Quantum Mechanics in Climate Science:
An In-Depth Review of its Incorporation in Analyzing Climate Change and the Quantum Behaviors of Carbon Dioxide

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The identification of effectual climate shifts and their causes are not uncommonly known through biological and chemical analyses (such as examining the effects of climate change on wildlife or studying the basic composition of greenhouse gases in the atmosphere). However, one of the most accurate approaches in attempting to begin to understand and resolve the climate crisis involves an area of study rarely associated with climate change or other environmental problems. Quantum mechanics involves one of the most essential theories in physics that provides an in-depth understanding of the smallest to scale physical properties of nature, such as atoms and subatomic particles. It is an incredibly theoretical and elaborate field that disproves nature is physically as simple as classical physics initially represented it to be. How can such a distinct subject be correlated so perfectly to climate science? Through multiple analyses and detailed research, we can come to a conclusion regarding this connection (Ghil & Lucarini, 2020).

Observed beginning between 1850 and 1900, climate change has posed a threat to environmental and human health. The world runs on fossil fuels and industrial farming techniques that continue to release greenhouse gases into the atmosphere, thus exacerbating the greenhouse effect (NASA, 2021). Although it is a natural process that regulates Earth's surface temperature, too much warming is incredibly harmful. Once solar radiation hits the Earth's atmosphere, some of it reflects back into space, while the rest is absorbed and utilized. Some heat is then radiated back up towards the atmosphere and greenhouse gases begin trapping an efficient amount of heat (enough to sustain life and processes); however, the more greenhouse gases are released, the more heat is trapped, thus causing an unnatural rise in temperature of the Earth's surface. This in turn leads to more environmental problems (natural disasters, pollution, etc.) (Department of Agriculture, Water and the Environment, n.d.).

Climate change continues to be explored through chemical, biological, and physical research. A large portion of the scientific community is confident in their understanding of climate science. Most of the modern research that is conducted has to do with resolutions rather than perception. When physics is incorporated in environmental sciences, it is typically through a classical lens (Busch, 2010) (Ravilious, 2018). However, researchers sometimes fail to incorporate quantum mechanics into climate science, especially in terms of greenhouse gas quantum molecular structure and behavior. An accurate representation of how certain studies in quantum mechanics contribute to climate science can be found through climate models. Climate modeling is a useful tool that we can use in the intervention process that requires accurate quantum mechanical information. General circulation models (GCMs) use systems of equations and mathematical approaches to represent certain environmental patterns or interactions, or climate phenomena (NOAA, 2018). For example, you can find models calculating surface and atmospheric temperatures based on greenhouse gas data (Helmis, 2012).

Since 1750, years before the industrial revolution, the atmospheric concentration of carbon dioxide (CO_2) has increased by 46% (Stein, 2018). Approximately 20% of that rise is just from the past 40 years (U.S. Global Change Research Program, n.d.). Carbon dioxide is one of the most important greenhouse gases found in our atmosphere. It is powerful and effective in trapping heat and radiation. Even a small percentage of atmospheric CO_2 increase can and will worsen the greenhouse effect. Since the 1990s, the increase of greenhouse gases in the atmosphere by human activities created a 45% increase of warming effect (Environmental Protection Agency, 2021).

The surface temperature of the Earth has increased by an average of 0.14 $°F$ over the past decade and approximately 1.8 $°F$ since 1750 (Dahlman, 2021). Temperature change is not uniform throughout the entire world and its surrounding environments. 1.8 $°F$ from the past 270 years may not seem like a big deal, but not only are ecosystems and its organisms sensitive to unnatural temperature changes as so, an average surface increase of 1.5 $°F$ will cause a hotter day to be around 5.4 $°F$ hotter than a typical day, and an average surface increase of 2 $°F$ will cause a hotter day to be 7.2 $°F$ hotter than a typical day (Lieberman, 2021).

Before the industrial revolution, the average pH of the ocean had basic values ranging from 8.2-8.3. Post industrialization, the pH decreased by a mean value of 0.15, roughly a 30% change (Andersen, 2016). The global mean sea level has risen roughly 8-9 inches since the start of the rise in 1880, and nearly 1/3 of that rise took place in the past 25 years (Lindsey, 2020). Ocean acidification negatively affects marine life, which in turn affects our food supply. Rising sea levels increase the risk of natural disaster. It's difficult to statistically calculate the surge of natural disasters throughout the past few decades or so in an accurate way; however, according to meteorology tracking websites, they seem to have increased by a factor of five in the past 50 or so years.

We continue to advance technologically in ways that very clearly and directly benefit us. What do I mean by this and what does this have to do with protection from natural disasters? There are endless convenient ways of telecommunication and alarms used for warnings that can alert citizens even weeks before a disaster strikes, and weather is constantly being monitored in order to ensure safety comes first. This was quick to come about and continues to expand as we rely more and more on technology simply because natural disasters are fear provoking. The average person living in a city can't necessarily see air pollution (until a code orange) or infrared radiation being trapped in the atmosphere and creating heat. They can't see ocean acidification or sea levels rise, and if they could, they wouldn't be sent into a straight state of shock. Hurricanes, tornados, floods and massive storms create an immediate instinctive response, and therefore a larger dedication to monitor in order to put our safety and comfort first. Funny, if we were to be as afraid of every other effect of climate change, ideas for resolutions would come into effect much more rapidly.

Every aspect of life, from the formation of microorganisms to unthinkable technological advances, relies on Earth. Every biological organism and material item has been or can be created because of Earth's natural resources. Because these resources are now depleting, everything we rely on may be gone faster than we may notice. We can compare the climate and atmosphere of other planets to ours to help us better understand the impact of greenhouse gases in the atmosphere. There are countless arguments made by

astrophysicists that communicate how certain studies in physics can solve countless environmental problems. Take for example this article written by Richard D Schwartz (2011), an astrophysicist and professor. “Even within the scientific community there sometimes seems to be a lack of understanding of the physics of greenhouse gas warming, especially among scientists who are not familiar with molecular physics. It is often assumed, especially within the general public, that global warming can be understood by supposition only” (Schwartz, 2011). Greenhouse gases were first understood from a classical physics perspective through absorption and emission of electromagnetic radiation theories, as well as through multiple concepts in thermodynamics. It continued to create a firmer and more proper understanding through the development of quantum mechanics in the 1920s because of accurate calculations of scattering, absorption, and emissions of electromagnetic radiation.

The main goals of this research include studying the optical properties of carbon dioxide, executing a simple climate model described by Harte (1988) to calculate the surface and blackbody temperatures of the Earth in order to understand the impact of the greenhouse effect, analyzing the importance of radiation, waves and photons, and emission/absorption properties of greenhouse gases, as well as studying future quantum technology that can be used to solve the climate crisis. We start off by reviewing the most fundamental parts of climate change, quantum mechanics in climate science, the quantum behaviors of carbon dioxide, and the creation of the climate model as well as its results and what they represent. To conclude, we describe current and future quantum technologies and how we can continue to use quantum mechanics to help solve the climate crisis.

Chapter One

An In-Depth Introduction to Climate Change

1.1 – The Greenhouse Effect

1.1.1 – What is the Greenhouse Effect?

The greenhouse effect is widely known as the main cause of climate change. Our atmosphere is composed of principal gases and gaseous traces, each playing a role in protecting us from harmful radiation and keeping us warm by moderating our climate. It is an imperative process. Without the greenhouse effect, Earth's surface temperature would be approximately -0.4 $°F$. Our atmosphere is composed of 71% nitrogen gas, 21% oxygen, 0.9% argon, and 0.038% carbon dioxide & other trace gases including water vapor (Egger, 2017). These smallest percentages are collectively greenhouse gases; however, even a sliver of a larger percentage composing the atmosphere is incredibly harmful and effective.

