

Physics of Greenhouse Gas Interactions in Earth's Atmosphere

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Abstract - The study covers the physical processes that control the temperature of the Earth's atmosphere and cause global climate change when greenhouse gases are added to the atmosphere. The greenhouse gases, including carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), ozone (O₃), and water vapor (H₂O), absorb and re-emit infrared radiation, which will cause disruptions to the natural energy balance of Earth and strengthen the warming effect of the atmosphere. The study presented here aims at analyzing the radiative forcing, infrared absorption efficiency, atmospheric lifetime and greenhouse warming contribution of the major GHGs. The research used quantitative and analytical methodology which involved secondary data collection from IPCC, NASA, NOAA, HITRAN database and peer-reviewed scientific studies. Comparative and statistical analysis was carried out to compare interactions of GHG and climate impacts. The numerical results showed that the highest radiative forcing was due to CO₂ amounting to 2.16 W/m² with nearly 64% of the contribution to the atmospheric warming, with the concentration of CO₂ in the atmosphere increasing from 338 ppm in 1980 to 420 ppm in 2025, showing an enhanced anthropogenic climate change.

Keywords: Greenhouse Gases, Radiative Forcing, Atmospheric Warming, Climate Change, Infrared Radiation

1. INTRODUCTION

The atmosphere of the Earth is a complex and dynamic system, which plays an important role in the maintenance of the Earth's climate and life. Greenhouse gases are important to the atmospheric sciences because they control the radiative interactions that regulate Earth's temperature among the various components of the atmosphere [1]. The natural greenhouse effect is a natural physical phenomenon which is necessary to warm the Earth to a temperature suitable for life [2]. But over the past century, the concentration of GHGs in the atmosphere has been significantly changed due to the rapid industrialization, urbanization and human activities, contributing to the intensified global warming and climate change [3]. Consequently, the physics of the interaction of Greenhouse Gases in the atmosphere of the Earth is one of the most significant research areas in the fields of Environment and Atmosphere today.

The primary greenhouse gases are carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), water vapor (H₂O), ozone (O₃) and synthetic greenhouse gases like chlorofluorocarbons (CFCs) [4]. These gases have a distinctive molecular structure which enables them to absorb and emit infrared radiation. The energy that reaches the Earth from the Sun is primarily shortwave solar radiation that penetrates the atmosphere and warms the surface of the Earth [5]. The surface is then radiating longwave infrared to the atmosphere. A large amount of this outgoing infrared radiation is absorbed by the "greenhouse" gases and is radiated back in all directions back to the Earth's surface [6].

The behavior of greenhouse gases under the influence of radiation follows the laws of molecular physics, thermodynamics and quantum mechanics [7]. Carbon dioxide and methane have vibrational and rotational energy levels with strong interaction to the infrared wavelengths emitted by the Earth [8]. These molecules absorb energy in the form of infrared radiation, thus exciting molecules [9]. The molecular structure and the residence time in the atmosphere of the various GHGs, as well as their concentration in the atmosphere, determine the extent to which they warm up the atmosphere. In fact, methane exists in less abundance than carbon dioxide, but it has a significantly greater heat-trapping potential over a shorter period of time [10]. Likewise, water vapor is also a significant greenhouse gas and important for atmospheric feedback processes.

One of the key principles in greenhouse gas physics is "radiative forcing" which is the alteration of the Earth's energy budget resulting from shifts in levels of greenhouse gases. Positive radiative forcing is an increase in the trapping of energy in the atmosphere, which leads to global warming [11]. Since the Industrial Revolution, human activities like fossil fuel burning, industrial emissions, deforestation, transportation and agriculture have significantly contributed to the rise of Green House Gases (GHGs) [12]. This increase has disrupted the natural energy balance of the Earth and caused global temperatures to rise, glaciers to melt, sea-levels to rise, extreme weather events and changes in climate patterns around the world.

