature of the Earth. Humans are at a difficult crossroad. Carbon dioxide is the lifeblood of civilization as we know it. It is also the direct cause fueling an impending climate disaster. There is no other viable alternative that will counteract global warming except direct human effort to reduce the atmospheric carbon dioxide level.

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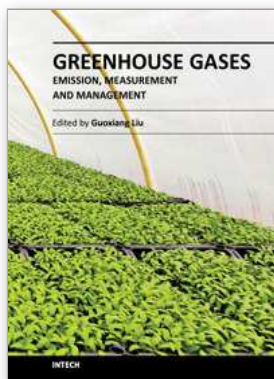
Greenhouse Gases - Emission, Measurement and Management
Edited by Dr Guoxiang Liu

Understanding greenhouse gas sources, emissions, measurements, and management is essential for capture, utilization, reduction, and storage of greenhouse gas, which plays a crucial role in issues such as global warming and climate change. Taking advantage of the authors' experience in greenhouse gases, this book discusses an overview of recently developed techniques, methods, and strategies: - A comprehensive source investigation of greenhouse gases that are emitted from hydrocarbon reservoirs, vehicle transportation, agricultural landscapes, farms, non-cattle confined buildings, and so on. - Recently developed detection and measurement techniques and methods such as photoacoustic spectroscopy, landfill-based carbon dioxide and methane measurement, and miniaturized mass spectrometer.

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