1.1.2 – Greenhouse Gases

It is important to note that the majority of sunlight exists in the visible part of the electromagnetic spectrum, the majority of radiation from the earth exists in the infrared part of the spectrum, and that greenhouse gases trap energy because they are transparent to the visible spectrum. Greenhouse gases *such as*carbon dioxide (CO_2), nitrous oxide (N_2O), ozone (O_3), and methane (CH_4) collectively absorb and emit radiation causing an influence on the Earth's climate (Bolin, 1986). These gases trap the sun's reflected infrared radiation (IR) and create heat that remits back to Earth's surface. However, an excess of the process creates too much heat therefore causing climate change and continuous detrimental effects to the environment. We feel infrared light as heat. All objects in the universe with an absolute temperature above zero emit a certain amount of IR, with the most prominent and commonly known emitter being the sun (Lucas, 2019). Most atmospheric gas molecules have a balanced number of positive protons and negative electrons, keeping electrons specific to one side (also known as polarization). Molecules like so tend to rotate and vibrate in a way that allow them to absorb incoming infrared radiation, which is what makes an excess of greenhouse gases so dangerous (Minute Earth, 2015).

1.1.3 – Greenhouse Gases, Photons, and Electrons

If we were to break up sunlight through a prism, there would be visible gaps separating each color of the represented rainbow (Scheire, 2014). These gaps are caused by gases absorbing certain parts of the spectrum. Why does this happen? Atoms and molecules have distinct energy levels available for its electrons. Electrons can't shift to a higher state unless they have access to a specific amount of energy that would enable an electron transition. This energy is obtained from light and the photons that make it up. Each light particle, or photon, also carries a certain amount of energy, which is directly correlated to its color in the visible part of the electromagnetic spectrum. Red light for example has lower energy amounts. Lower energy corresponds with longer wavelengths, and shorter wavelengths correspond with higher energy. Sunlight can emit all the photons of the rainbow, so when the sun emits radiation, gases can absorb a photon with the energy required for an electron transition. Once the connection is made, the absorbed photon disappears, causing a micro gap in the rainbow. Greenhouse gases trap energy because they are transparent to visible light. Most greenhouse gases, such as carbon dioxide, however, don't absorb energy directly from the sun but instead from the surface of the Earth and its emission of infrared light. The majority of radiation from the Earth is in the IR spectrum. Similar to how oxygen gas absorbs red light photons, carbon dioxide and other greenhouse gases absorb infrared photons because it allows them to reach a desired level of energy. As stated before, these gases can reemit these infrared photons back towards the surface and contribute to warming. Any surface cannot keep absorbed energy forever, so it reradiates this radiation at longer wavelengths (or less energy) than how it initially came in (Scheire, 2014).

FIG 1

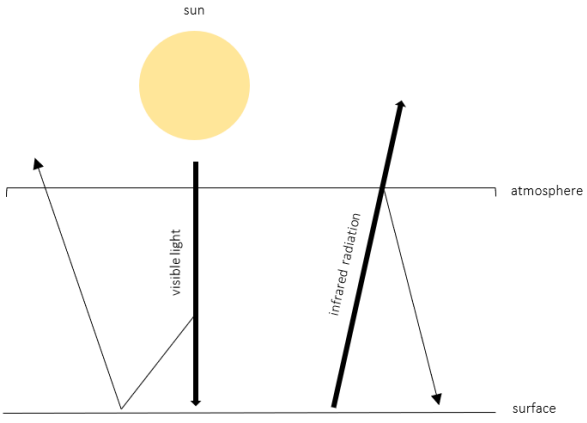


Figure 1 A simple representation of the basic processes of the greenhouse effect. As solar radiation comes in to Earth's surface, some may be reflected back into space, some absorbed and reemitted by the atmosphere, and some simply absorbed by the Earth's surface and converted to heat.

1.2– The Harm Done

1.2.1 - Introduction

According to continuous studies, the average surface temperature of the Earth has increased by an average of 0.14 $°F$ over the past decade (Dahlman, 2021). This warming mainly takes place in our lower atmosphere closest to our surface, in our oceans, and in the cryosphere. The increase in our average surface temperature is however only a small implication of climate change.

1.2.2 – Ocean Acidification

Ocean acidification, a reduction in carbonate and pH imbalance in seawater, is also a major consequence of climate change. If you were to add carbon dioxide to water, the pH would decrease drastically enough to cause the water to become incredibly acidic. Carbon dioxide and water combine to form carbonic acid. It can dissociate into bicarbonate by losing a hydrogen ion and dissociate *again*by losing a second hydrogen ion, creating carbonate (Andersen, 2016). PH is the -log[H^+], meaning the more hydrogen ions in a solution, the lower the pH will be. So, if we were to continue to add CO_2, because the reaction is reversible, it will continue to add hydrogen ions and therefore increase the acidity (Andersen, 2016). The lower the pH value, the more acidic. Using this simple experiment, we can compare it to marine life and how they're affected by CO_2 entering waterways. This life is balanced by proteins (of which require a specific pH). The creation of new molecules, such as calcium carbonate from combining calcium in the ocean with the dissociated carbonate resulting from carbonic acid, will break down and therefore effect coral reefs and other systems in the ocean. Ocean acidification continues to affect food chains and marine life, therefore in turn affecting food supply to humans (Andersen, 2016). Marine life slowly ends up becoming toxic from an increase in algal blooms, and therefore eventually becomes unsafe to eat (NCCARF, 2017). When our food supply is threatened, we instinctively jump to find resolutions for our sakes. Unfortunately, these resolutions are harmful to the environment. For example, factory farming techniques are now used for the mass production of meat.

1.2.3 – Rising Sea Levels and Natural Disasters

Rising sea levels is also a commonly known issue caused by and involved in climate change, and also negatively impacts marine life and ecosystems. Glaciers continue to melt and contribute to the sea level rise. It creates erosion and increases the likelihood of natural disasters, such as flooding, to occur (Lindsey, 2020).

1.2.4 – Environmental Health

One of the more concerning effects of climate change relates to human health. Our physical bodies are evolutionarily not used to or comfortable with temperature changes. When we're sick, our body becomes slightly warmer, and even a few degrees down is a depiction of hypothermia. Heat waves are not necessarily caused by climate change itself; however, the number of phenomena has increased because of it. Thermal stress can be so severe that it can lead to death, especially when a body is already attempting to heal and handle a pre-existing underlying condition or infection. Air pollution, the contamination of the natural surrounding environment, is more directly related to health conditions and has a slower continuous effect. An important and underrated uprise has to do with infectious diseases. Changes in weather and temperature affects all living organisms. Mosquitos, fleas, rats, and other disease carrying pests are more sensitive and prone to spreading viruses and diseases when changes to their environment take place (Haines, 2004). Several other factors contribute to health-related issues caused by climate change, such as malnutrition, increased allergies, water-related diseases, and so on (Haines, 2004).

1.2.5 – The Consequences

The negative outcomes of climate change may be compounded by one another. Every consequence creates another, and eventually continues to harm vegetation, wildlife, insects, ecosystems, and in turn, humans. As organisms, we adapt in order to survive environmental changes as wildlife does. There is, however, a limit to adaptation. Any single-celled life form reacts to its surroundings, whether it's in a negative or positive way, and every outcome of climate change fabricates a negative reaction. An increase in natural disasters, heat waves, rising sea levels, ocean acidification, and an unnatural rise in surface and water temperatures are all continuous contributing factors in the effective downfall of the Earth rooted by

climate change. Other common indirect outcomes include an increase in invasive species, ocean oxygen levels decreasing (which in turn lead to dead zones, areas of low oxygen induced water where aquatic life is not supported), loss of biodiversity and overall protective habitats, extinction increase, and economic/ corporate damage (Buis, 2020).