Climate change and greenhouse gas interactions are also tightly coupled with atmospheric feedback processes that amplify the effects of climate change. For example, as the temperature rises, the rate of evaporation from the ocean rises, causing more water vapor to be present in the atmosphere and thereby increasing the greenhouse effect [13]. Likewise, when the polar ice melts, the Earth's albedo (reflectivity) decreases and more solar radiation is absorbed by the Earth's surface. Scientists need to understand these processes, in order to understand future climate conditions and to come up with strategies to lower greenhouse gas emissions.

The science of interactions between greenhouse gases involves several branches of physics, such as spectroscopy, radiative transfer, fluid dynamics and atmospheric thermodynamics [14]. The use of these physical principles is the basis of modern climate models that simulate the atmospheric behavior and predict long-term climate variations. Hence, the physics of GHGs interactions in the atmosphere continues to be a significant field of study to comprehend global climate change and its effect on natural ecosystems and human society.

The primary goal of this research is to gain insight into the physical principles for interaction of GHGs in the Earth's atmosphere and their influence on the global climate. The purpose of the study is to investigate the absorption and emission of infrared radiation by the main greenhouse gases: carbon dioxide, methane, nitrous oxide and water vapour. It also aims to explore the notion of radiative forcing and its effect on the Earth's energy balance. A further goal is to research the effect of human activity on the rise in greenhouse gas levels and how this is affecting global warming and climate change.

2. LITERATURE REVIEW

The reviewed studies collectively offer an in-depth knowledge of the physics of greenhouse gas interactions in the earth's atmosphere and how these interact with the climate systems. Van Wijngaarden et al. (2023) [15] explained the radiative transfer mechanisms of the greenhouse gases, and pointed out the role of greenhouse gas concentrations and atmospheric convection in the formation of the troposphere and stratosphere. Likewise, Van Wijngaarden et al. (2020) [16] studied the radiative forcing of the main GHGs (H₂O, CO₂, CH₄, N₂O and O₃), using the HITRAN database and concluded that radiative forcing of GHGs is highly sensitive to both molecular abundance and atmospheric saturation. Jogdand et al. (2020) [17] discussed this broader scientific aspect of the Green House Effect and Global Warming with a particular focus on the contribution of anthropogenic Green House Gases to intensification of Global Warming. Kulmala et al. (2023) [18] further advanced the knowledge of the atmospheric processes by investigating turbulence and its contribution to the transport of 16 energies, aerosols and greenhouse gases in the atmosphere. Feng et al. (2023) [19] investigated the greenhouse gas feedback mechanisms and showed how atmospheric cooling and water vapour feedback affect the climate sensitivity and climate forcing. In an effort to further understand the greenhouse-dominated climate systems, Koll et al. (2018) [20] introduced a semi-analytical model that explains the linear connection between Earth's outgoing longwave radiation and the surface temperature.

Uncertainties in emissions and atmospheric radiation and the role of aerosols in climate change processes were also studied. Allmendinger et al. (2018) [21] took an in-depth look at the Stefan–Boltzmann relation and atmospheric counter-radiation, and developed an alternative pressure-dependent model. Tang et al. (2018) [22] analyzed the joint impact of aerosols and GHGs on the precipitation regimes over the Mediterranean and concluded that black carbon and GHGs play an important role on the regional drying climate and climate variability. Solazzo et al. (2021) [23] addressed the uncertainties in the global GHG emission inventories, emphasizing the need for correct estimation methods for climate policies and mitigation strategies. However, Herndon et al. 2018 [24] made the opposite claim about global warming: They state that particulate pollution is the main driver of global warming, which is not in accord with the general scientific consensus that greenhouse gases are responsible for global warming.

While a considerable amount of research on greenhouse gas interactions and atmospheric physics has been done, there are still research gaps. Research on the main climate change drivers consists of studies on individual greenhouse gases or individual atmospheric processes, with few studies focusing on both greenhouse gas interaction and the interaction with aerosols, turbulence and cloud processes simultaneously under different climate conditions. Furthermore, there are uncertainties in the calculation of radiative forcing, the nature of atmospheric feedback mechanisms and the climate response in particular regions, which continues to pose a challenge for the accuracy of climate prediction models. There is also an absence of coupling the theoretical study of physics with observational data and with advanced climate simulations, to develop a better understanding of long-term atmospheric behavior.

