



Radiation Physics and Climate Change: Fundamental Processes and Environmental Impacts

Rohit Limbraj Mote

Assistant Professor, Department of Physics,

Arts, Science and Commerce College Naldurg, Dharashiv, Maharashtra-413602, India

Corresponding Author - Rohit Limbraj Mote

DOI - 10.5281/zenodo.22069896

Abstract:

Increased greenhouse gas emissions and climate change (also leading to heating of the atmosphere) are severe environmental issues now impacting the energy budget and global temperature distribution of the Earth. The basic framework for comprehending how energy enters, passes through, and exits the Earth system is provided by adiation physics. Changes in the equilibrium between incoming solar radiation and outgoing terrestrial radiation are intimately related to climate change. By absorbing, scattering, reflecting, and releasing electromagnetic radiation, atmospheric gasses, aerosols, clouds, ozone, and modifications to land and surface characteristics alter this equilibrium. The absorption of outgoing longwave radiation is improved by rising quantities of greenhouse gasses such carbon dioxide, methane, and nitrous oxide, resulting in positive radiative forcing and warming. At the same time, aerosols can scatter sunlight back to space or absorb radiation, producing regionally complex cooling and warming effects. Changes in stratospheric ozone also influence ultraviolet radiation and atmospheric temperature. Observations of global dimming and brightening demonstrate that variations in surface solar radiation can affect hydrological processes, ecosystems, agriculture, and cryospheric systems. Modern climate assessments increasingly use effective radiative forcing to quantify the influence of individual climate drivers. This review discusses the fundamental radiation processes responsible for climate change, including solar and terrestrial radiation, greenhouse-gas absorption, radiative forcing, aerosol-radiation interactions, cloud effects, ozone-related processes, and changes in surface radiation.

Keywords: *Radiation Physics, Climate, Greenhouse, Temperature.*

Introduction:

One of the biggest environmental and scientific problems of the twenty-first century is climate change. It is more crucial than ever to understand how the atmosphere is heated because of the buildup of greenhouse gasses, global warming, melting glaciers, rising sea

levels, and an increasing number of catastrophic atmospheric occurrences. One of the many scientific disciplines that are helping to understand climate and how solar energy interacts with the earth's atmosphere, land, and oceans is radiation physics. Understanding the earth's energy balance, the greenhouse effect, and the

mechanisms regulating atmospheric temperature is based on theoretical and experimental knowledge of radiation physics. Climate remains relatively stable when incoming and outgoing energy are approximately balanced. Any persistent alteration of this balance can change atmospheric and surface temperatures and initiate feedbacks throughout the climate system. Radiation physics therefore represents one of the fundamental scientific foundations for understanding climate change. The atmosphere is not transparent to all wavelengths of electromagnetic radiation. Different atmospheric constituents interact selectively with radiation according to their molecular and physical properties. Greenhouse gases absorb and emit longwave radiation, aerosols scatter and absorb shortwave and longwave radiation, clouds reflect incoming solar radiation and absorb terrestrial infrared radiation, while ozone strongly absorbs ultraviolet radiation and participates in radiative processes in the stratosphere. Changes in these constituents alter Earth's radiation budget and consequently influence climate. The development of radiative-transfer theory, satellite observations, ground-based radiation measurements, and climate models has substantially improved understanding of these processes. Forster *et al.* (2007) demonstrated that changes in atmospheric constituents can be expressed in terms of radiative forcing, providing a

quantitative framework for connecting atmospheric composition with climate response. Furthermore, the study of radiation physics contributes to our understanding of how clouds and aerosols affect climate regulation. While clouds have an impact on both solar reflectance and outgoing long-wave (infrared) radiation, the physical and chemical characteristics of aerosols determine whether they have a cooling or warming effect. One of the most complex scientific aspects of climate is the interplay between radiation and air particles, which is continuously being researched. The discipline of radiation physics has been increasingly important in the last several decades for the creation of climate change adaptation and mitigation strategies.