Chapter Two

Quantum Mechanical Incorporations in Climate Science

2.1 – A Fundamental Review of Quantum Physics

Quantum physics involves the study of matter and energy using probabilistic tools. It is most commonly used to detect certain properties and behaviors of the smallest to scale parts of nature, such as subatomic particles. In doing so, we have the ability to uncover more information than we initially could from a classical perspective. It is a fairly new field of study. One of the first experimental observations that demonstrated the limitations of classical physics involved the discovery of atoms. From this, we discovered photons, electrons, and other subatomic particles. Some of the most central concepts in quantum include: wave-particle duality, which expresses that quantum-scale objects cannot be fully described as simply a particle or wave; superposition, used to describe how an object can be in multiple different states at one time (meaning if something is solely based on probability, the general state must be a combination of all these states, like Schrödinger's cat); the uncertainty principle, a mathematical concept that describes how two different properties of an object cannot be known at the same time; and finally, entanglement, when two or more objects are connected, no matter how far apart (Caltech, n.d.). These topics are complicated and require many more details to understand, but this research doesn't necessarily involve these concepts. They are however some of the most important concepts in quantum, leading quantum research further and creating new ideas along the way. This is predominant because our use of materials, new technology, and research all rely on quantum discoveries. For example, lasers, transistors, and the understanding of space and time theories are all possible because of these discoveries.

Surprisingly, another research topic that can utilize principles of quantum mechanics for a more precise evaluation is climate change. Most research techniques used in climate science involve the evaluation of chemical and biological properties of greenhouse gases, the impacts climate change has on ecosystems, and statistics. The greenhouse gas effect also tends to be portrayed in a classical way, as exhibited throughout chapter one. An incredibly necessary approach to climate science research involves fundamental parts of quantum mechanics, such as determining blackbody, surface, and atmospheric temperature values through the Stefan-Boltzmann law, determining behaviors of greenhouse gases in our atmosphere on a quantum level, and explaining the greenhouse effect in precise detail (including through radiation, wavelength values, and absorption and emission properties.).

2.1.1 – Waves & Photons

Electromagnetic radiation can be described using wave or particle language. Similar to how we understand other behaviors of nature, we take the simplest approach, as long as it's consistent with accuracy. Photons carry energy, angular momentum, and linear momentum. Although in classical terms we understand that momentum is equal to mass times velocity, in quantum terms, we know that this isn't always the case. Momentum is a property that may or may not exist based on the mass and velocity of something. So, someone who only understands classical physics may be confused when we state that a photon is massless despite carrying angular and linear momentum. On the other hand, waves are much simpler to understand than photons, characterized by frequency and direction (Bohren, 2006).

2.1.2 – Stefan-Boltzmann Law

The Stefan-Boltzmann law states that radiation energy of a blackbody is equal to a constant multiplied by a thermodynamic temperature to the fourth power. It is derived from the Planck distribution. Below is a step-by-step representation of the derivation. Most of the derivation was inspired by Lawrence T Sein Jr (2020). All variables used in the derivation are defined to the right.

$$E = aT^4$$

$$a = \frac{4\sigma}{c}$$

$$dE = \frac{8\pi hc}{\lambda^5} \frac{d\lambda}{e^{\frac{hc}{\lambda kT}} - 1}$$

E: Radiation energy of a blackbody
a: An undefined constant
T: Temperature
c: Speed of light (3.0×10^8 m/s)
h: Planck's constant (6.63×10^{-34} J s)
k: Boltzmann constant (1.38×10^{-23} m^2kg/s^2K)

We then integrate lambda from zero to infinity (all possible wavelength values)

$$E = \int_0^\infty \frac{8\pi hc}{\lambda^5} \frac{d\lambda}{e^{\frac{hc}{\lambda kT}} - 1}$$

To keep things cleaner, we need to make a substitution

$$\frac{1}{x} = \frac{hc}{\lambda kT}$$

or

$$x = \frac{\lambda kT}{hc}$$

We need to know that:

$$\frac{1}{\lambda} = \frac{kT}{hcx}$$

meaning:

$$\frac{1}{\lambda^5} = \frac{k^5T^5}{h^5c^5x^5}$$

$$dx = \frac{kT}{hc}\,d\lambda$$

$$d\lambda = \frac{hc}{kT}\,dx$$

Apply substitutions to our integration equation.

$$E = \int_0^\infty \frac{8\pi hck^5T^5}{h^5c^5x^5} \frac{\frac{hc}{kT}\,dx}{e^{\frac{hc}{\lambda kT}} - 1}$$

Pull out constants.

$$E = \frac{8\pi hck^5T^5}{h^5c^5}\left(\frac{hc}{kT}\right)\int_0^\infty \frac{dx}{x^5(e^{\frac{1}{x}} - 1)}$$

Simplify.

$$E = \frac{8\pi k^4T^4}{h^3c^3}\left(\frac{\pi^4}{15}\right) = \frac{8\pi^5k^4T^4}{15h^3c^3} = aT^4$$

Solve for the constant a.

$$a = \frac{8\pi^5 k^4}{15h^3c^3} = \frac{4\sigma}{c}$$

$$\sigma = \frac{2\pi^5 k^4}{15c^2h^3}$$

(Sein, 2020)

This is an example of how to derive a value for the Stefan-Boltzmann constant (σ). The Stefan-Boltzmann constant is valued at approximately 5.67 x 10^{-8}W/m ^{2}K^4.

2.2 – The Basics of Mechanical Methods in Climate Science

In 1887, Heinrich Hertz discovered the photoelectric effect. The photoelectric effect tells us that electrons are emitted from a surface when light is shined onto it. The electrons emitted in this manner are known as photoelectrons. Through this, we were able to discover new understandings of the quantum nature of light and electrons (which in turn also formed the concept of wave-particle duality). Electrons, however, had not been discovered yet at this time. It instead was observed that when an ultraviolet light was shined onto a metal surface with a circuit, electric currents were produced. By the 20th century, it was confirmed that a change of frequency, or the color of the light, increased the energy of the individual photoelectrons but was not dependent of the intensity of the radiation, or brightness of the light. Instead, the current created was dependent on the light's intensity. At the time of these observations, light was known to be composed of waves. Energy carried by a wave does not depend on the frequency of the wave, so the frequency dependance of the photoelectron's energies did not make any sense.
Finally, in 1905, Albert Einstein solved the contradiction by representing light as composed by photons rather than waves (Boundless Physics, n.d.).
The photoelectric effect also in turn tells us that the energy from the light being shined onto the metal plate is absorbed by the electrons in the plate, which gives them the capability to escape. However, the electrons don't always absorb the energy from the light coming in. When the energy and frequency coming in is below a certain level, not enough electrons will absorb said energy to create a current (Ghose, 2015).

Why is this? The energy hitting the surface doesn't flow in in a continuous manner. Instead, it is absorbed in packages of energy, or photons (quantized light). This is exactly what Albert Einstein had discovered. As time went on and experiments continued, the idea of quantized energy also began to show up in matter. For example, CO_2vibrates and rotates, and we can calculate the energies that correspond to these behaviors thanks to quantum physics. This will be explained more in depth in chapter three. For now, we can know that many of these energetic states match with infrared radiation absorbed by these molecules. Greenhouse gases however don't have quantized energies that match with most visible light wavelengths, so it passes straight through, later reemitting it as infrared radiation and allowing greenhouse molecules to absorb said radiation. Quantum physics can also be applied to new concepts to help better the planet, which will also be discussed in chapter five. (Ghose, 2015).