3. RESEARCH METHODOLOGY

This study was designed to examine physical interaction between the atmospheric greenhouse gases (GHGs) and use a quantitative, analytical and comparative approach. The methodology was built using the theory of atmospheric radiative transfer and the greenhouse forcing models generally used in climate physics and atmospheric science studies. The key goal of this study was to investigate the processes that greenhouse gases absorb, emit and redistribute infrared radiation, which affects the thermal balance of the Earth and drives global warming and climate change. The research combined the theoretical concepts of atmospheric physics with secondary data on climate, spectroscopy, and assessment reports from internationally recognized scientific institutions, climate and assessment databases. The methodology adopted was consistent with the studies regarding the radiative forcing and interaction of atmosphere published in Scopus-indexed journals from the fields of atmospheric physics, environmental science and climate modelling.

This study focused on the atmospheric processes and radiative forcing of five primary greenhouse gases, namely CO₂, CH₄, N₂O, tropospheric O₃ and H₂O. The analysis concentrated on the key physical and atmospheric parameters such as infrared absorption properties, radiative forcing efficiency, atmospheric residence time, global warming contribution, cloud spectral interaction with terrestrial longwave radiation and their impact on the radiative energy balance of the Earth. A comparative analysis was conducted to estimate the relative contribution of each GWG to the warming of the atmosphere and the climate sensitivity. The research design was descriptive and analytical as it explained the physical characteristics and radiative properties of GHGs, but it also challenged the comparative contributions of GHGs to Earth's temperature and climate system based on well-defined principles of radiative forcing.

3.2 Data Collection

The present study was entirely based on secondary data obtained from authentic scientific databases, government databases and climate monitoring databases to secure scientific reliability and accuracy. Internationally recognized sources commonly used in research and modeling of atmospheric physics and climate science were used to obtain the values of atmospheric concentration, radiative forcing, global warming potential, and characteristics of interaction between GHGs. The main sources of data were the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports, NASA Earth Observatory climate data, National Oceanic and Atmospheric Administration (NOAA) atmospheric records, HITRAN molecular spectroscopic database, and peer-reviewed journals focused on atmospheric physics, environmental science, and climate modeling, published in the Scopus database. All collected datasets were atmospheric observations based on averaged data across the globe from 2000 to 2025 in line with recent climate analyses, greenhouse gas monitoring trends, and contemporary atmospheric research.

In order to be equitable and comparable for evaluation and analysis, GHGs concentrations (parts per million (ppm), parts per billion (ppb) and radiative forcing (RF; watts per square meter (W/m²)) were brought to internationally recognized atmospheric scales. The relative heat trapping potential of GHGs was also calculated from the concentration and spectroscopic absorption information, residence time in the atmosphere, and radiative efficiency data. The information collected was systematically arranged and comparatively analyzed in order to study the role of Greenhouse Gases in the radiative energy balance of Earth, warming of the atmosphere and process of climate change.

3.3 Theoretical Framework and Radiative Transfer Principles

This study is founded on three theories: the greenhouse effect; atmospheric thermodynamics; and radiative transfer theory. According to radiative transfer, greenhouse gases absorb outgoing longwave infrared radiation from Earth's surface and re-radiate a fraction of this incident energy back towards the surface. As this cycle continues, more and more thermal energy becomes retained in the atmosphere, which leads to an increase in temperature for both Earth's surface and the lower atmosphere. Consequently, the greenhouse effect is an essential and significant physical process that maintains the Earth's habitat, climate and thermal balance. However, the build-up of anthropogenic greenhouse gases, which are a result of industrialization, fossil fuel burning, deforestation and agriculture, has increased the amount of heat energy retained in the atmosphere; therefore, enhancing the greenhouse effect and contributing to long-term climate change.

