Searching for experimental evidence demonstrating greenhouse gases actually cause global warming

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Global mean surface temperatures warmed >1 ºC since 1950, and warming from 1969 to 1998 may well have been caused by humans, but there are numerous reasons to question whether greenhouse gases can physically be the primary cause. Greenhouse-warming theory has never been verified by experiment, a cornerstone of the scientific method. Terrestrial infrared radiant energy is absorbed into the bonds holding each greenhouse-gas molecule together. Air temperature, however, is proportional to the average translational velocity squared of all air molecules. We assume bond energy is converted by collisions to translational velocity and partitioned among the 2500 other gas molecules to increase air temperature. The efficiency and effects of such conversions have never been determined. This paper describes why experiments are needed and why they are difficult to do.

Nearly all countries in the world committed, under the Paris Agreement (UN, 2017), to work together to reduce greenhouse-gas emissions with the aim of "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels." The problem is that observed increases in atmospheric concentrations of carbon dioxide (CO_2) have never been demonstrated in a scientific experiment to actually cause several degrees of global warming as widely assumed. This is odd. As Steven Chu, Nobel laureate in Physics and former Secretary of Energy, puts it: "In the scientific world … the final arbitrator of any point of view are experiments that seek the unbiased truth." Greenhouse-warming theory is based on several assumptions concerning thermal energy and radiation that have never been demonstrated by experiment. This fundamental breakdown in the scientific method needs to be evaluated and corrected soon. Time is of the essence. Otherwise, trillions of dollars could be wasted.

Greenhouse-warming theory: The Intergovernmental Panel on Climate Change (IPCC) defines the greenhouse effect as: "*The infrared radiative effect of all infrared-absorbing constituents in the atmosphere. Greenhouse gases, clouds, and (to a small extent) aerosols absorb terrestrial radiation emitted by the Earth's surface and elsewhere in the atmosphere. These substances emit infrared radiation in all directions, but, everything else being equal, the net amount emitted to space* *is normally less than would have been emitted in the absence of these absorbers because of the decline of temperature with altitude in the troposphere and the consequent weakening of emission. An increase in the concentration of greenhouse gases increases the magnitude of this effect*" (Planton, 2013). This absorption and re-radiation of terrestrial infrared radiation is thought to cause global warming quantified as climate sensitivity, "*the equilibrium (steady state) change in the annual global mean surface temperature following a doubling of the atmospheric equivalent carbon dioxide concentration"* (Planton, 2013) and thought, "with high confidence", to be in the range of 1.5 to 4.5 °C (IPCC, 2013). Climate scientists calculate climate sensitivity by assuming observed increases in concentrations of greenhouse gases are the primary cause of observed global warming.

The physical link between observed absorption of terrestrial infrared radiation and anticipated climate sensitivity is thought to be provided by one or more of the following five mechanisms:

1. direct heating of air,
2. direct heating of air that slows the rate of heat loss from Earth,
3. re-radiation of absorbed energy that slows the rate of heat loss from Earth,
4. re-radiation of absorbed energy back to Earth where it is absorbed and causes warming of Earth, and
5. climate feedbacks, which are interactions "*in which a perturbation in one climate quantity causes a change in a second, and the change in the second quantity ultimately leads to an additional change in the first*" (Planton, 2013).

This paper examines direct observations and experimental evidence for the effects of carbon dioxide absorbing infrared radiation and for how effective each of these five widely assumed mechanisms is likely to be for producing observed increases in global temperature.

The physical basis for temperature: "*By measuring temperature, we're measuring how fast the atoms in the material are moving*" (Grossman, 2014). According to the kinetic theory of gases, gas temperature is proportional to the average kinetic energy of translation of all molecules, atoms, and electrons making up the gas, where the translational kinetic energy of each constituent is equal to one-half its mass times its translational velocity squared. The hotter the gas, the higher the average translational velocity. Decrease gas temperature towards absolute zero, the velocities of the molecules approach zero.

Temperature of a body of matter, on the other hand, results from a broad continuum of frequencies of oscillation of all bonds holding matter together.