An important relationship we need to understand for radiation through our studies, as well as to create our climate model, is the Stefan-Boltzmann law. In 1879, Stefan conducted an experiment where he found that at a given temperature, the energy radiated by a body could be integrated to find that the total energy is proportional to the temperature held at a power of four multiplied by $5.67 \times 10^{-8} W/m^2K^4$, now known as the Stefan-Boltzmann constant (2.2.1). This constant is what was derived in the last section (Encyclopedia Britannica, n.d.).

$$E = \sigma T^4 \quad (2.2.1)$$

2.2.1 – Radiative Equilibrium

Consider two uniform slabs aligned with one another with one at a fair distance from the other on top. The temperature of the top slab is labelled as T_t, and the temperature of the bottom slab as T_b. The bottom slab is assumed to be a blackbody, and the radiation it emits is absorbed by the top slab. The absorptivity coefficient for this is α. The emissivity (ε) of the top slab is assumed to be equal to α, considering the temperatures of the two slabs are equal. The top slab should not reflect the radiation emitted by the bottom slab, so its transmissivity (τ), the fraction of radiation transmitted, is $1 – \varepsilon = 1 – \alpha$. The variable S represents irradiance (the flux of radiant energy onto a surface per unit area), and it comes into play with the source of radiation coming from up above of which the top slab is also transparent to. If this system is in radiative equilibrium (the radiation entering the system is equal to the radiation exiting the system), the irradiance must be equal to the radiation emitted by the bottom slab plus the radiation emitted by the top slab. This is represented by equation 2.2.2. When a radiative energy balance is applied to the top slab, we get equation 2.2.3. When solving the equations for a function for T_b, we get equation 2.2.4, and because $\alpha = \varepsilon = 1 – \tau$, we can reformat it as equation 2.2.5. This simple system is a representation of Earth from the surface to its atmosphere. The top slab represents our atmosphere, while the bottom slab represents Earth's surface. The solar radiation reemitted by Earth's surface is $S_0\pi R_e^2$, where R_e is Earth's radius. In order to have a more accurate understanding of solar irradiance, we need to include Earth's albedo. With albedo included, the equation we yield for an average net solar radiant energy input to Earth is equation 2.2.6, and we end up getting a value of 240 W/m^2.

$$S = \sigma T_b^4(1-\varepsilon) + \varepsilon T_t^4 \quad (2.2.2)$$

$$2\varepsilon\sigma T_t^4 = \alpha\sigma T_b^4 = \varepsilon\sigma T_b^4 \quad (2.2.3)$$

$$T_b^4 = \frac{S}{\sigma(1-\frac{\varepsilon}{2})} \quad (2.2.4)$$

$$T_b^4 = \frac{2S}{\sigma(1+\tau)} \quad (2.2.5)$$

These equations are important to understand because there can be no such thing as*the* singular average temperature of the Earth. What I mean when I say "average" is rather a collection of temperatures in the troposphere (lowest layer of the atmosphere, discussed later in section 2.3). Based on this, all we know for a fact is that T_b is the temperature of a slab that absorbs around 240 W/m^{2}of radiant energy at radiative equilibrium, and above it is another slab that does *not* absorb solar radiant energy but rather has an emissivity value of 0.8. This system is an incredibly basic representation of why climate change gets increasingly worse with time. For example, it shows us that ε is not constant, but rather increases with the increase of infrared powered greenhouse gases in the atmosphere, such as carbon dioxide and water vapor. Equation 2.2.5 represents that as the transmissivity of the atmosphere decreases, the radiative equilibrium surface temperature increases (Bohren, 2006). Equation 2.2.4, although just a different version of equation 2.2.5, rather represents the increase of emission as the cause for global warming. This representation, although similar to the other, is more straightforward. Equation 2.2.5 interprets the atmosphere as layers of air that just prevents something from happening, such as too large of harmful radiation entering our system, whereas equation 2.2.4 interprets the atmosphere as actually emitting. There is however a major issue with this model. Our atmosphere cannot possibly be represented by a single slab – not only because it is composed of multiple layers, but also, because it doesn't allow us to have an accurate calculation of the effect that putting extra infrared absorbing gases into the atmosphere would have on Earth's surface temperature (Bohren, 2006). We therefore need to consider a set of *n*slabs of which are transparent to incident shortwave radiation (other than the bottom slab) and can absorb all longwave radiation. When we do so, we get an equation that of 2.2.6.

(2.2.6) $$S = \sigma T_N^4, 2\sigma T_N^4 = \sigma T_{N-1}^4, 2\sigma T_{N-1}^4,\ \sigma T_{N-2}^4, 2\sigma T_{N-2}^4, \ldots$$

2.3 – Our Atmosphere

Earth's atmosphere is a thin barrier of air consisting of multiple layers with different temperature values. It protects us from harmful radiation, regulates the air that we breathe and that plants use to build nutrients for growth, and provides us with important cycles, such as rain. The layers of our atmosphere are as follows: the troposphere, the first and lowest layer where weather changes take place, and the most important layer regarding oxygen levels; the stratosphere, which goes about 50 km above ground and contains the ozone layer; the mesosphere, the middle layer that meteors typical break down in before having the capability of reaching the surface of the Earth; the thermosphere, the second to last layer, reaching up to 1,000 km above the surface and protecting us from the ultraviolet radiation and x-rays coming from the sun; and lastly, the exosphere, which also defends us from the sun's rays (Čirjak, 2020).

One of the most prominent greenhouse gases in our atmosphere is carbon dioxide. When sunlight reaches the surface of our Earth, some of it is reradiated as infrared blackbody radiation. If our atmosphere's composition consisted only of oxygen and nitrogen gas, all the blackbody radiation emitted would go right back into space. Our atmosphere is however 78% nitrogen, 21% oxygen, 0.9% argon, and 0.038% carbon dioxide, including other gas traces and water vapor (Egger, 2017). Water is an incredibly important aspect of our atmosphere. It exists as all three phases: liquid, solid, and gas. Water vapor, for example, can change its phase by emission or absorption of heat, such as condensation into clouds and rain.

The composition of the Earth's atmosphere experiences changes starting about 25 km up from the surface of the Earth. It is mostly affected by the sun's ultraviolet radiation. Two of the most important gases in our atmosphere, nitrogen and oxygen, are affected by this, causing them to break up which leads to the formation of ozone in the stratosphere and atoms/ions in the mesosphere and above. According to geological history studies, Earth's atmosphere used to also be composed of lighter gases, such as hydrogen and helium. According to Maxwell's law of distribution of velocities, all molecules in a gas will not move with the same velocity, meaning some molecules exceed the velocity of escape and therefore do so (Saha, 2008). Molecular loss increases with higher temperatures and lower molecular weight, so we can conclude that as the Earth's atmospheric temperatures started to increase, these lighter gases started to escape the atmosphere.

2.4 – Fundamentals of Radiation and its Interactions with the Earth's Atmosphere and Surface

Radiation is a unique process of energy transfer. Electromagnetic waves emitted by the atoms inside a hot body transmit energy. The quantum theory tells us that energy from a hot body is radiated in quanta through electronic transitions in an atom or the vibration/rotation of atoms/molecules (Saha, 2008). In electronic transitions, the energy difference between two quantized energy states is in conjunction with the energy of the emitted radiation, meaning that when an electron in an orbit jumps from a higher energy state to a lower one, the calculated energy difference comes out as electromagnetic radiation that travels at the velocity of light. This energy travels in waves. This concept is where equation 2.4.1 represented to the right comes from. E is the energy of the radiation emitted, λ is the wavelength of the radiation emitted, c is the velocity of light valued at approximately 3.0 x 10^{8}m/s, and h is Planck's constant valued at 6.62 x 10^{-34} J s. This equation can be derived simply from the Planck relation (equation 2.4.2 listed to the right), where ν is wave frequency (Saha, 2008). These equations are relevant for our future comparisons. Equation 2.4.3 is described in section 2.4.2.

(2.4.1) $$E = \frac{(c)(h)}{\lambda}$$

(2.4.2) $$E = (\nu)(h)$$

(2.4.3) $$E_\lambda / A_\lambda = f(\lambda, T)$$

2.4.1 – Radiation, Energy Levels, and Light

Inside an atom or molecule, the transitions between energy states occur from one energy level to an opposite energy level when radiation is absorbed. According to certain laws in the quantum theory, the absorption may only occur on the condition that the radiation's energy equals the difference in energy of any two quantum states. Otherwise, the radiation may simply pass through the body. It can however absorb the radiation if the energy is high enough to knock an electron off from its atom, leaving the atom in an ionized state. Some of the most important properties of radiation relate to certain properties of light. For example, radiation travels in straight lines at 3.0×10^8 m/s, as does light. According to the inverse square law, the intensity of radiation correlates to distance, as does light. Radiation's energy may be reflected or absorbed when fallen on matter, like that of light's (Saha, 2008). Based on these similarities, we can conclude that radiation is just a demonstrative term for heat energy.