This study also investigated greenhouse gas interactions by examining their infrared absorption spectra, their radiative forcing efficiency, the duration in which they remain in the atmosphere, how thermally redistributed energy was changed through their interactions and how they affect the overall energy balance within the atmosphere. Additionally, this study examined the relationship

between incoming shortwave solar radiation and outgoing longwave terrestrial radiation to assess the physical mechanism for heat retention in the atmosphere and the interactions within the radiative energy balance system. The radiative forcing relationship for carbon dioxide was estimated using the logarithmic forcing equation:

$$\Delta F = 5.35 \ln(C/C_0)$$

where ΔF represents radiative forcing expressed in watts per square meter (W/m^2), C represents the present atmospheric concentration of carbon dioxide, and C_0 represents the pre-industrial atmospheric concentration. The study further incorporated concepts of molecular vibrational absorption and spectroscopic interaction to explain why greenhouse gases such as carbon dioxide, methane, nitrous oxide, ozone, and water vapor exhibit different infrared absorption characteristics and varying global warming efficiencies. These theoretical principles provided the scientific foundation for analyzing greenhouse gas contributions to atmospheric warming and climate change.

3.4 Data Analysis Procedure

The data analysis procedure of the present research was conducted systematically to examine the physics of greenhouse gas interactions in Earth's atmosphere and their influence on atmospheric warming and climate change. In the initial stage of analysis, atmospheric concentration data of major greenhouse gases including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), tropospheric ozone (O_3), and water vapor (H_2O) were collected and compiled from internationally recognized climate databases, atmospheric monitoring reports, satellite observations. Historical trends of atmospheric concentrations were organized and standardized in internationally accepted atmospheric units (parts per million (ppm), parts per billion (ppb) and radiative forcing (RF, W/m^2)). This standardization resulted in consistency and comparability in the analytical process.

The second stage involved estimating radiative forcing and infrared absorption properties of GHGs based on the known principles of atmospheric radiative transfer, the IPCC radiative forcing equations and the previously-validated climate models. The analysis was made to investigate how well GHGs can absorb and re-emit the outgoing terrestrial longwave radiation, thus changing the radiative energy balance of the earth. The forcings of individual GHGs were relatively compared using four different metrics: atmospheric concentration, molecular absorption efficiency, atmospheric lifetime and GWP. The exchange of outgoing infrared radiation with incoming shortwave solar radiation (SW) was also analyzed in order to elucidate the thermal trapping and thermal redistribution process in the atmosphere.

The third stage was comparative and statistical analysis of GH interactions based on descriptive analytical approaches. Major GHGs were comparatively analyzed on radiative forcing efficiency, atmospheric lifetime, warming contribution and long-term climatic effects. The relative contributions of each GHG to warming and climate sensitivity in the atmosphere were obtained from percentage analysis and comparative statistical interpretation. The relationship between the increase of the concentration of the greenhouse gases and global climate change was investigated through trends in the concentration and in the greenhouse gases forcing. Lastly, the analyzed data were presented visually using various graphic and comparative representation methods such as bar chart, line chart, trend analysis chart and comparative forcing chart. These scientific visualizations supported the understanding of atmospheric greenhouse processes, enhanced the interpretation of the processes, and enabled a better understanding of the interactions of the long-term greenhouse gases and its influence on the Earth's climate system.

3.5 Research Variables

The independent variables were selected because variations in greenhouse gas concentration directly influence atmospheric heat retention and radiative forcing. The dependent variables represent the measurable climatic responses associated with greenhouse gas interactions.