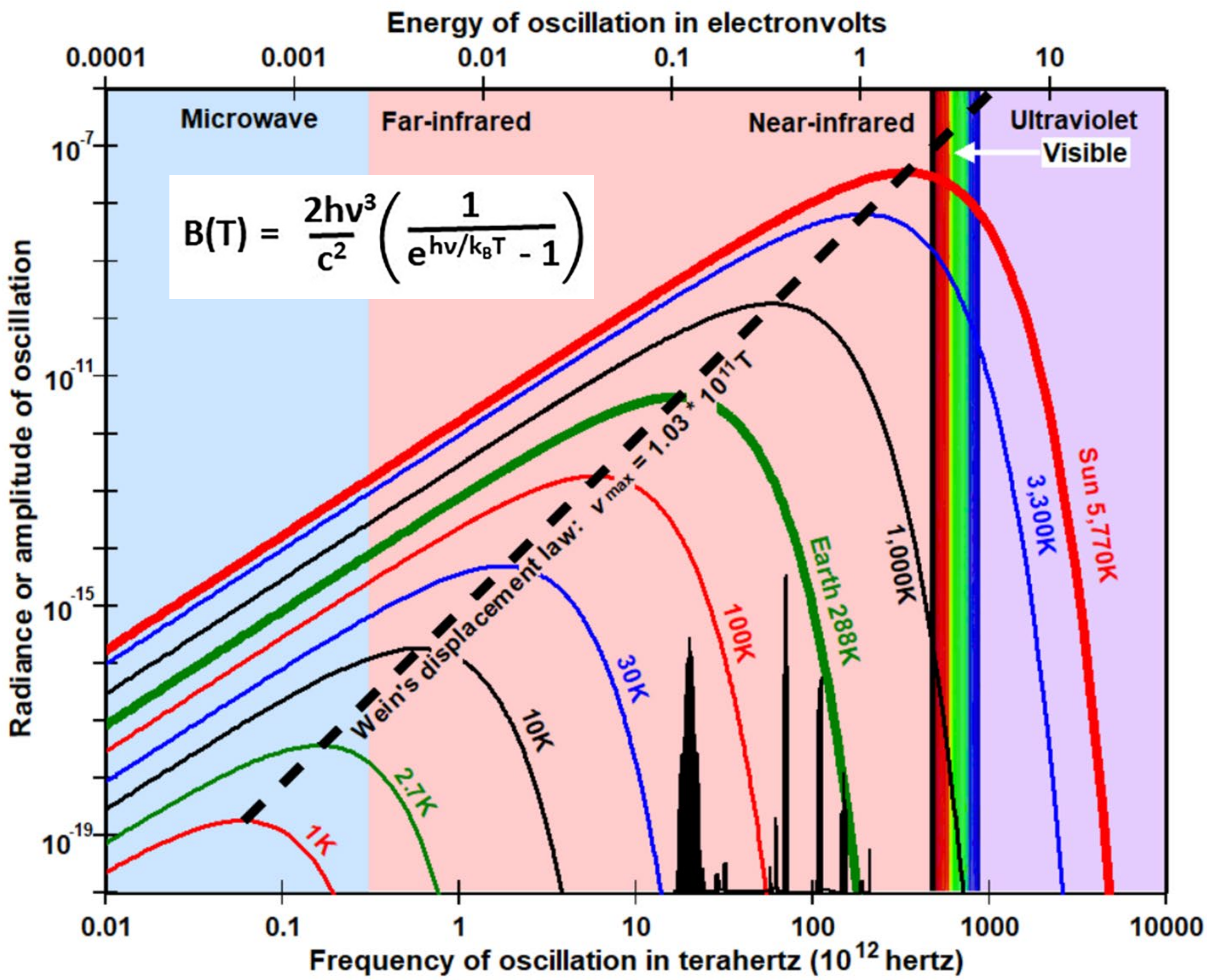

Figure 1. Planck's law describes thermal radiation emitted as a function of temperature by a black body at thermal equilibrium. The vertical black bars show the frequencies of oscillation absorbed by CO_2 as also shown in Figures 2 and 3. Variables are radiance (B), temperature (T), Planck's constant (h), frequency of oscillation (v), velocity of light (c), and the Boltzmann constant (k_B).

Planck (1900) developed empirically an equation describing electromagnetic radiation observed to be emitted by a black body of matter at thermal equilibrium as a function of temperature. Planck's law (Figure 1) shows body temperature determines the physical nature of the body's thermal radiation, consisting of a broad continuum of frequencies of oscillation, each with a unique radiance that increases with increasing temperature. The frequency with the maximum radiance (v_{max}) is also observed to increase as a function of the body's temperature according to Wien's displacement law (dashed black line) where $v_{max}=1.03*10^{11}$ T. Increase temperature of matter, these frequencies and radiances increase. Decrease temperature towards absolute zero, these frequencies and radiances approach zero.

Thermal radiation is thought to be transmitted into air and space by oscillation of all bonds on the surface of radiating matter inducing, by charge-acceleration and/or dipole oscillation, an electric field just above the surface, which induces a magnetic field, which induces an electric field, ad infinitum, forming electromagnetic radiation. Thus, the broad continuum of frequencies and radiances plotted in Figure 1 for observed radiation also shows the broad continuum of frequencies and radiances on the surface of the radiating body. In this way, the electromagnetic field provides the physical means to transmit thermal energy contained in this broad continuum of frequencies and radiances on the surface of matter through air and space via line of sight. Each frequency can be thought of as propagating independently in the same manner as a single-frequency radio signal propagates from transmitter to receiver.

Frequencies are observed to travel galactic distances through air and space without any interaction or change other than Doppler effects, while radiances are observed to decrease proportional to the inverse square of the distance travelled. These frequencies and radiances, when absorbed by matter, increase the frequencies and radiances of the absorbing matter, increasing its temperature to some value that is observed to always be less than or equal to the temperature of the radiating body of matter. The higher the temperature of the radiating body, the higher the maximum temperature to which the absorbing body can be raised.

Note for the Planck equation (Figure 1) that radiance is a function of frequency of oscillation cubed (ν^3). Note that frequencies of oscillation radiated by Earth (thick green line) include a very broad continuum extending in this plot from <0.01 terahertz (trillion cycles per second) to more than 135 terahertz. Note that bodies with higher temperatures are observed to emit much higher frequencies of oscillation than bodies with lower temperatures, and that warmer bodies emit higher radiance than cooler bodies at each and every frequency. The higher the frequencies of oscillation with substantial radiance, the higher the temperature to which the absorbing body can be raised. Temperature in matter, in this way, is a complicated function of a continuum of frequencies of oscillation of the bonds holding matter together.

Visible light has two physical characteristics: color and brightness, which are, within matter, frequency of oscillation and amplitude of oscillation. Traditionally, we think of intensity or brightness as radiance with units including watts because of the way radiance was measured in the late 1800s. As explained in detail in the supporting online materials, however, radiance as measured appears to be a proxy for amplitude of oscillation in picometers on the surface emitting the radiation decreased by one over the square of the distance travelled from the radiating surface. The physical constant or equation converting radiance to amplitude needs to be determined in the laboratory. Meanwhile, I will use the label "amplitude of oscillation" without units to describe the y-axis of Planck's law.

Planck's empirical law thus defines the relationship between temperature of a body of matter and the broad continuum of frequencies of oscillation, each with a specific amplitude of oscillation, that constitutes the physical basis for that temperature. It is very important to realize that, at thermal equilibrium, all frequencies of oscillation with the amplitudes of oscillation shown in Figure 1 must be present in any body of matter for that body to be at that temperature.