2.4.2 – Emission and Absorption of Radiation

As stated in section 2.4.1, gases may only absorb radiation on the condition that its energy equals the difference of the energy of any two quantum states, or if the energy is high enough to knock an electron off from its atom. There are multiple important laws relating to the emission and absorption properties and behaviors of radiation. Kirchhoff discovered the idea for equation 2.4.3. This is a relationship where the absorptive power, $A_{\lambda,}$ the temperature T, wavelength λ, and emissive power E_{λ}correlate to one another in order to represent that the body may be transparent to radiation of a certain wavelength and not emit radiation of that wavelength but can however absorb radiation of different wavelength values as well as emit them. This is known as selective absorption and emission of radiation and is common behavior of several atmospheric gases. For example, water vapor will almost never absorb short-wave solar radiation but will instead absorb greatly long-wave radiation emitted by the Earth's surface (Saha, 2008).
Certain black body laws represent that there is a limit to the amount of radiation that a body can emit depending on the temperature and wavelength values. When a body can absorb every wavelength of radiation that is on it, it is known as a black body. Our sun is a black body, meaning it is a great absorber, which also always makes a body a great emitter of radiation. It is also important to understand Wien's displacement law. Wien discovered that radiated energy when at a maximum value has a specific wavelength at a given temperature T (Saha, 2008). The displacement law is $\lambda_m T$, valued at approximately 2,900 μK.

2.4.3 – Our Sun and its Basic Radiation Properties

Our sun, located at the center of our solar system, is a G-2 class dwarf star with a surface temperature of approximately 5,778 K. It constantly emits radiation and energy in all different directions. High frequency radiation that forms in the inside of the sun is emitted from the photosphere, the outermost layer. Most of the electromagnetic radiation emitted by the sun includes ultraviolet, visible, and infrared rays, although every part of the electromagnetic spectrum is emitted. An important aspect of our set of equations formed later on is known as Earth's albedo. In this case, the albedo is the amount of solar radiation reflected off of the surface of the Earth. Our current knowledge of the albedo is valued at an average of 0.3, meaning approximately 30% of solar radiation on Earth is immediately reemitted back into space by the surface.

2.4.4 – Radiation in Earth's Atmosphere

Ultraviolet, infrared, and visible radiation are the main forms of solar radiation found in the atmosphere. Any radiation that is not absorbed by the atmosphere or bounced back into space reaches the Earth's surface. The greenhouse effect is largely caused by the temperature decrease with altitude in the troposphere. Greenhouse gases active in the atmosphere absorb radiation emitted by warmer surfaces and tends to reemit radiation at colder atmospheric temperatures (Brasseur, 1999).

Chapter Three

Quantum Behaviors of Carbon Dioxide

3.1 – Understanding CO_2Through Quantum Mechanics

3.1.1 – Carbon Dioxide

Carbon dioxide is a well-recognized greenhouse gas whose concentration in the atmosphere continues to steadily increase (Gates, 1993). It is emitted from natural sources such as volcanoes, animals and plants, but also from man-made sources, such as power plants and industrial farms (The Trustees of the National History Museum, n.d.).We are focusing on carbon dioxide in this research because although it is not the most powerful greenhouse gas in the atmosphere (as compared to water vapor), it is the most prominent in the sense that technology being created to fight climate change is designed to reduce the output of CO_2. These new technologies will also be discussed further into the research.

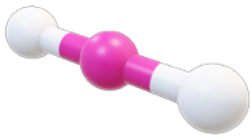
3.1.2 – Absorption Properties of CO_2

Absorption properties are affected by temperature, concentration of emission, and wavelength values of incoming photons. It is important to understand that carbon dioxide has absorption bands of 15, 4.3, 2.7, and 2 μm (Wei, 2018). Absorption bands are defined as energies, frequencies, or different wavelength values in the electromagnetic spectrum that can represent what wavelength a particle is most likely to absorb. For example, in our case, carbon dioxide will *not* absorb infrared radiation in the range of 8-12 microns and will instead most likely absorb radiation valued at 2, 2.7, 4.3, or 15 microns. In order to determine an absorption spectrum, we can, in this case, irradiate CO_2 with infrared light (Anton Parr, 2022). CO_2 undergoes vibrational and rotational energy transitions that allow it to absorb infrared radiation and emit it as heat. Oxygen and nitrogen gas, however, do not absorb infrared radiation on any condition because they are symmetric diatomic molecules with no permanent dipole moment (Wei, 2018). The sun emits all kinds of photons, and infrared photons just so happen to have a certain energy level that CO_2desires in order to reach an ideal state. Infrared photons have wavelength values between 0.78-1000 μm, however, as stated before, carbon dioxide will *not* absorb infrared photons in the range of 8-12 microns and will instead most likely absorb radiation valued at 2, 2.7, 4.3, or 15 microns. When a photon initially hits a molecule, it vibrates in a way to take on the energy provided by the photon. When a carbon dioxide molecule vibrates, it bends its two oxygen molecules downward, or away from the carbon

molecule, while the carbon molecule bends in an upward direction, also away from the oxygen molecules. It is known as antisymmetric stretching vibration (NOAA, n.d.). Infrared photons with a satisfactory wavelength value when interacting with a carbon dioxide molecule will either accelerate or slow down their rotation speed.

3.1.3 – Vibrational Spectra of CO_2

Carbon dioxide is a triatomic linear molecule because the central atom, carbon, uses all of its electrons in the bond of the surrounding oxygen molecules, meaning carbon does not have any lone pairs surrounding it. This is what gives it the linear shape as represented in the figure to the right. In order to calculate the number of fundamental vibrations, we can use the equation used for linear molecules ($3n$-5). In this case, n is equal to three (there are three atoms in a carbon dioxide molecule.). So, CO_2has a total of four different fundamental vibration modes. These modes are: symmetrical stretching, asymmetrical stretching, and two types of symmetrical bending. During symmetrical stretching vibrations, the two oxygen molecules stretch away from the carbon molecule in a uniform manner. In asymmetrical stretching vibrations, one oxygen molecule compresses towards the center atom, while the other stretches away from it. In symmetrical bending vibrations, the angles of the molecules change. This can also be known as scissoring (Edmerls, 2019).



3.1.4 – Why Carbon Dioxide?

Carbon dioxide is one of the most abundant greenhouse gases and lingers the longest in the atmosphere. It is responsible for approximately 67% of the total energy imbalance in the atmosphere which in turn increases Earth's surface temperature (Lindsey, 2021). A majority of the innovations that are in the process of being created or planned have to do with removing CO_2 as such a major threat. For example, a new catalyst that may be able to "scrub" CO_2 directly from the atmosphere is currently being created using methods in quantum computing.

Chapter Four

Climate Modeling

4.1 – The Importance of a Climate Model

Climate models are primarily used to help us understand and predict important future environmental events. They are continuously utilized to make better informed and more logical environmental decisions for national and regional importance, such as agricultural, political, and transportation plans. They are mathematical representations of the most major climate elements. In this case, the most commonly treated components in a climate model are the atmosphere, land surface, the ocean, and sea ice. These mathematical models can be turned into three dimensional interactive models or can simply be used to determine and predict certain values such as future temperatures (NOAA, n.d.).

In our case, by using different systems of equations, we can find certain temperature values that allow us to understand how big of an effect the greenhouse effect really has on our planet. By finding values for an average surface temperature, blackbody temperature, and atmospheric temperatures, we can compare them and understand how drastic of a temperature change the greenhouse effect causes. This model can also be altered in the future to keep track of surface temperature changes caused by climate change.