Fundamental Principles of Radiation Physics:

Radiation is the transfer of energy through electromagnetic waves or particles. In the climate system, electromagnetic radiation is particularly important because energy from the Sun reaches Earth primarily as shortwave radiation, while the warmed Earth emits energy predominantly as longwave infrared radiation. The solar spectrum reaching the top of the atmosphere includes ultraviolet, visible, and near-infrared wavelengths. A portion of this radiation is reflected directly to space by clouds, atmospheric particles, ice, snow,

and land surfaces. The remaining radiation is absorbed by the atmosphere and Earth's surface. The surface subsequently emits thermal infrared radiation according to its temperature. The relationship between temperature and emitted radiation is described by the Stefan-Boltzmann law. An idealized blackbody emits radiation according to:

$$E = \sigma T^4$$

where E is emitted radiative energy, σ is the Stefan-Boltzmann constant, and T is absolute temperature. Consequently, even relatively small changes in surface temperature can produce substantial changes in outgoing longwave radiation. The wavelength distribution of emitted radiation is described by Planck's law. Because the Earth is much cooler than the Sun, terrestrial radiation is concentrated primarily in the infrared region. This spectral difference is important because atmospheric gases interact differently with shortwave solar radiation and longwave terrestrial radiation. The Earth's radiation budget represents the balance between absorbed solar radiation and outgoing longwave radiation. At the top of the atmosphere, approximately one-third of incoming solar radiation is reflected back to space, while the remainder is absorbed by the atmosphere, land, and oceans. The balance is influenced by atmospheric composition, cloud cover, surface albedo, aerosols, and solar variability. If the Earth

absorbs more energy than it emits, energy accumulates within the climate system and temperatures rise. Conversely, if outgoing energy exceeds incoming energy for a sustained period, cooling occurs. Modern assessments use effective radiative forcing (ERF) to evaluate how different perturbations modify the Earth's energy balance. Myhre *et al.* (2013) showed that anthropogenic greenhouse gases produce substantial positive radiative forcing, while aerosols provide an important offsetting negative forcing. The IPCC assessment indicates that human-caused radiative forcing has become strongly positive because of increasing greenhouse-gas concentrations, with aerosol effects partially counteracting this warming influence.

Greenhouse Effect and Longwave Radiation:

The natural greenhouse effect is essential for maintaining temperatures suitable for life. Water vapour, carbon dioxide, methane, nitrous oxide, ozone, and other gases absorb specific wavelengths of terrestrial infrared radiation. These gases subsequently emit radiation in different directions, including back toward the Earth's surface. Human activities have increased atmospheric concentrations of several greenhouse gases. Fossil-fuel combustion, industrial activity, agriculture, land-use change, and other activities have altered atmospheric

composition. Increased greenhouse-gas concentrations increase the probability that outgoing infrared radiation will be absorbed before escaping to space. This process produces positive radiative forcing. The climate system responds by warming until outgoing radiation increases sufficiently to restore energy balance. Myhre *et al.* (2013) emphasized that anthropogenic increases in well-mixed greenhouse gases have substantially enhanced the greenhouse effect. Carbon dioxide is particularly important because of its long atmospheric persistence and strong influence on the radiative balance. Methane and nitrous oxide are present at lower concentrations but have significant radiative efficiencies. Water vapour acts primarily as a feedback rather than a direct long-term anthropogenic forcing because its atmospheric concentration is strongly controlled by temperature. Cloud feedbacks are particularly complex. Clouds influence climate by reflecting incoming sunlight while simultaneously trapping outgoing infrared radiation. The balance between these effects depends on cloud altitude, thickness, optical properties, geographic distribution, and particle characteristics. Boucher *et al.* (2013) identified clouds and aerosols as major sources of uncertainty in estimates of the Earth's changing energy budget.

Aerosols and Radiation Interactions:

Atmospheric aerosols are tiny solid or liquid particles suspended in air. They originate from natural sources such as dust, sea spray, volcanic activity, and biological emissions, as well as anthropogenic sources including fossil-fuel combustion, industrial processes, biomass burning, and transportation. Aerosols influence radiation through direct and indirect mechanisms. Direct interactions involve scattering and absorption of solar radiation. Sulfate and many other light-coloured particles tend to scatter sunlight and can produce a cooling effect. Black carbon strongly absorbs solar radiation and can warm the atmosphere.