Planck's law shows that a body of matter can only be warmed by absorbing radiation from a warmer body with higher amplitudes of oscillation at every frequency of oscillation. No amount of radiation from a body at the same temperature can cause warming. The net thermal energy, the net heat, that must flow to raise the temperature of a body from T_1 to T_2, is most accurately described by the region between the Planck curves for T_1 and T_2, representing a broad continuum of frequencies of oscillation, each with a specific amplitude of oscillation.

Planck's empirical law shows clearly that the maximum temperature to which matter absorbing radiation can be raised is a function of the temperature of the radiating matter, not a function of radiative flux, which is how many joules of radiant energy are absorbed per second per square meter, as currently assumed and calculated under greenhouse-warming theory and in thermodynamics in general. The amount or flux of radiation does determine how long it will take to heat a given body and the difference of flux in minus flux out will determine how hot the body will become, but the Planck distribution of frequencies and amplitudes determines the maximum temperature to which the absorbing body can be raised.

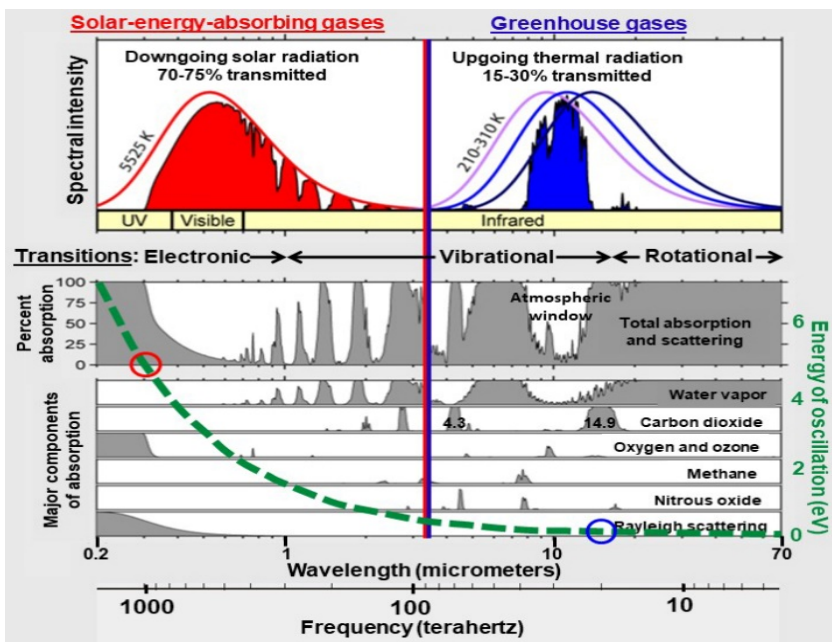

Figure 2. Absorption bands for greenhouse gases in Earth's atmosphere from Rohde (2017).

What radiation is absorbed by greenhouse gases? The gray-shaded areas in Figure 2 show the frequency bands of absorption for key greenhouse gases. Figure 3 shows individual spectral lines of absorption within the major absorption band for CO_2 centered near 14.9 micrometers (Rothman et al., 2013). These spectral lines are clearly observed by spectral physicists to be the resonant frequencies of all normal modes, of all degrees of freedom, of all bonds holding the CO_2 molecule together. Compound gases containing three or more atoms are greenhouse gases precisely because they contain more bonds with many more degrees of freedom, storing more thermal energy than nitrogen, oxygen, and argon making up 99.96% of Earth's dry atmosphere.

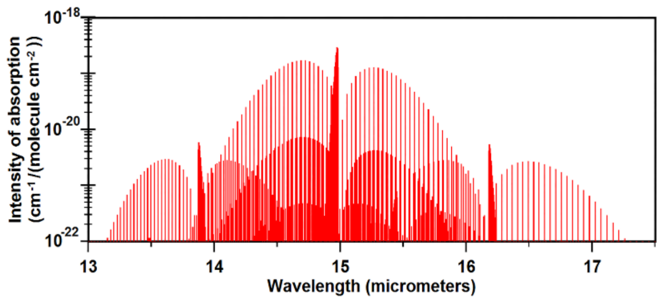

Figure 3. Spectral lines of absorption for CO_2 (Rothman et al., 2013).

The vertical black lines in Figure 1 show these spectral lines of absorption for CO_2. The relative heights of these lines are based on observations, but the absolute height is arbitrary to fit under the green line. Note that CO_2 absorbs only a small percentage of the frequencies radiated by Earth. Ångström (1900) concluded "*it is clear, first, that no more than about 16 percent of [the frequencies making up] earth's radiation can be absorbed by atmospheric carbon dioxide, and secondly, that the total absorption is very little dependent on the changes in the atmospheric carbon dioxide content, as long as it is not smaller than 0.2 of the existing value.*"

If the less than 16% of the frequencies of oscillation contained in terrestrial radiation and absorbed by CO_2 was re-emitted without any loss of energy and was then completely absorbed by a body of matter, it could not heat that matter to the temperature of Earth because a body of matter at thermal equilibrium must possess 100% of the frequencies of oscillation shown under the green line in Figure 1, at the amplitudes of oscillation shown, to be heated to the temperature of Earth. This is an extremely important point. Please read this paragraph again.