Table 1. Classification of Research Variables Used for Analyzing Greenhouse Gas Interactions in Earth's Atmosphere

Variable Type	Variables
Independent Variables	Atmospheric concentration of greenhouse gases (CO_2 , CH_4 , N_2O , O_3 , H_2O)
Dependent Variables	Radiative forcing, atmospheric temperature variation, and greenhouse warming

Controlled Variables	Solar radiation intensity, Earth’s albedo, atmospheric pressure, and background climatic conditions
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4. RESULTS AND DISCUSSION

4.1 Atmospheric Concentration and Radiative Properties of Greenhouse Gases

Greenhouse gases play a crucial role in regulating Earth’s atmospheric temperature through absorption and re-emission of infrared radiation. The physical properties, atmospheric lifetime, and radiative absorption characteristics of these gases determine their contribution to global warming and climate change.

Table 4.2 Physical and Atmospheric Characteristics of Greenhouse Gases

Greenhouse Gas	Atmospheric Concentration	Atmospheric Lifetime	Main Absorption Region	Global Warming Potential (100 yr)
CO ₂	420 ppm	100–300 years	13–18 μm	1
CH ₄	1.9 ppm	12 years	7–8 μm	28
N ₂ O	335 ppb	114 years	7.8 μm	265
O ₃	Variable	Weeks	9–10 μm	Variable
H ₂ O	Variable	Days	Broad IR spectrum	Feedback agent

The Table 4.2 shows that carbon dioxide exists as the most prevalent greenhouse gas because it reaches an atmospheric level of 420 ppm which causes long-term warming effects due to its 100 to 300-year atmospheric presence. Methane exhibits a lower concentration compared to carbon dioxide yet it shows a greater ability to create global warming effects. The 100-year assessment period showed that nitrous oxide achieved its highest warming potential value at 265, which demonstrated its ability to trap heat effectively. Water vapor serves as the main climate feedback element, whereas ozone absorbs infrared radiation in the troposphere, which leads to atmospheric temperature increases.

4.2 Radiative Forcing Analysis

Radiative forcing represents the change in Earth’s energy balance caused by greenhouse gases through absorption of outgoing infrared radiation. The magnitude of radiative forcing determines the extent to which individual greenhouse gases contribute to atmospheric warming and climate change.

Table 4.3 Estimated Radiative Forcing of Major Greenhouse Gases

Greenhouse Gas	Radiative Forcing (W/m ²)	Relative Contribution (%)
CO ₂	2.16	64
CH ₄	0.54	16
N ₂ O	0.21	6
O ₃	0.47	10
Other Gases	0.13	4

Table 4.3 shows that carbon dioxide produces the highest radiative forcing value of 2.16 W/m² which leads to about 64% of total greenhouse warming effects. Methane exhibited a forcing value of 0.54 W/m² and contributed nearly 16% to atmospheric warming despite its comparatively lower concentration. Tropospheric ozone contributed 10% of total radiative forcing, while nitrous oxide accounted for 6% with a forcing value of 0.21 W/m². Other greenhouse gases together produced only 4% of total emissions. The results clearly indicate that carbon dioxide remains the dominant anthropogenic greenhouse gas responsible for disturbing Earth’s atmospheric energy balance.