Aerosols also influence clouds by acting as cloud condensation nuclei. Changes in aerosol number and properties can modify cloud droplet concentrations, sizes, lifetimes, and reflectivity. These aerosol-cloud interactions contribute significant uncertainty to climate forcing estimates. Samset *et al.* (2018) highlighted that absorbing aerosols can alter atmospheric stability, cloud properties, circulation, and the hydrological cycle. Boucher *et al.* (2013) similarly emphasized the importance of aerosol-cloud interactions in understanding climate forcing.

Global Dimming and Brightening:

Radiation measurements have revealed substantial multidecadal changes

in surface solar radiation. The terms "global dimming" and "global brightening" describe periods of decreasing and increasing surface solar radiation, respectively. Wild *et al.* (2009) reported widespread decreases in surface solar radiation from approximately the 1950s to the 1980s, followed by partial recovery at many locations. These changes were associated with variations in atmospheric aerosols and clouds. Wild *et al.* (2012) further demonstrated that changes in surface solar radiation have implications for temperature, evaporation, hydrological processes, glacier melting, and terrestrial ecosystems. The phenomenon illustrates the importance of considering both greenhouse-gas warming and changes in atmospheric transparency. Strong aerosol pollution can reduce solar radiation reaching the surface and partially mask greenhouse-gas warming. When aerosol emissions decline, surface solar radiation may increase, potentially revealing more of the underlying greenhouse-gas warming. Bais *et al.* (2015) demonstrated that aerosols, clouds, surface reflectivity, and other atmospheric elements all have an impact on surface UV radiation in addition to ozone. The intricate relationships between ozone depletion, UV radiation, atmospheric processes, ecosystems, and climate change were further highlighted by Bais *et al.* (2018). The recovery of stratospheric ozone following reductions in ozone-depleting substances

demonstrates the importance of international environmental policies. However, climate change can itself modify ozone chemistry and atmospheric circulation, making the ozone-climate relationship complex.

Radiation Physics and the Cryosphere:

Snow and ice strongly influence Earth's radiation balance because of their high albedo. They reflect a substantial fraction of incoming solar radiation back to space. When warming reduces snow and ice cover, darker land or ocean surfaces become exposed, increasing solar absorption. This produces a positive feedback that can amplify regional and global warming. Changes in surface radiation are particularly important in polar regions, where snow and ice conditions can change rapidly. The loss of sea ice also modifies the amount of solar energy absorbed by the ocean. Dark ocean surfaces absorb much more solar radiation than reflective sea ice. Consequently, changes in radiation and cryospheric cover interact in a feedback loop that can accelerate regional warming.

Environmental and Human Impacts:

Radiation-driven climate change has broad environmental consequences. Increasing temperatures can alter species distributions, ecosystem productivity, water availability, agricultural systems, and the frequency of climate extremes.

Changes in UV radiation can affect human health, terrestrial vegetation, aquatic organisms, and materials. Bais *et al.* (2018) reported that interactions among ozone depletion, UV radiation, and climate change can influence ecosystems and environmental processes in complex ways. Changes in aerosol concentrations also have important environmental consequences. While reducing particulate pollution provides major benefits for human health, reductions in cooling aerosols can reveal additional greenhouse-gas-induced warming. Therefore, climate policy must consider both air-quality benefits and changes in radiative forcing.

Role of Radiation Physics in Climate Modelling:

Radiative-transfer calculations are central to modern climate models. Models divide the electromagnetic spectrum into wavelength bands and calculate absorption, emission, scattering, and transmission through the atmosphere. Accurate representation of greenhouse gases, aerosols, clouds, ozone, water vapour, surface albedo, and solar variability is essential for reliable climate projections. Improvements in satellite measurements and atmospheric observations have strengthened constraints on radiative processes. The IPCC Sixth Assessment Report emphasizes that radiative forcing is a fundamental driver of changes in the Earth's energy budget. The

assessed total anthropogenic effective radiative forcing for 1750–2019 was strongly positive, dominated by greenhouse gases and partly offset by aerosols.