Most scientists since Tyndall (1859) have assumed by the conservation of energy that thermal radiant energy absorbed by CO_2 must heat air. Yet thermal radiant energy is clearly observed, by the existence of spectral lines (Figures 2 and 3), to be absorbed into the bonds holding CO_2 molecules together. Temperature of air, as discussed above, is proportional to the average translational kinetic energy with which all the molecules making up air are moving. Conversion of bond energy in small concentrations of CO_2 to translational kinetic energy of all gas molecules has never been demonstrated and quantified in the laboratory. Since CO_2 makes up

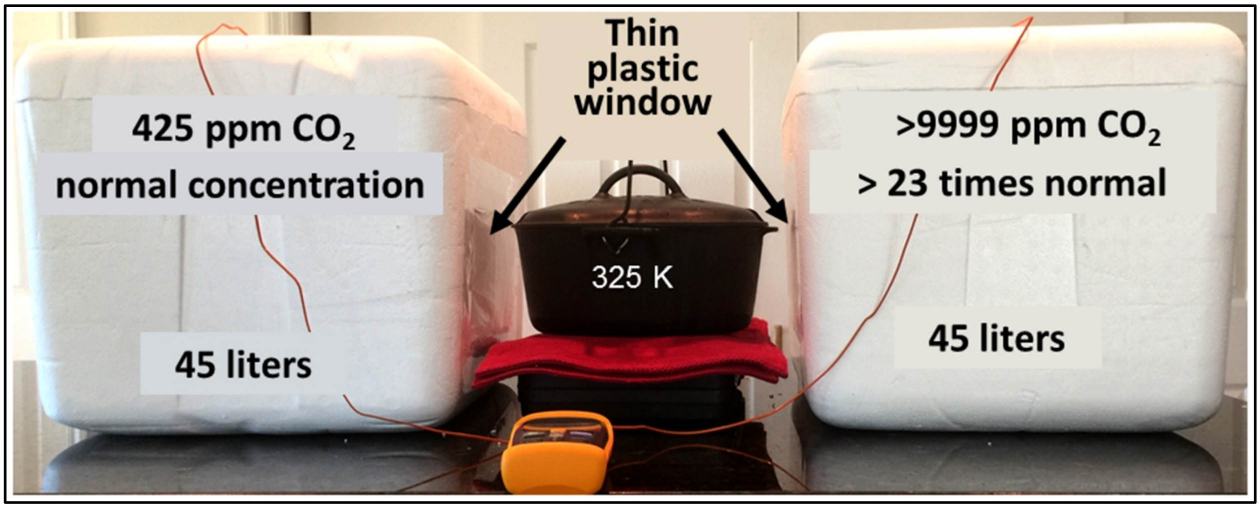

Figure 4. The Styrofoam box on the left contains normal air with 425 ppm CO_2. The box on the right contains more than 9999 ppm CO_2 measured at the end of the experiment. The cast-iron Dutch oven is full of water with the outside surface at 325 Kelvin. The red wires lead to thermistors inserted 2.5 cm below the inside of the top lid.

only 0.04% of all air molecules and CO_2 molecules absorb <16% of the frequencies making up Earth's thermal radiation, even under the most favorable assumptions, the average kinetic energy of all air molecules can only be increased by <0.0064%, which is 0.18 K for a body like Earth at 288 K. Greenhouse gases simply do not absorb enough heat to have a significant effect on global temperatures.

Mechanism 1, direct heating of air: To check these conclusions, I performed an experiment, described in detail in the supporting online materials, comparing

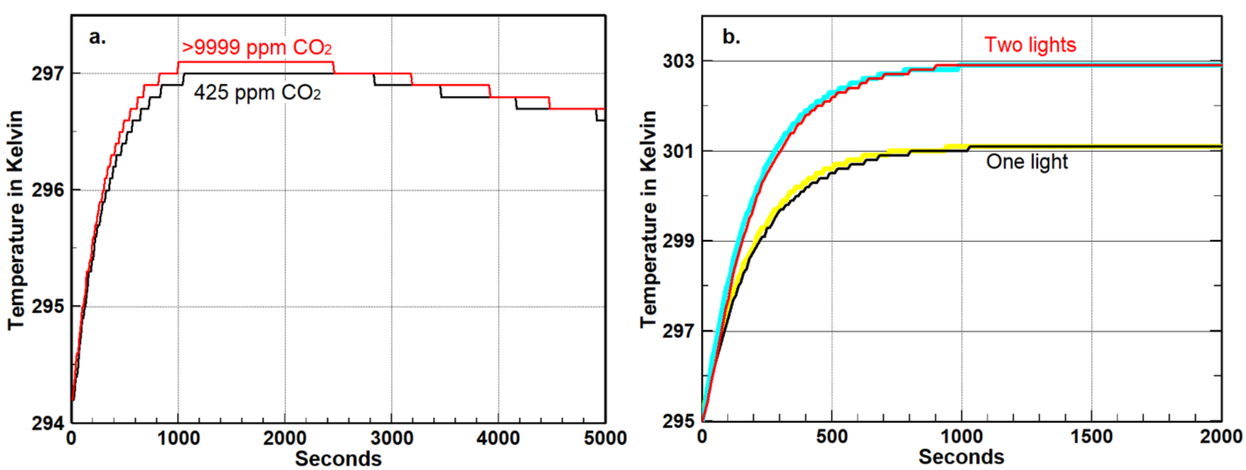

Figure 5a.) The volume of air containing >9999 ppm CO_2 (red line) appeared to warm 0.1 K more than a similar volume of normal air (black line) containing 425 ppm CO_2. b.) Temperature increases rapidly when beginning to warm a metal plate by radiation from a light, but decreases exponentially as it approaches the ultimate temperature.

temperature increase when two different volumes of air, each about 45 liters, contained within insulating Styrofoam containers, were exposed to infrared radiation from a black pot of water at 325 K (Figure 4). One volume on the left consisted of normal air containing 425 ppm CO_2. The second volume on the right contained more than 9999 ppm CO_2, the upper limit of my CO_2 meter. The boundary conditions of both containers are identical and both were warmed by the same heat source at the same time.

The CO_2-rich air (red line, Figure 5a) appeared to warm 0.1 K more than normal air (black line). The resolution of the digital thermometers, however, is 0.1 K and a similar variation of ±0.1 K between the two thermometers was observed when repeating this experiment in many different ways including when heating both volumes of air containing the same normal concentration of CO_2.