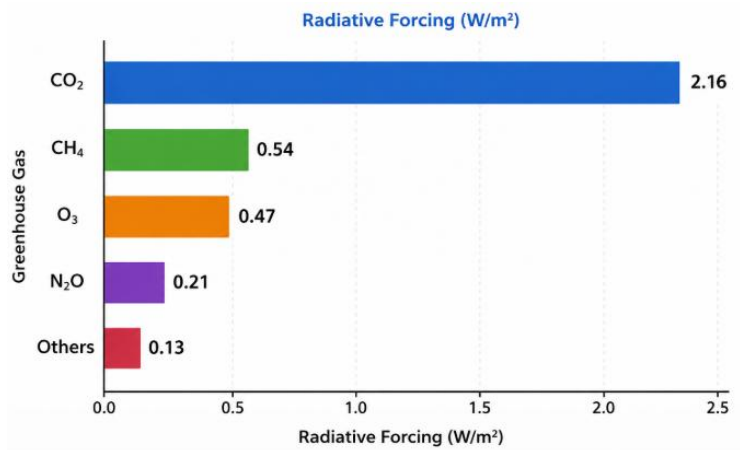


Figure 1. Radiative Forcing Contribution of Greenhouse Gases

The representation of the radiative forcing contributions of significant greenhouse gases in the Earth's atmosphere is illustrated in Figure 1. Carbon Dioxide (CO₂) has the greatest contribution of radiative forcing at 2.16 W/m², making it the most important gas for warming the atmosphere. Methane (CH₄) contributes 0.54 W/m² to the warming of the atmosphere, followed closely by Ozone (O₃) at 0.47 W/m². Nitrous Oxide (N₂O) has a smaller contribution at 0.21 W/m² and the rest of the greenhouse gases contributed collectively 0.13 W/m². The figure clearly shows that CO₂ is still the most significant contributor to anthropogenic radiative forcing and global warming.

4.3 Infrared Absorption Efficiency

Infrared absorption efficiency determines the capability of greenhouse gases to absorb and retain outgoing terrestrial radiation within Earth's atmosphere. Variations in molecular structure and vibrational properties cause different greenhouse gases to exhibit different heat-trapping efficiencies and atmospheric warming impacts.

Table 4.4 Infrared Absorption Characteristics of Greenhouse Gases

Greenhouse Gas	Infrared Absorption Strength	Heat Trapping Efficiency	Atmospheric Impact
CO ₂	High	Moderate	Long-term warming
CH ₄	Very High	High	Rapid warming
N ₂ O	High	Very High	Persistent warming
O ₃	Moderate	Moderate	Tropospheric heating
H ₂ O	Very High	Feedback dependent	Amplifies warming

The results shown in Table 4.4 indicate that methane and water vapor possess very high infrared absorption strength, which enables them to trap outgoing longwave radiation with high effectiveness. Methane demonstrated high heat-trapping efficiency and it contributes to rapid atmospheric warming because of its high climate impact despite its lower concentration. Nitrous oxide exhibited very high heat retention capability and persistent climatic impact because of its long atmospheric lifetime. Carbon dioxide showed high absorption characteristics which caused sustained long-term warming. Water vapor mainly functions as a climate feedback mechanism that increases existing warming patterns. Tropospheric ozone showed moderate absorption efficiency which results in localized atmospheric heating and radiative imbalance.

4.4 Temporal Increase in Greenhouse Gas Concentration

The concentration of greenhouse gases in Earth's atmosphere has increased continuously over recent decades due to anthropogenic activities such as fossil fuel combustion, industrialization, deforestation, and agricultural emissions. Monitoring historical concentration trends is essential for understanding long-term atmospheric warming and climate change patterns.

Table 4.5 Historical Increase in Atmospheric Greenhouse Gases

Year	CO ₂ (ppm)	CH ₄ (ppm)	N ₂ O (ppb)
1980	338	1.62	301
1990	354	1.72	310
2000	369	1.77	316
2010	390	1.81	323
2020	414	1.89	332
2025	420	1.92	335

The Table 4.5 indicate that levels of atmospheric GHGs have been steadily increasing since 1980 through 2025. Carbon dioxide rose by the most absolute amount (338 – 420 ppm) of the gases studied between 1980 and 2025. The concentration of methane grew slowly between 1.62 ppm and 1.92 ppm during the same time. The amount of nitrous oxide in the atmosphere increased from 301 ppb in 1980 to 335 ppb in 2025, with an ongoing build-up. The observed upward trends are mostly linked to the higher industrial activity, the consumption of fossil fuels, agricultural emissions and fast urbanization, all of which exert a significant effect on the increase in greenhouse warming.

