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Atmospheric Radiative Transfer and Its Role in Global Warming

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Abstract: *This article reviews the procedures of atmospheric radiative transfer as it relates to understanding the Earth's energy budget and mechanisms involved in global warming. It brings together existing information on the processes involved in radiative transfer within the atmosphere and examines the contribution of greenhouse gases (GHG's), aerosols, and clouds to the modulation of longwave & shortwave radiation transfer to/from the Earth. The article discusses the effects of anthropogenic emissions from* CO_2, CH_4, N_2O *& synthetic halocarbons on radiative forcing and the resulting amplification of the greenhouse effect. It discusses recent advances in line-by-line radiative transfer modelling, satellite remote sensing, and general circulation model (GCM) parametrizations that have been developed utilising all available measurements of the atmosphere. The article will discuss some of the current key uncertainties surrounding cloud-radiative feedbacks & aerosol indirect effects, and indicate potential new avenues for future research on this topic.*

Keywords*:* radiative transfer, greenhouse effect, radiative forcing, global warming, aerosols, clouds, climate feedback

I. INTRODUCTION

Electromagnetic radiation exchanged between the Sun, Earth's surface, and atmosphere drives Earth's Climate System. Radiative transfer, how radiation moves through a medium that absorbs, emits, and scatters radiation, determines thermal properties of the atmosphere and thus surface temperatures. Greenhouse gas concentrations have increased since the start of the industrial era, which disrupts this balance, yielding a net positive radiative forcing that is the primary cause of observed global warming (Myhre et al., 2013).

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) estimates the anthropogenic radiative forcing due to greenhouse gases relative to 1750 at a total of +2.29 W m−2 (with a 95% confidence interval of 1.13 to 3.33 W m−2) with CO2 alone contributing +1.68 W m−2 (Myhre et al., 2013). Radiative transfer and knowledge of atmospheric composition, temperature profiles, as well as cloud and aerosol characteristics are required for understanding the different mechanisms by which radiative forcing occurs.

We provide an overview of the principles of Atmospheric Radiative Transfer (ART), including a survey of the characteristics of individual constituents that are radiatively active in the atmosphere, an examination of current modelling technologies, and a discussion on how observations can be used as constraints to model predictions. In addition, we provide a list of the most pressing uncertainties related to ART, along with emerging research areas where further investment would significantly improve scientific understanding of art.

II. FUNDAMENTALS OF ATMOSPHERIC RADIATIVE TRANSFER

The Radiative Transfer Equation

The radiative transfer equation (RTE) describes the change in spectral radiance $I\nu$ as radiation passes through a medium:

$dI\nu/ds = -k\nu\rho I\nu + k\nu\rho B\nu(T)$

where kν is the mass absorption coefficient, ρ is the air density, and Bν(T) is the Planck function at temperature T. This equation must account for absorption, emission, and scattering by gases, aerosols, and cloud particles across a wide spectral range (Liou, 2002). In the thermal infrared (4–100 µm), emission and absorption dominate; in the solar spectrum (0.2–4 µm), scattering is also critical.

Earth's Energy Budget

At the top of the Earth's atmosphere (TOA), approximately 1361 W m-2 of solar irradiance is received, with about 30% of that being reflected to space (the planetary albedo), and approximately 70% being absorbed by the surface and atmosphere (Stephens et al. 2012). The surface emits longwave radiative energy (~ 396 W m-2) and is partially absorbed by the GHGs and then re-emitted. As a result, the net upward longwave flux at TOA is reduced to approximately 239 W m-2. The difference between the absorbed solar radiation (that which is intercepted by the planet) and the outgoing longwave radiation determines the planetary energy imbalance, which is currently estimated to be approximately 0.6 W m-2 (Hansen et al. 2011), consistent with the observed ocean heat uptake.

III. GREENHOUSE GASES AND RADIATIVE FORCING

Carbon Dioxide

To date, carbon dioxide has been the most significant manmade greenhouse gas. Carbon dioxide absorbs most strongly in the 15 µm band, and to a lesser extent in the 4.3 µm band as an overtone. The concentration of carbon dioxide in the atmosphere exceeded 410 ppm in 2019; this represents an increase of about 46 per cent over the pre-industrial equivalent of 280 ppm (Keeling et al., 1958; NOAA/ESRL, 2019). The effect of carbon dioxide upon radiative forcing is logarithmic to concentration, which means that at each doubling of carbon dioxide concentration, about 3.7 Watts/m2 of radiative forcing will result (Myhre et al., 1998). The high accuracy and resolution needed to accurately describe carbon dioxide absorption require data from high-resolution spectral databases such as HITRAN (Gordon et al., 2017), which contains millions of lines of spectral data.