Future Research Perspectives:

Several challenges remain in radiation-climate research. Aerosol-cloud interactions remain difficult to quantify because aerosol properties vary greatly in space and time. Cloud feedbacks continue to represent an important uncertainty in climate sensitivity. Improved measurements of atmospheric composition, surface radiation, cloud properties, and aerosol optical characteristics are therefore required. Satellite observations, ground-based radiation networks, spectroscopic measurements, and high-resolution climate models can help improve understanding. Artificial intelligence and machine-learning approaches may also assist in identifying relationships between radiation measurements, atmospheric composition, and climate variables. Future research should increasingly integrate atmospheric physics, remote sensing, environmental chemistry, ecology, and climate modelling. Such interdisciplinary approaches can provide improved estimates of regional radiative forcing and environmental impacts.

Conclusion:

Radiation physics provides a fundamental explanation for the mechanisms through which human activities influence Earth's climate. Changes in greenhouse-gas concentrations modify longwave radiation and produce positive radiative forcing, while aerosols and clouds influence both incoming solar and outgoing terrestrial radiation. Ozone changes modify ultraviolet radiation and interact with atmospheric chemistry and climate. Variations in surface solar radiation, including global dimming and brightening, demonstrate that atmospheric transparency can strongly influence climate and environmental processes. The environmental consequences extend beyond temperature changes to the hydrological cycle, cryosphere, ecosystems, agriculture, and human health. Modern effective radiative forcing frameworks provide an important quantitative basis for evaluating these processes. Continued improvements in radiation measurements, satellite observations, atmospheric modelling, and climate simulations will be essential for reducing uncertainties.

References:

1. Bais, A. F., Lucas, R. M., Bornman, J. F., Williamson, C. E., Sulzberger, B., Austin, A. T., ... & Heikkilä, A. M. (2018). Environmental effects of ozone depletion, UV radiation and

interactions with climate change: UNEP Environmental Effects Assessment Panel, update 2017. *Photochemical & Photobiological Sciences*, 17(2), 127-179.

2. Bais, A. F., McKenzie, R. L., Bernhard, G., Aucamp, P. J., Ilyas, M., Madronich, S., & Tourpali, K. (2015). Ozone depletion and climate change: impacts on UV radiation. *Photochemical & Photobiological Sciences*, 14(1), 19-52.
3. Boucher, O., Randall, D., Artaxo, P., Bretherton, C., Feingold, G., Forster, P., ... & Zhang, X. Y. (2013). Clouds and aerosols. In *Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change* (pp. 571-657). Cambridge University Press.
4. Forster, P., Ramaswamy, V., Artaxo, P., Bernsten, T., Betts, R., Fahey, D. W., ... & Whorf, T. (2007). Changes in atmospheric constituents and in radiative forcing. *Climate change 2007: The physical science basis. Contribution of working group I to the 4th assessment report of the intergovernmental panel on climate change*.
5. Myhre, G., Shindell, D., Bréon, F. M., Collins, W., Fuglestedt, J.,

- Huang, J., ... & Zhang, H. (2014). Anthropogenic and natural radiative forcing. *Climate Change 2013-The Physical Science Basis*, 659-740.
6. Samset, B. H., Stjern, C. W., Andrews, E., Kahn, R. A., Myhre, G., Schulz, M., & Schuster, G. L. (2018). Aerosol absorption: Progress towards global and regional constraints. *Current climate change reports*, 4(2), 65-83.
7. Solomon, S., Portmann, R. W., & Thompson, D. W. (2007). Contrasts between Antarctic and Arctic ozone depletion. *Proceedings of the National Academy of Sciences*, 104(2), 445-449.
8. Wild, M. (2009). Global dimming and brightening: A review. *Journal of Geophysical Research: Atmospheres*, 114(D10).
9. Wild, M., Gilgen, H., Roesch, A., Ohmura, A., Long, C. N., Dutton, E. G., ... & Tsvetkov, A. (2005). From dimming to brightening: Decadal changes in solar radiation at Earth's surface. *Science*, 308(5723), 847-850.