Thus, the measurable thermal effect of having far more than 23 times normal amounts of CO_2 absorbing infrared radiation from a black body under these circumstances was <0.1 K.

One can wonder whether the 45-liter volume of air involved is large enough to approximate atmospheric conditions. Since warming is assumed to be caused by increasing concentration and thus density of CO_2 molecules in well-mixed air, temperature increase should be the same for any volume of air.

A much bigger problem is that temperature of the surface of the insulating walls of each container equilibrates very quickly with gas temperature. Thus, it is difficult to measure how much the gas is heated by absorbing infrared radiation and how much the gas is heated by the walls of the container absorbing the remaining infrared radiation. We can assume the walls are more important because temperature increase is normally proportional to thermal energy absorbed, and the walls absorb >86% of the frequencies radiated while the gas absorbs <16% of the frequencies, but it is difficult to prove it experimentally. This is a serious problem with any experiment measuring gas within a container of any size. After all, Earth's atmosphere is heated daily primarily by solar radiation heating Earth's surface, the lower boundary of the atmospheric container.

Mechanism 2, direct heating of air that slows the rate of heat loss from Earth: Even if air were directly heated by an increase in greenhouse-gas concentrations, the rate of heat loss from Earth's surface is observed to be determined primarily by convection caused by differences in density of warm air and cool air. Convection is driven by warm air rising and by warm air moving from the tropics to the poles. The widespread importance of these motions is shown clearly by wind systems, weather systems, and ocean currents. We all know from practical experience that our bodies lose heat much faster standing in a breeze than standing with no wind.

The rate of heat loss is also influenced greatly by water-vapor concentrations and by precipitation. The lapse rate, the rate at which tropospheric temperature is observed to decrease with increasing altitude, is approximately 5 ºC per kilometer for moist air, 9.8 ºC for dry air, averaging closer to 6.5 ºC. Water is the primary absorber of thermal energy in the atmosphere, as shown clearly in Figure 2, and moist air rising and condensing nearly doubles the rate of heat loss.

The fundamental role of resonance: Thermal energy is the oscillation of all bonds holding a body of matter together resulting in the body's temperature (Figure 1). The energy of oscillation (E) of a single frictionless atomic oscillator, a single degree of freedom of a single molecular bond, is defined by the Planck-Einstein relation as equal to the Planck constant (h) times the frequency of oscillation (ν, the Greek letter nu) so that $E=h\nu$. Since h is a constant and frequency of oscillation (ν) is observed to be a broad continuum of frequencies from radio signals to gamma rays (Figures 1 and S1), energy (E) of a large ensemble of atomic oscillators must be a broad continuum of energies of oscillation ($E=h\nu$) explained in more detail by Ward (2016). Thus, thermal energy is clearly not quantized. This is a very surprising observation because $E=h\nu$ is commonly thought to be a quantum of energy, the energy contained in a photon.

Oscillations of atomic and molecular bonds, often modeled as Morse potential energy functions, are frictionless. While the frequency and thus energy of oscillation is increased by increasing temperature and decreased by decreasing temperature, the only way amplitudes of oscillation, intensities of oscillation, can be shared between frictionless oscillators making up bodies of matter is via resonance. This is an extremely important observation. Resonance explains all four laws of thermodynamics and accurately describes how thermal energy is observed to flow physically within matter and via radiation (Figure 5).

Resonance is where two discrete oscillators, oscillating at the same frequency, "share" or average amplitudes of oscillation. In matter, this sharing is the basis for conduction, facilitated by physical contact. In air and space, however, this sharing is done between molecules of matter via line of sight through an electromagnetic field. The oscillator with the highest amplitude of oscillation "gives up" half the difference in amplitude of oscillation to the oscillator with the lower amplitude of oscillation, causing both oscillators to end up with the same amplitude of oscillation. This averaging, due to the way resonance works, results in more energy being transferred when the difference in amplitude of oscillation, which is related to the difference in temperature (Figure 1), is large and very little energy being transferred when the difference in amplitude of oscillation, the difference in temperature, is small.

This averaging of amplitudes of oscillation at the molecular level in bodies of matter is well observed at the macroscopic level as an averaging of temperature of matter. If the physical properties of two bodies of matter are identical except for temperature and they are joined thermally, the resulting temperature at thermal equilibrium will be the average of the two initial temperatures. This averaging can be observed experimentally by shining a bright light on a small piece of black metal in experiment 2 described in the supporting online materials. Temperature rises quickly at first and then much more slowly as the metal approaches its warmest temperature (Figure 5b). The black line shows temperature measured every 10 seconds. The yellow line shows temperature every ten seconds calculated as an increase of five percent of the difference between the previous temperature and the ultimate temperature. Both curves are essentially identical.

Note that the flux of thermal energy, the rate of change of temperature, starts high and decreases exponentially with time, a stepwise averaging explained clearly by resonance. Having two identical light sources doubles the flux of thermal energy available while not changing the simultaneous loss of thermal energy, leading to an increase, but not a doubling of the ultimate temperature (Figure 5b). If the metal plate were not simultaneously losing energy by re-radiation, by convection, and by conduction, its temperature would approach the temperature of the light source (3000 K).

Resonance plays the primary role in absorption of infrared radiation by greenhouse gas molecules. The spectral lines discussed above (Figures 2 and 3) are the resonant frequencies of the molecule. We think of a specific degree of freedom of a specific bond holding a molecule of gas together as resonating with an electromagnetic field, extracting a spectral line of energy. A more precise way to explain the physics at the molecular level appears to be that a specific degree of freedom of a specific bond holding the absorbing molecule together is resonating with a specific oscillator on the surface of the radiating matter via line of sight. Energy only flows from the oscillator with higher amplitude of oscillation to the oscillator with lower amplitude of oscillation at the same frequency, which, as shown in Figure 1, means from higher temperature to lower temperature, a fact so widely observed that it is one form of the second law of thermodynamics.