Other Well-Mixed Greenhouse Gases

Methane has a 20-year global warming potential that is 84 times greater than that of carbon dioxide. Methane absorbs in 3.3 µm and 7.7 µm bands of the electromagnetic spectrum. Although present in very low concentrations, nitrous oxide and halocarbons (e.g., CFCs, HFCs) are very significant contributors to radiative forcing due to their high absorption per molecule (Etminan et al., 2016). Collectively, these gases correspond to around 0.97 Watts/m2 of radiative forcing in addition to carbon dioxide.

Water Vapour

Water vapour is the most powerful greenhouse gas (GHG) in terms of absolute radiative effect and contributes approximately 50% of the greenhouse effect in clear-sky conditions (Schmidt et.al. 2010). Initially, water vapour acts as a feedback mechanism rather than a forcing mechanism. As temperature increases within the climate system, atmospheric water vapour increases according to the Clausius-Clapeyron relation (~7% per K), which produces an approximate 1.8- fold amplification of the original warming (Soden & Held, 2006).

IV. AEROSOLS, CLOUDS, AND RADIATIVE FEEDBACKS

Aerosol Radiative Effects

Aerosols interact with radiation through direct scattering and absorption (direct effect) and by modifying cloud microphysics (indirect effects). The direct aerosol effect is estimated at -0.45 W m^{-2} globally, though with large uncertainty (±0.5 W m^{-2}) owing to spatial heterogeneity in composition and optical properties (Boucher et al., 2013). Absorbing aerosols—primarily black carbon—warm the atmosphere while cooling the surface, potentially altering precipitation patterns and the atmospheric lapse rate (Bond et al., 2013). The aerosol indirect effect, whereby aerosols increase cloud droplet number concentration and thereby cloud albedo, is estimated at -0.45 W m^{-2} but carries the largest uncertainty of any forcing agent.

Cloud-Radiative Feedbacks

Clouds exert a net cooling effect of approximately −20 W m^{-2} on the current climate, reflecting solar radiation (shortwave cloud forcing ≈ −47 W m^{-2}) while simultaneously trapping longwave radiation (+27 W m^{-2}) (Hartmann et al., 1992). How this balance shifts in a warming climate is the largest source of uncertainty in climate sensitivity estimates. Low-level clouds, in particular marine stratocumulus, are projected to decrease in extent as sea surface temperatures rise, providing a positive feedback (Zelinka et al., 2017). High cirrus clouds, by contrast, exert a positive longwave forcing, and their response to warming involves complex microphysical processes.

V. RADIATIVE TRANSFER MODELING

Line-by-Line Models

LBL models, such as LBLRTM (Clough et al., 2005) and ARTS (Buehler et al., 2018), compute the individual molecular absorption lines across the entire spectrum; hence, they are the most accurate models available. The development of simplified parameterizations, which are used in GCMs, is based on the support received from LBL models, as they have been compared to the ARM spectroradiometric observations on a continuous basis.

Band Models and Correlated-k Methods

For GCMs to operate efficiently, band models approximate the spectrally averaged radiative fluxes. CKD is a method of segregating the spectral interval by absorption coefficient, so that computations can be performed with accuracy at a fraction of the LBL cost (Fu & Liou, 1992). The most commonly used radiation scheme in operational climate models is RRTMG (Iacono et al., 2008). The results of comparing RRTMG with LBL reference calculations indicate that typically the flux error will be ≤ 1 W m−2.

Remote Sensing and Observational Constraints

Satellite instruments are key components for constraining parameterizations of radiative transfer. Satellite instruments such as the Clouds and Earth's Radiant Energy System (CERES) have achieved unprecedented accuracy in measuring top-of-atmosphere (TOA) radiative fluxes (Loeb et al. 2018). Satellite instruments also include the Moderate Resolution Imaging Spectroradiometer (MODIS). MODIS provides global observations of aerosol optical depth, cloud fraction, and cloud optical thickness. Hyperspectral measurements from Satellite instruments such as the Infrared Atmospheric Sounding Interferometer (IASI) and Atmospheric Infrared Sounder (AIRS) permit the determination of greenhouse gas (GHG) concentrations and atmospheric temperature profiles (Chahine et al. 2006).