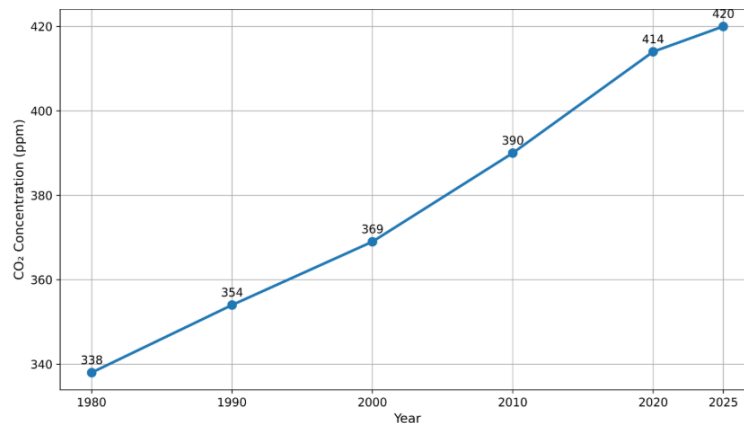


Figure 4.2 Increase in Atmospheric CO₂ Concentration (1980–2025) CO₂ Concentration (ppm)

The figure 4.2 shows the increase in carbon dioxide (CO₂) in the atmosphere since 1980 up until 2025. The concentration rose from 338 ppm in 1980 to 354 ppm in 1990 and further increased to 369 ppm in 2000. A significant rise was observed after 2000, reaching 390 ppm in 2010 and 414 ppm in 2020. In 2025, the amount of CO₂ in the atmosphere was 420ppm. The curve shows an overall rising trend in the concentration of CO₂, which is linked to industrialization, the use of fossil fuels and anthropogenic CO₂ emissions causing the rise in global warming.

4.5 Atmospheric Energy Balance Disturbance

Greenhouse gases significantly influence Earth’s atmospheric energy balance by regulating the absorption and re-emission of outgoing infrared radiation. Variations in greenhouse gas concentration alter the natural thermal equilibrium of the atmosphere, resulting in increased heat retention and surface warming.

Table 4.5 Effect of Greenhouse Gases on Earth’s Energy Balance

Parameter	Without Greenhouse Effect	Present Atmospheric Condition
Average Surface Temperature	−18°C	+15°C
Outgoing Infrared Radiation	High escape	Partial trapping
Atmospheric Heat Retention	Low	High
Surface Warming	Minimal	Significant

The Table 4.5 demonstrate the substantial impact of greenhouse gases on Earth’s thermal balance and climatic stability. The global surface temperature without greenhouse gases would drop to about −18°C which would make Earth mostly unlivable. The current

atmospheric conditions enable greenhouse gases to capture most of the outgoing infrared radiation which results in a surface temperature increase that reaches almost +15°C. The research demonstrates that atmospheric heat retention has increased because of the rising levels of greenhouse gases in the atmosphere. Excessive radiative trapping has resulted in increased surface warming while disrupting the natural atmospheric energy balance which exceeds sustainable climatic thresholds.

5. CONCLUSION

Based on the present study, it is concluded that GHGs have a basic part to play in controlling Earth's atmospheric temperature by absorbing and re-emitting infrared radiation. The research clearly shows that the enhancement of the natural radiative energy balance of Earth has led to increased global warming and climate change, due to the increase of GHGs (greenhouse gases) concentration in the atmosphere, such as CO₂, CH₄, N₂O, O₃ and H₂O. CO₂ was selected as the most important GHG for atmospheric warming due to its high concentration in the atmosphere, long atmospheric lifetime and the large radiative forcing contribution. Methane and nitrous oxide also had some powerful heat-trapping properties, but their levels in the atmosphere were relatively low.

It was also found that the greenhouse gas concentration has remained steady and will continue in the future until 2025, most notably because of industrialization, fossil-fuel use, transport, deforestation and agriculture. The radiative forcing analysis verified that GHGs increase the heat trapping in the atmosphere and play a large role in the increase of global temperatures. The study also highlighted the role of water vapour in regulating atmospheric feedback, which enhances warming. Overall, the study emphasizes the need for implementing effective measures to mitigate GHGs emissions, increase energy efficiency, and enhance climate policies to minimize future climatic risks and provide long-term environmental stability.

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