Amplitude of oscillation in radiation is well observed to decrease inversely proportional to the square of the distance travelled. This can be understood in terms of resonance to result from the reality that rays of light diverge, so that the density of molecular bonds on the surface of the radiating body within line of sight from the resonating bonds on the surface of the absorbing body decreases with the square of distance traveled, meaning fewer bonds can resonate simultaneously, so that the amplitude absorbed must be shared by conduction among more bonds on the surface of the absorbing body.

Mechanism 3, re-radiation of absorbed energy that slows the rate of heat loss from Earth: Central to the greenhouse effect defined above is the widespread assumption that greenhouse-gases “emit infrared radiation in all directions.” The only frequencies that can be re-emitted, however, are those absorbed, which make up <16% of terrestrial radiation (vertical black bars in Figure 1). Furthermore, at temperatures prevalent in Earth’s atmosphere, molecular electronic transitions are not involved. An electronic transition is where an electron is excited into a higher energy level by absorbing radiant energy and the molecule is thought to radiate this energy as the electron returns to its lower energy level. Thus, a molecule of CO_2 gas in Earth’s troposphere is unlikely to spontaneously re-emit radiation.

A molecule of CO_2 can lose amplitude of oscillation by resonance with another oscillator at the same frequency but with a lower amplitude of oscillation. Such a molecule would not be in the direction of Earth, however.

One can also imagine that a layer of air could radiate thermal energy, but air is not a black body—it is not a perfect absorber and emitter of radiation. For air to radiate, the energy radiated must be replaced immediately by absorption for the radiation to continue. This is how the photosphere of Sun and the stratopause of Earth can be radiative surfaces because the heat radiated is immediately replaced from below by heat rising in a positive thermal gradient.

Water vapor, alternatively, absorbs a very broad range of frequencies of oscillation (Figure 2), makes up, on average, 0.1% of atmospheric gases, and reaches high concentrations in clouds. A water molecule on top of a cloud can resonate with a molecule on the photosphere of Sun, warming the cloud. A water molecule near the base of the cloud can resonate with a molecule on Earth’s surface thereby slowing the rate of heat loss from that particular point on Earth. Pointing an infrared thermometer gun into the blue sky, it might read 1 ^{o}C, while pointed at a cloud, it might read 18 ^{o}C (NASA, 2017), showing that a cloud, warmed by Sun, is a radiative surface whose molecules can resonate, can share amplitude with molecules on Earth and on Sun. Radiation downwelling from the atmosphere is measured (Turner et al., 2012), but the specific sources of this radiation have yet to be clearly identified.

Water vapor and precipitation play major roles determining local and regional temperatures on Earth and a warmer climate is likely to evaporate more water vapor into the atmosphere. Long-term changes in average global concentrations of water vapor, however, have not been proposed as a cause for long-term changes in global mean surface temperatures.

Mechanism 4 , re-radiation of absorbed energy back to Earth where it is absorbed and causes warming of Earth: Kiehl and Trenberth (1997), Trenberth and Fasullo (2012) (Figure 6), and Wild et al. (2013) conclude that average flux of downwelling radiation from greenhouse gases in the atmosphere (333 Wm^{-2}) is more than twice the incoming flux of solar radiation absorbed by Earth's surface (161 Wm^{-2}). This does not make physical sense. Radiative flux is the amount of thermal energy that flows per second—the higher the flux, the warmer you feel. We all know by personal experience that radiation from Sun feels much hotter than radiation from clouds in the lower atmosphere, or radiation from the atmosphere when Sun is not in view day or night. Furthermore, assuming such downwelling radiation requires that heat flows from a colder atmosphere to a warmer Earth, breaking the second law of thermodynamics. In addition, radiation from a colder body does not contain high enough amplitudes of oscillation at all frequencies of oscillation to warm a warmer body (Figure 1).

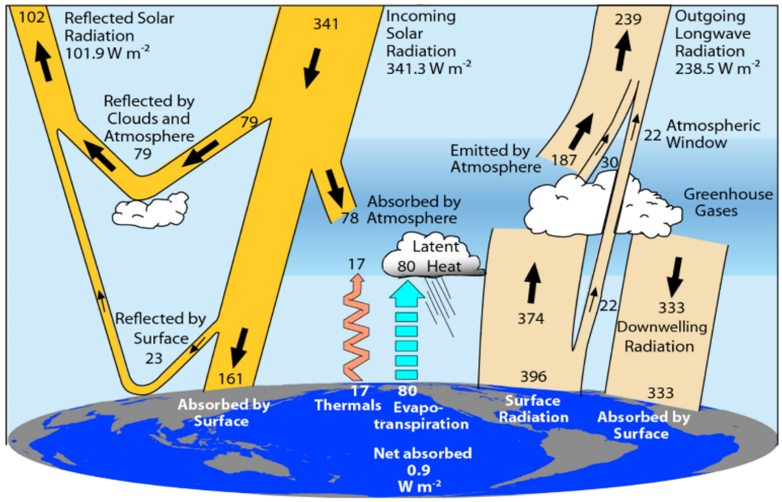

Figure 6. The global annual mean Earth's energy budget for 2000 to 2005 suggesting that observed global warming is the result of the net radiant energy absorbed by Earth (0.9 $W\ m^{-2}$) (Trenberth and Fasullo, 2012).

Mechanism 5, climate feedbacks: Numerous feedbacks thought to amplify greenhouse warming have been proposed including snow and ice albedo, water vapor and lapse rate, clouds, aerosols, carbon sinks, and wetland methane emissions (IPCC, 2013). It is not clear that greenhouse warming is significant as described above, so the importance of these feedbacks must be reevaluated recognizing that thermal energy is a function of a continuum of frequencies of oscillation of the bonds holding matter together (Figure 1). Ultraviolet radiation, for example, has enough energy to sublimate snow, explaining why snow banks on the south side of my house at 6200 feet disappear on sunny days without evidence of water runoff.