VI. RADIATIVE FORCING, CLIMATE SENSITIVITY, AND OBSERVED WARMING

The equilibrium climate sensitivity (ECS) is defined as the temperature change in the global average surface temperature caused by a doubling of carbon dioxide (CO2) in the atmosphere; the ECS is estimated to range from 1.5 to 4.5 degrees Kelvin (K) and has not changed significantly from 1.5 to 4.5 K since the publication of the Charney Report in 1979. However, the feedback from clouds is responsible for most of the uncertainty in the ECS (Sherwood et al., 2014). The transient climate response (TCR)—a measure of the temperature response to increased CO2 on relevant policy timeframes—is estimated at 1.0 to 2.5 K/doubling CO2.

The temperature change from preindustrial to the present time is estimated at approximately 1.0 °C, consistent with the estimated effective radiative forcing (ERF) from greenhouse gases, aerosol cooling and variability, and the estimated transient climate response (TCR) (IPCC, 2018). The ERF takes into account adjustments within the atmosphere and generally provides a more reliable measure of the temperature response than does the instantaneous radiative forcing. The ERF is increasingly being used as the measure of impact in studies of the attribution of climate change (Sherwood et al., 2015).

VII. DISCUSSION AND FUTURE DIRECTIONS

Although considerable progress has been made in the field of atmospheric radiative transfer, there are still many areas where there is limited knowledge. The uncertainty associated with the representation of cloud-radiation interactions in global climate models (GCMs) represents one of the largest sources of uncertainty associated with future climate projections. Using large eddy simulation (LES) models to study low-level cloud feedback processes by using a detailed microphysics model is one approach that has the potential to better constrain these low-level cloud feedbacks (Schneider et al., 2017). There remains uncertainty regarding how near-infrared solar radiation is absorbed by water vapour and other gases, and recent studies indicate that the parameterization of these absorptions is likely to be underestimated by 15-25 W m-2 for cloudy conditions (Trenberth et al., 2009).

The direct and indirect radiative effects of water vapour in the upper troposphere and stratosphere, both of which are controlled by tropical cold-point temperature and deep convection, have yet to be accurately represented in GCMs. Further study is also needed to determine how primary organic aerosol and secondary organic aerosol (SOA) formation can modify direct and indirect radiative effects (Jimenez et al., 2009). Advances in machine learning could lead to the ability to perform computationally-intensive line-by-line (LBL) calculations in much less time, which may result in the ability to create reliable radiation schemes for kilometer (km) scale models (Chevallier et al., 1998).

VIII. CONCLUSION

The greenhouse effect is primarily driven by the greenhouse effect and emits carbon dioxide into the atmosphere, resulting in atmospheric emissions that contribute to global warming. This article has discussed the basic principles of radiation and how individual Greenhouse Gases (GHG), aerosols, and clouds all play a role in the Earth's energy balance through Radiation Transfer, as well as the tools available to estimate the radiation emitted from each of these sources. Although the fundamentals of radiative transfer are known, significant uncertainties exist in understanding cloud-radiative feedbacks (in particular) and aerosol-cloud interactions, both of which hinder efforts to better constrain climate sensitivity. Continued refinements in satellite observational databases, higher resolution process modelling, and an improved spectral database will be essential for diminishing these uncertainties and providing a better foundation for reliable climate predictions for the rest of the century.

REFERENCES

[1]. Bond, T. C., et al. (2013). Bounding the role of black carbon in the climate system: A scientific assessment. Journal of Geophysical Research: Atmospheres, 118(11), 5380–5552.

[2]. Boucher, O., et al. (2013). Clouds and aerosols. In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the IPCC. Cambridge University Press.

[3]. Buehler, S. A., et al. (2018). ARTS, the Atmospheric Radiative Transfer Simulator—version 2.2, the planetary toolbox edition. Geoscientific Model Development, 11(4), 1537–1556.

[4]. Chahine, M. T., et al. (2006). AIRS: Improving weather forecasting and providing new data on greenhouse gases. Bulletin of the American Meteorological Society, 87(7), 911–926.