4.2 – The Process of Creating our Model

Section 2.2.1 describes an example of a radiative equilibrium model representing the atmospheric layers and Earth's surface. This time around, a simple climate model will be described and executed to calculate temperature values that will allow us to understand the effect on climate our atmosphere currently has.

Solar radiation is involved in many steps of the greenhouse effect. It emits to Earth's surface from the sun.
There are certain mathematical approaches that can be used to relate the amount of heat absorbed vs emitted by our surface. We can relate the heat leaving Earth to solar radiation coming in through equation 4.2.1 listed to the right. The left side of the equation represents heat leaving the surface of the Earth. The variable *S*represents solar radiation, which is valued at approximately 1,361 W/m^2. For clarification, Ω is also used to represent solar radiation. There is a factor of ¼ because the entire Earth cannot be constantly illuminated by the sun at all times, so we consider the ratio of the area of a sphere to the area of a disk (for the disk of Earth catching sunlight.). We can then find the value of the temperature of the Earth according to our equation: 255 K. This value, however, is not fully accurate. Of course, we can only be so accurate off of one simple equation. We should, in reality, get about 286 K. Why is this? There are many lingering factors that we are forgetting to involve as we begin to come up with a relevant system of equations for our climate model. For example, we need to include waste heat, latent heat, convective heat, and many other variables in order to get the most accurate temperature result as we can.

(4.2.1) $$\sigma T^4 = \frac{1}{4}(1-a)S$$

The most important and fundamental part of creating a climate model has to do with our systems of equations. In this case, the most relevant equations have to do with surface and atmospheric temperatures. The blackbody temperature is defined as the temperature of a planet if its atmosphere were to have no effect on it. (Oxford University Press, 2021). It is an important variable in our set of equations because it allows us to understand the impact our atmosphere has on our resulting surface temperature. In order to derive the blackbody temperature of the Earth, we have to first consider the principle of energy conservation with a radiation balance equation. The radiation balance equation involves the flux of outgoing infrared radiation (σT^4) being set equal to the non-reflected solar flux ($\Omega(1 - a)/4$). These variables are defined earlier, but to review, a represents the albedo, σT^4 is from the Stefan-Boltzmann law, and Ω is used for the solar flux. To solve for and calculate the surface temperature, we can consider radiation transfer between both Earth's surface and atmosphere, and within the atmosphere. Our model will be one-dimensional, meaning describing only the vertical dimension or ignoring latitudinal and longitudinal climate parameters. The main idea of our first set of equations is that energy flowing out has to be equal to energy flowing in. Let's relate relevant equations to one another.

Before anything, it is important to set variables equal to their specific values. Figure 3 displays the formatting used in Mathematica when setting these values. Because it is not exactly appropriate to include units in the code, I will describe every defined variable.

Our incoming solar radiation is $\frac{\Omega}{4}$, which is valued at 343 W/m^2. Earth's albedo, a, as talked about before is set to 0.3, estimated from approximately 0.28, or 28% reflectance. The Stefan-Boltzmann constant is a determining factor for our model and resulting values, lying at approximately 5.67 x 10^{-8} $\frac{W}{m^2 K^4}$. F_w is the portion of infrared radiation from the surface that is reradiated directly back into space, 20 W/m^2. F_e represents the flux of latent heat leaving Earth's surface, 80 W/m^2, While $F_c$represents the flux of *convective* heat leaving Earth's surface, 17 W/m^2. The flux of latent heat is the heat that travels or passes from the Earth's surface to the atmosphere, specifically associated with water evaporation at the surface level, and the condensation (the process of vapor turning into liquid) of water vapor in the troposphere (National Geographic Society, 2012). Convective heat is currents of moving fluid or gas causing a heat transfer between two bodies (Sokolova, 2007). For our last variable, we have the segment of atmosphere absorbed solar flux, F_s, 86 W/m^2.

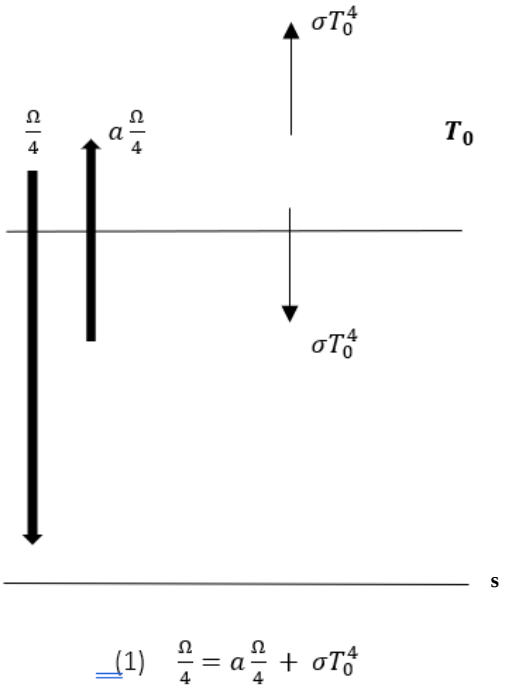
FIG 2

```
Ωover4 = 343;
a = 0.3;
σ = 5.6704 * 10^-8;
Fw = 20;
Fe = 80;
Fc = 17;
Fs = 86;
```

Figure 2 Variable values

The incoming solar flux has to be equal to that same solar flux value multiplied by Earth's albedo and added to the emitted infrared radiation produced from absorbed visible light. This is the outgoing equation for solving the blackbody temperature, T_0. Allow me to visualize it for you. Figure 1 portrays the most basic representation of equation 1. In that diagram, the only atmospheric layer presented is the top layer with the blackbody temperature. As you can see, the solar flux $(\frac{\Omega}{4})$ absorbed is followed by the solar flux reflected $(a\frac{\Omega}{4})$. a exhibits Earth's albedo, or the reflectivity of the Earth (valued at 0.3, or 30% reflection). In this case, we're representing the amount of sunlight reflected. The infrared radiation produced from absorbed visible light is absorbed and emitted as shown in the figure.

FIG 3



$$\frac{\Omega}{4} = a\frac{\Omega}{4} + \sigma T_0^4 \quad (1)$$

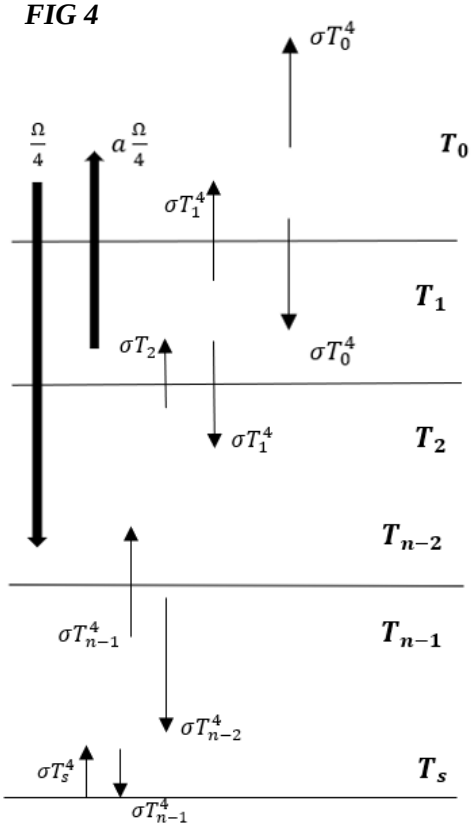
Figure 3 A basic representation of equation 1. Only the highest layer of the atmosphere used in our climate model is presented.

Let's take a look at a second equation. Equation 2 represented to the right sets the infrared flux absorbed in the top zone equal to the infrared flux emitted from the zone. The infrared flux in the top zone is absorbed from the layer below it. This factor is multiplied by two because every surface of a blackbody radiates a flux, and there is a top and bottom surface on the zones.