Conclusion: Global warming is a problem, but there are now numerous observations and some simple experiments summarized in this paper suggesting that a doubling of greenhouse-gas emissions physically cannot cause observed global warming. These issues need to be resolved soon, before nations spend trillions of dollars reducing greenhouse-gas emissions as urged, for example, by Figueres et al. (2017).

Supporting Online Materials

The electromagnetic spectrum
The y-axis problem with Planck's law
Experiment 1, measuring the direct heating of air
Experiment 2, warming a metal plate with radiation

The electromagnetic spectrum is well observed to be a continuum of frequencies of oscillation extending from very low frequencies used in radio communication to very high frequency gamma rays (Figure S1). Since Maxwell (1865), it has been traditional to think of electromagnetic radiation in terms of waves, calculating a wavelength, which is equal to the velocity of light divided by wave frequency. The concept of wavelength is useful in estimating the length scale of the physical oscillators involved shown at the top of the figure. For example, cone cells in the human retina have lengths on the order of 0.5 micrometers making them resonate

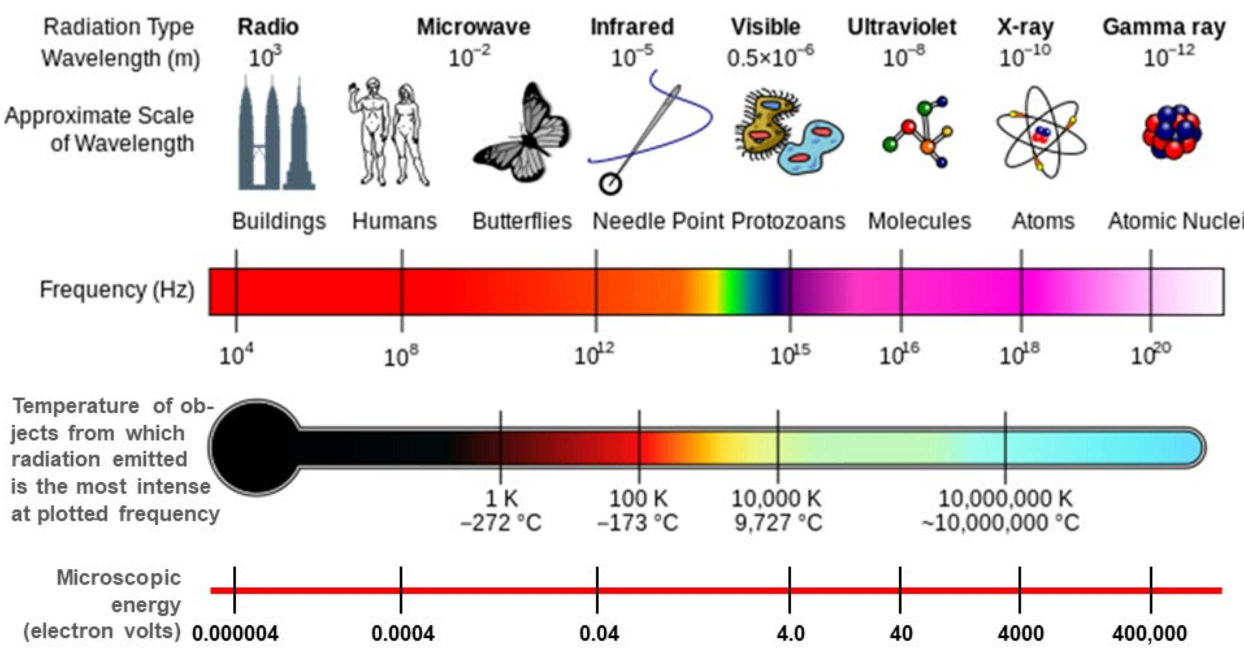

Figure S1. The electromagnetic spectrum extends over at least 14 orders of magnitude of frequency. Energy is equal to the frequency times the Planck constant. The temperature of objects for which the radiation at a given frequency is the most intense similarly increases with frequency and energy.
(Based on commons.wikimedia.org/wiki/File:EM_Spectrum_Properties_edit.svg)

at frequencies of oscillation in the range of 430 to 770 terahertz, the minimum and maximum frequencies of visible light. Gamma rays, the highest frequency, highest energy electromagnetic radiation, can only be formed by oscillations of the tiny bonds within an atomic nucleus.

The y-axis problem with Planck's law: Planck's law (Figure 1) was formulated empirically to explain measurements in the laboratory collected during the 1880s and 1890s by separating the radiation of interest into a rainbow spectrum, using a glass prism for visible and ultraviolet frequencies and a halite prism for infrared frequencies that are not energetic enough to penetrate glass. The scientists then placed a temperature sensor within each narrow spectral band, measuring the increase in temperature of a small piece of mass within the sensor as volts. They were, therefore, measuring the thermal effect of this narrow band of radiation on a small piece of matter. Based on Maxwell's wave theory for radiation, they thought they were measuring the amount of energy required to cause this thermal effect in units including watts per square meter on the y-axis as a function of frequency of oscillation in cycles per second on the x-axis (Figure 1).

Yet energy (E) at the molecular level in both matter and radiation is equal to the Planck constant (h) times frequency of oscillation (ν): $E=h\nu$. Thus, energy should be plotted on an alternative x-axis, the upper x-axis in Figure 1, not on the y-axis. What they were measuring in volts and thinking of as flux in watts was actually a proxy for amplitude of oscillation along a continuum. The fundamental physical properties of frictionless atomic oscillators and the electromagnetic radiation they induce are frequency of oscillation and amplitude of oscillation. Amplitude of oscillation needs to be calibrated experimentally in the laboratory. That is why no units for amplitude of oscillation are shown on the logarithmic y-axis in Figure 1, only orders of magnitude. As shown in Figure 1, macroscopic temperature is determined by a broad continuum of frequencies of oscillation at the molecular level, each with a specific amplitude of oscillation calculated using Planck's law. This continuum of energy at the molecular level is best represented at the macroscopic level by a single number for temperature, the result of all these molecular level energies after the ensemble of oscillations reaches thermal equilibrium.