[5]. Chevallier, F., Chéruy, F., Scott, N. A., & Chédin, A. (1998). A neural network approach for a fast and accurate computation of a longwave radiative budget. Journal of Applied Meteorology, 37(11), 1385–1397.

[6]. Clough, S. A., et al. (2005). Atmospheric radiative transfer modeling: A summary of the AER codes. Journal of Quantitative Spectroscopy and Radiative Transfer, 91(2), 233–244.

[7]. Etminan, M., Myhre, G., Highwood, E. J., & Shine, K. P. (2016). Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. Geophysical Research Letters, 43(24), 12,614–12,623.

[8]. Fu, Q., & Liou, K. N. (1992). On the correlated k-distribution method for radiative transfer in nonhomogeneous atmospheres. Journal of the Atmospheric Sciences, 49(22), 2139–2156.

[9]. Gordon, I. E., et al. (2017). The HITRAN2016 molecular spectroscopic database. Journal of Quantitative Spectroscopy and Radiative Transfer, 203, 3–69.

[10]. Hansen, J., et al. (2011). Earth's energy imbalance and implications. Atmospheric Chemistry and Physics, 11(24), 13421–13449.

[11]. Hartmann, D. L., Ockert-Bell, M. E., & Michelsen, M. L. (1992). The effect of cloud type on Earth's energy balance: Global analysis. Journal of Climate, 5(11), 1281–1304.

[12]. Iacono, M. J., et al. (2008). Radiative forcing by long-lived greenhouse gases: Calculations with the AER radiative transfer models. Journal of Geophysical Research: Atmospheres, 113(D13), D13103.

[13]. IPCC (2018). Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels. Masson-Delmotte, V. et al. (eds.). World Meteorological Organization, Geneva.

[14]. Jimenez, J. L., et al. (2009). Evolution of organic aerosols in the atmosphere. Science, 326(5959), 1525–1529.

[15]. Keeling, C. D., et al. (1958). The concentration and isotopic abundances of atmospheric carbon dioxide in rural areas. Geochimica et Cosmochimica Acta, 13(4), 322–334.

[16]. Liou, K. N. (2002). An Introduction to Atmospheric Radiation (2nd ed.). Academic Press.

[17]. Loeb, N. G., et al. (2018). Clouds and the Earth's Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) Top-of-Atmosphere (TOA) Edition-4.0 data product. Journal of Climate, 31(2), 895–918.

[18]. Myhre, G., et al. (1998). New estimates of radiative forcing due to well mixed greenhouse gases. Geophysical Research Letters, 25(14), 2715–2718.

[19]. Myhre, G., et al. (2013). Anthropogenic and natural radiative forcing. In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the IPCC. Cambridge University Press.

[20]. NOAA/ESRL (2019). Trends in Atmospheric Carbon Dioxide. Global Monitoring Division, Earth System Research Laboratory.

[21]. Schmidt, G. A., et al. (2010). Attribution of the present-day total greenhouse effect. Journal of Geophysical Research: Atmospheres, 115(D20), D20106.

[22]. Schneider, T., et al. (2017). Climate goals and computing the future of clouds. Nature Climate Change, 7(1), 3–5.

[23]. Sherwood, S. C., et al. (2014). Spread in model climate sensitivity traced to atmospheric convective mixing. Nature, 505(7481), 37–42.

[24]. Sherwood, S. C., Bony, S., Boucher, O., Bretherton, C., Forster, P. M., Gregory, J. M., & Stevens, B. (2015). Adjustments in the forcing-feedback framework for understanding climate change. Bulletin of the American Meteorological Society, 96(2), 217–228.

[25]. Soden, B. J., & Held, I. M. (2006). An assessment of climate feedbacks in coupled ocean-atmosphere models. Journal of Climate, 19(14), 3354–3360.

[26]. Stephens, G. L., et al. (2012). An update on Earth's energy balance in light of the latest global observations. Nature Geoscience, 5(10), 691–696.

[27]. Trenberth, K. E., Fasullo, J. T., & Kiehl, J. (2009). Earth's global energy budget. Bulletin of the American Meteorological Society, 90(3), 311–324.

[28]. Zelinka, M. D., Randall, D. A., Webb, M. J., & Klein, S. A. (2017). *Clearing clouds of uncertainty.* Nature Climate Change, 7(10), 674–678.

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