(2) $2\sigma T_0^4 = \sigma T_1^4$

If we go back to figure 1, we can add more atmospheric layers in order to represent the flow of energy in an n-layer atmosphere. We can now relate equations 1, 2, and 3 to three other relevant equations.

FIG 4



$$(3) \quad 2\sigma T_{n-1}^4 = \sigma T_{n-2}^4 + \sigma T_s^4$$

Figure 4 Now representing an n-layer atmosphere's flow of energy (Harte, 1988).

Equations 4-6 are different versions of equations 1-3. It is important to have a revised model because we don't want to get incorrect values caused by certain factors that could be easily reviewed and fixed. Let's talk about some of the key components that may be mistakenly surpassed when creating our system of equations. Some of the defects of equations 1-3 include:

(4) $$W + \frac{\Omega}{4} = a\left(\frac{\Omega}{4}\right) + \sigma T_0^4 + F_w$$

(5) $$2\sigma T_0^4 = \sigma T_1^4 + 0.5F_e + 0.7F_s$$

(6) $$2\sigma T_1^4 = \sigma T_0^4 + \sigma T_s^4 - F_w + F_c + 0.5F_e + 0.3F_s + W$$

- The fact that a certain amount of solar flux is absorbed in the atmosphere as opposed to Earth's surface
- Some infrared radiation emitted from Earth's surface will *not* be absorbed through the atmosphere and will radiate straight to space (specifically IR in the wavelength band of 8-12 microns)
- We need to consider latent heat transfer and upward convection in transferring heat from the surface to the atmosphere

Once we consider these inputs, we end up getting *lower*temperature values because they lead to less heat input to the surface or to a greater rate of heat removal (Harte, 1988). In order to alter our system of equations from here, we can consider more about Earth's two atmospheric radiation zones. Because the atmosphere's infrared radiation absorption capacity is mostly due to water vapor, it would make sense to assume that the border between the upper and lower atmospheric zones lies where half the atmospheric water vapor lies (about 1.7 km apart). However, it lies higher (≈ 1.8 km). This is because IR absorbing

atmospheric gases are found at higher elevations than water vapor.

From this information, we can take into account that at an altitude of 1.8 km, atmospheric pressure is about 80% sea-level pressure, meaning weight wise, 80% of the atmosphere is above that 1.8 km boundary and 20% lies below (Harte, 1988). We can now link this information to the three faults listed earlier. Approximately 86 W/m^2 of solar energy are absorbed in the atmosphere from the incoming sunlight beam and from the sunlight reflected off of the surface of the Earth. Using the fact that 80% of the air and 50% of the water vapor is found in the upper atmosphere, we know that approximately 75% of those 86 W/m^2 is absorbed in the upper atmosphere ((0.8 x 0.8) + (0.5 x 0.2) ≈ 0.75), leaving ≈ 25% to be absorbed in the lower atmosphere. We do however have to round. Dust is also an absorber, and it lies lower in the atmosphere than air. So therefore, we should round to 70% and 30%. Approximately 20 W/m^2 of surface emitted infrared radiation radiates straight through to outer space (Harte, 1988). Therefore, later on in our new set of equations, we can simply add that value to the IR flux to space and subtract it from the absorbed IR flux in the lowest absorption atmospheric zone. Lastly, let's touch on convection and latent heat transfer. Our convective heat flow value is 17 W/m^2. The flux of latent heat, valued at 80 W/m^2, is added to the portion of the solar flux absorbed in the atmosphere.

In summary, and through simpler terms, radiation absorbed from the sun is reemitted at different wavelengths (Power input and output). In terms of a steady state, the intensity coming into the Earth must equal the intensity emitted from the Earth. The intensity input is equation 4.2.2, and the intensity output is 4.2.3. Setting these equations equal to one another and solving for temperature, we get equation 4.2.4. The term *e*represents emissivity, which is the effectiveness of a surface in emitting energy as radiation (Doner, 2017). The emissivity of the Earth's surface is valued at approximately 0.64 when accounting for the clouds/atmosphere. When solving for the temperature, we get 288 K. We can however upgrade our equations by treating the atmosphere as a blackbody radiator. When doing so, we include the Stefan-Boltzmann law ($e\sigma T^4$) and come up with equation 4.2.5.

(4.2.2) $\frac{S}{4}(1-a)$

(4.2.3) $e\sigma T^4$

(4.2.4) $T = \left(\frac{\left(\frac{S}{4}\right)(1-a)}{4e\sigma}\right)^{\frac{1}{4}}$

(4.2.5) $\frac{S}{4}(1-a) + e_a\sigma = e_e\sigma T^4$

4.3 – The Code

Now we can use our system of equations in order to create a model and solve for T_0, T_1, and $T_s$using the solve function in Wolfram Mathematica. Let's take a step by step process of creating the code.

The solve function in Mathematica is used to solve a system of equations for named variables (*Solve*, n.d.). Notice the formatting in figure four below.

FIG 4

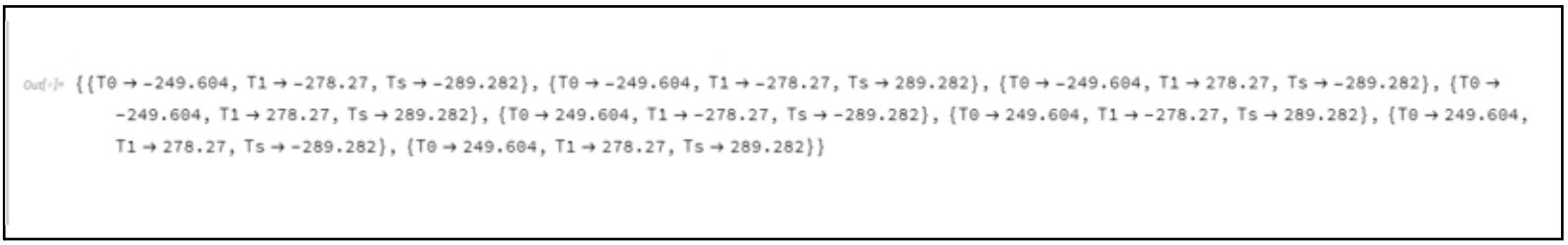
```
Solve[{Ωover4 == ((a * (Ωover4)) + (σ * (T0)^4) + (Fw)), ((2 * σ) * (T0)^4) == (σ * (T1)^4) + (0.5 * Fe) + (0.7 * Fs), ((2 * σ) * (T1)^4) == (σ * (T0)^
    4) + (σ * (Ts)^4) - (Fw) + (Fc) + (0.5 * Fe) + (0.3 * Fs)}, {T0, T1, Ts}, Reals]
```

The code ends by asking for real results of T_0, T_1, and T_s. T_0 is the blackbody temperature of the Earth, T_1 is the intermediate layer temperature, and T_s is the surface temperature of the Earth.

4.4 – Results

Shift + enter is the command used to execute the Mathematica script. As seen in figure 5, there are multiple irrelevant results. The last set of positive numbers are applicable for our results.

FIG 5



$T_0 \approx 249.6$ K, $T_1 \approx 278.3$ K, and $T_s \approx 289.3$ K. Comparing T_0 and T_s, we find that the atmosphere warms the planet by absorption of radiation approximately 39.7 K, allowing Earth to sustain life.

4.4.1 - Using Quantum Mechanics to Create a More Accurate Climate Model

This simple model can be edited in a more accurate or unique way using quantum mechanics. For example, if we look at each of the energy levels in the electromagnetic spectrum, we could use them to determine how much energy on average is absorbed by Earth's atmosphere. This could help us understand how much infrared radiation is absorbed as compared to others. By breaking up energy levels in the first model, we are modifying it for accuracy. For example, infrared radiation has photon energy values from 1.7 eV to 1.24 meV and wavelength values from 700 nm to 1 mm (Wikimedia Foundation, 2022). We could use

this information and create a model that calculates how much infrared radiation contributes to temperature change.