This same confusion is contained in the Stefan-Boltzmann law (Stefan, 1879), where the total energy (j^*) radiated per unit surface area of a black body across all wavelengths per unit time is thought to equal a constant (σ) times temperature to the fourth power, $j^*=\sigma T^4$, which can be derived by integrating Planck's law. Planck's law and the Stefan-Boltzmann law do not allow for the fact that energy is a function of a continuum of frequencies, and is not a function of bandwidth as currently assumed.

Experiment 1, measuring the direct heating of air: I first took two one gallon (3.8 liter), wide mouth, food-grade plastic jars, inserting a thermistor 2 cm through a small hole in the plastic top of each jar. I filled one jar with normal air containing 425 ppm CO_2 as measured with an Amprobe CO_2-100 carbon dioxide meter and filled the other with CO_2 from a Genuine Innovations G2153 16 gram CO_2 cartridge measuring in the jar, at the end of the experiment, >9999 ppm CO_2, the upper limit of the meter. I put both jars next to a black, cast iron, Dutch oven (30 cm diameter and 10 cm tall) with lid, filled with water and heated to 312 K, measured using an Etekcity Lasergrip 1080 Digital Laser Infrared Thermometer. Both thermistors were monitored using a Fluke 54-2 Dual Input Digital Thermometer with a sensitivity of 0.1 K, logging one sample every ten seconds, with data downloaded to FlukeView Forms software.

No difference in temperatures in the two jars was noted during 90 minutes of recording. I had chosen plastic because infrared does not penetrate glass. I then found that putting the infrared thermometer inside one of these plastic jars and pointing the beam to a surface outside of the jar, the meter read 23.2°C instead of 33.7°C measured without the jar. Clearly some infrared was not penetrating the food-grade plastic jar. Therefore, I took two thin plastic bags used in grocery stores to put vegetables in, checking that the infrared thermometer read the same value through one layer of bag and without the bag. I hung these bags on the thermistor cables in a black enclosure meant to reduce convection surrounding the bags. Still no difference in temperatures measured, but heat was clearly being lost rapidly through the bag surfaces.

I then took two Styrofoam boxes commonly used to ship frozen meats with dry ice (solid CO_2) that each contained about 45 liters of air (inside dimensions 47.6 by 33.7 by 27.9 cm). I cut a hole in one side of each box 27.6 cm wide by 12.7 cm high to match the dimensions of the Dutch oven and glued and taped one-layer thickness of a grocery plastic bag on the outside of each hole to prevent exchange of heat by convection and to keep the CO_2 within the box. I inserted a thermistor through the center of the top of each box, protruding inside 2.5 cm below the Styrofoam with the wire taped on the outside. Placing the boxes as shown in Figure 4 with the Dutch oven at 325 K, the box on the right, containing >9999 ppm CO_2 measured at the end of the experiment, warmed 0.1 K more than the box on the left containing 425 ppm CO_2, reached peak temperature at 1000 seconds, 50 seconds faster, and cooled approximately 400 seconds slower (Figure 5a). Thus, there was a barely detectable thermal effect resulting from having far more than 23 times as much CO_2 absorbing infrared radiation from a close-by black body under these circumstances.

The resolution of the thermometers is 0.1 K, however, and this variation of ±0.1 K in the difference of the two temperatures was observed in every experiment whether both boxed were filled with normal air or either box was filled with CO_2 rich air. I tried this experiment eight times in various configurations with essentially identical results. Clearly there is no evidence that a mere doubling of CO_2 concentration can directly cause degrees of warming of air as considered "highly likely" by the IPCC (2013).

This experiment is deliberately designed to be symmetrical so that the boundary conditions surrounding each body of air are identical. Rapid equilibration of the temperature of the surface of the Styrofoam walls with the gas, however, makes such experiments problematic as discussed in the main paper.

When a CO_2 cartridge is punctured, the gas and the capsule cool rapidly due to the release of pressure. Therefore, I did not start any experiment until the normal air and CO-rich air had reached the same temperature.

Experiment 2, warming a metal plate with radiation: I did nine 30-minute experiments illuminating a 30 by 46 cm, 16-gauge piece of sheet metal, painted flat black, suspended by two very fine wires, with one to four 50W MR16 ESX picture lights placed 90 cm away. The thermistor was bolted to the center of the back side of the plate with a 2-56 bolt and washer. I did an additional twelve 30-minute experiments illuminating a 5-cm-square, 16-gauge piece of sheet metal, painted flat black, held up by the thermistor wire similarly bolted to the center of the back side of the plate (Figure S2). The first of these latter experiments was with plate mounted on the vacuum base, the second with the glass vacuum dome (7.25 inch inside diameter) in place, and the rest with a vacuum of -24 inches of mercury to minimize transfer of heat by convection. All experiments showed warming similar to that plotted in Figure 5b. The 5-cm plate became 1.5 K warmer inside the vacuum dome, with or without a vacuum, rather than in open air. This is interesting given that the glass vacuum dome would inhibit the lower frequency infrared radiation from entering or leaving

Figure S2. Four picture lights shining in a 2-inch square black metal plate inside of a vacuum jar.

the dome. Each light added increased the maximum temperature of the plate approximately 2 K. The purpose of these experiments was simply to examine the logarithmic warming caused by radiation and the effects on the rate of warming and the maximum temperature reached.

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