On a more relatable note, we could use carbon dioxide's absorption and emission properties to determine how CO_2on its own effects the atmosphere/contributes to the greenhouse effect and compare it the rest of the greenhouse gases. A new set of equations could be determined and programmed into Mathematica for results.

$$T = T_0 + S\log_2\left(\frac{C}{C_0}\right) \quad (4.4.1)$$

For example, if we want to determine how CO_2 on its own effects the atmosphere/contributes to the greenhouse effect, we could use a starter equation (equation 4.4.1), where T is the new determined temperature of the Earth in Celsius, T_0 is the known temperature of the Earth in Celsius (dependent on time), S is the climate sensitivity (how much temperature changes based on an event), $C$is the new atmospheric concentration of CO_2, and C_0 is the atmospheric Concentration of CO_2at the same time that T_0 is represented. The current known value for S is approximately 276 K. So, if we were to use the year 2000 and current average values for example, T_0 is valued at 14.3 °C, C at 410 ppm, and C_0 at 370 ppm. We obtain an estimated value of 14.7 °C, meaning carbon dioxide is responsible for approximately 0.4 °C of Earth's temperature. This simple model was inspired by Russel (n.d.).

```
In[16]:=
T0 = 14.3;
c = 410;
c0 = 370;
S  = 3;
Solve[{T == ((T0) + (S * (Log2[(c / c0)])))}, {T}, Reals]

Out[20]= {{T → 14.7443}}
```

We can now take into consideration absorption and emission properties of CO_2 in order to get a more accurate value. For example, we can find energy values from CO_2 absorption and add it onto the equation. Equation 4.4.1 is a base equation that can be followed in numerous ways.

Chapter Five

The Physical Application of Quantum Mechanics in Climate Science

5.1 – Quantum Technology

5.1.1 - Introduction to Quantum Computing

Quantum computing uses the most fundamental and in-depth parts of quantum mechanics in order to create technology that can find solutions to certain issues. As researchers continue to discover more useful information regarding climate science, they can use it to begin creating ideas to help solve the climate crisis. Quantum computers perform computations that may solve certain problems within seconds that may have taken years to solve with classical technology (Guay, 2021). Advancing in quantum computing may allow us to simulate large complex molecules, for example.

5.1.2 – Carbon Capture

As readily discussed throughout this research, carbon dioxide is an incredibly harmful and prominent greenhouse gas. If we were to reduce the amount of CO_2 in the atmosphere, we would not have to worry about a significant number of environmental effects. It is currently possible to create technology that can capture CO_2 from the atmosphere. However, the idea is incredibly expensive and not readily available. Quantum computers, however, have the capability to discover a new catalyst that can be used for carbon capture through the simulation of atomic interactions on the quantum-level. This is known as “scrubbing”, and it has been an ongoing idea for years. In the world of geoengineering, carbon capture can be used at the source, meaning using a mechanical capture of CO_2 from greenhouse gas emissive industries, such as power plants. It can then be stored in underground saline aquifers (Joshi, 2020). Successfully, research on this development is already underway. In 2020, Total, an energy company, had announced their collaboration with Cambridge Quantum Computing. Their work focuses on improving materials for the capture of carbon dioxide (Joshi, 2020).

5.1.3 – Other Quantum Technology

A simple example of a quantum device specifically designed for a more positive environmental impact is an LED (light-emitting diode) lightbulb. In a traditional incandescent light, an electric current travels through a wire, emitting light. However, 90% of the energy in this method is lost as heat, making these lights incredibly inefficient. LEDs on the other hand use energetic electrons and broken chemical bonds between atoms, using energy to create light rather than heat. This is mainly what makes an LED light more efficient. This process depends on semiconductors. On the inside of an LED, there are two layers made from semiconductors. One contains energetic electrons, while the other contains the broken chemical bonds between atoms as explained earlier (George, n.d.). The energetic electrons fall into these broken chemical bonds when met at the interface and releases that energy it used to fall into it as light. Currently, there is a development of new semiconductors which will in turn improve the efficiency of LEDs even more (George, n.d.). Quantum entanglement (discussed earlier) is also a concept used to create environmentally friendly technology. It can be used in searching climate data. In quantum technology, we tend to look to nature's designs for inspiration.

5.2 – Solar Cells

The concept of a solar cell is based on its ability to absorb incoming light and convert it to energy. Quantum mechanics can be used to create organic solar cells of which are cheaper, lighter, and more malleable and flexible than the standard silicone-based solar cells. From what we currently know about creating organic solar cells, the issue lies in efficiency. Silicone-based solar cells are much more efficient in creating energy, therefore, we can use certain concepts in quantum mechanics to create a more efficient organic solar cell that can genuinely be used for solar energy. As we know, solar energy is beneficial for the environment and one of the best forms of renewable energy. However, the traditional way we create solar panels is incredibly expensive and material dependent. If we can figure out a way to change the chemical and material characteristics of these solar cells, we can create a cheaper, more efficient solar cell and have more solar energy based products (ScienceDaily, 2021). The current problem with organic solar cells has to do with diffusion. The absorbed energy from the sun needs to travel to the connection area, or interface, of the materials. This travel, or diffusion, however, is ineffectual. During diffusion, energy travels slowly, and in this case, slow enough for the energy to get lost as heat before reaching the interface. If we were to combine the materials in the solar cell, the cells would then not be in thermodynamic equilibrium (ScienceDaily, 2021). Therefore, there needs to be another method implemented that doesn’t involve combining the materials. Strongly coupling the materials, meaning blending the materials at a quantum level rather than a physical level, ensures that the energy reaches the interface in a timely manner while also containing thermodynamic equilibrium. Coupling is also represented between molecules in nature. In photosynthesis, the molecules in plants couple in order to transfer solar energy (ScienceDaily, 2021).

Conclusion

Climate change has been an ongoing threat to Earth and its organisms. The severity of it continues to increase with time. It is important for us to understand the root of the issue in order to come up with potential solutions to stop said threat. Climate science can be evaluated in many ways. It is a complex subject that branches through multiple different fields, such as biology (marine biology, botany, zoology), chemistry (organic chemistry, physical chemistry, biochemistry), and one that is less common, physics (thermodynamics, molecular physics, quantum mechanics).

Quantum mechanics deals with the study of subatomic particles, or the smallest to scale particles that we so far know of. It combines theoretical and mathematical approaches together to get a better understanding simply of how the world works. There are many different subjects in quantum physics, and some of these subjects allow us to get a deeper understanding of certain parts of climate science – such as climate change. There tends to be a misinterpretation of the ability to incorporate quantum mechanics into climate science. Because quantum physics can be used to solve just about anything scientific in detail, why would we deviate from it when asked to understand one of the largest threats to humanity? We can pinpoint truly specific details about certain parts of climate science, such as greenhouse gases, technology used to help the environment, atmospheric changes, and so on. This is critical to help us better prepare for the future.

An accurate representation of how certain studies in quantum mechanics contribute to climate science can be found through climate models. Climate modeling is a useful tool that we can use in the intervention process. General circulation models, or GCMs, use systems of equations and mathematical approaches to represent certain environmental patterns or interactions (NOAA, n.d.). For example, you can find models calculating surface and atmospheric temperatures based on greenhouse gas data. In this research, simple models were constituted to represent an essential outcome of the greenhouse effect – temperature. The first model results in the blackbody and surface temperatures of the Earth, allowing us to compare the values and understand how much our atmosphere affects our temperature. The second model is a simple start to understanding the composition of atmospheric carbon dioxide and how much it alone contributes to the greenhouse effect, also temperature wise.

This research can be used in the future as a starting point for creating new technologies that may be successful in solving climate change. Quantum computers, catalyst creations, and many other methods can be implemented in an attempt to create something innovative that can in turn help save the future.

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