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CO_2, the greenhouse effect and global warming: from the pioneering work of Arrhenius and Callendar to today's Earth System Models

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Climate warming during the course of the twenty-first century is projected to be between 1.0 and 3.7 °C depending on future greenhouse gas emissions, based on the ensemble-mean results of state-of-the-art Earth System Models (ESMs). Just how reliable are these projections, given the complexity of the climate system? The early history of climate research provides insight into the understanding and science needed to answer this question. We examine the mathematical quantifications of planetary energy budget developed by Svante Arrhenius (1859–1927) and Guy Stewart Callendar (1898–1964) and construct an empirical approximation of the latter, which we show to be successful at retrospectively predicting global warming over the course of the twentieth century. This approximation is then used to calculate warming in response to increasing atmospheric greenhouse gases during the twenty-first century, projecting a temperature increase at the lower bound of results generated by an ensemble of ESMs (as presented in the latest assessment by the Intergovernmental Panel on Climate Change). This result can be interpreted as follows. The climate system is conceptually complex but has at its heart the physical laws of radiative transfer. This basic, or ''core'' physics is relatively straightforward to compute mathematically, as exemplified by Callendar's calculations, leading to quantitatively robust projections of baseline warming. The ESMs include not only the physical core but also climate feedbacks that introduce uncertainty into the projections in terms of magnitude, but not sign: positive (amplification of warming). As such, the projections of end-of-century global warming by ESMs are fundamentally trustworthy: quantitatively robust baseline warming based on the well-understood physics of radiative transfer, with extra warming due to climate feedbacks. These projections thus provide a compelling case that global climate will continue to undergo significant warming in response to ongoing emissions of CO_2 and other greenhouse gases to the atmosphere.

Introduction

Climate change is a major risk facing mankind. At the United Nations Climate Change Conference held in Paris at the end of last year, 195 countries agreed on a plan to reduce emissions of CO_2 and other greenhouse gases, aiming to limit global temperature increase to well below 2 °C (relative to pre-industrial climate, meaning a future warming of less than 1.4 °C because temperature had already increased by 0.6 °C by the end of the twentieth century). The link between CO_2 and climate warming has caught the attention of scientists and politicians, as well as the general public, via the well-known "greenhouse effect" (Figure 1). Solar radiation passes largely unhindered through the atmosphere, heating the Earth's surface. In turn, energy is re-emitted as infrared, much of which is absorbed by CO_2 and water vapour in the atmosphere, which thus acts as a blanket surrounding the Earth. Without this natural greenhouse effect, the average surface temperature would plummet to about −21 °C,[1] rather less pleasant than the 14 °C experienced today.

The concentration of CO_2 in the atmosphere is increasing year on year as we burn fossil fuels, which enhances the natural greenhouse effect and warms the planet. To what extent, then, must CO_2 emissions be kept under control in order to restrict global temperature rise to within 2 °C? The projections of complex Earth System Models (ESMs) provide quantitative answers to this question. Run on supercomputers, these models integrate the many processes taking place in the atmosphere, on land and in the ocean. According to the Intergovernmental Panel on Climate

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[1] Andrew A. Lacis, Gavin A. Schmidt, David Rind, and Reto A. Ruedy, "Atmospheric CO_2: Principal Control Knob Governing Earth's Temperature," *Science* 330 (2010): 356–59.

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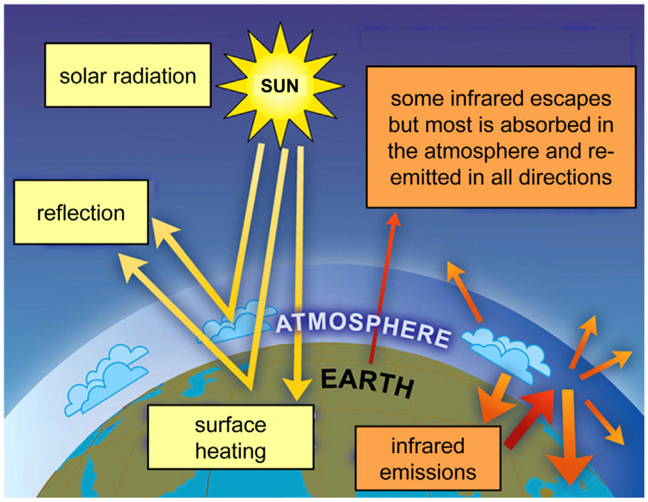

Figure 1. The ''greenhouse effect.'' The radiative balance between incoming solar radiation (yellow arrows) and the absorption of re-emitted infrared radiation by the atmosphere (orange arrows) drive surface heating. Adapted from: IPCC, *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press, 2007), 115.

Change (IPCC), the latest results of these models indicate that the temperature increase during the course of the twenty-first century will be between 1.0 and 3.7 °C, depending on the future emissions of greenhouse gases.[2] Taking into consideration the statistical properties of the ensemble of ESMs, and past observed warming, projected global temperatures are likely to exceed 2 °C above pre-industrial times for higher emission scenarios, with "likely" being defined as with a probability between 66 and 100%. This threshold can, however, likely be avoided in a low emission scenario. What are we to make of such statements and just how trustworthy are these projections?

The climate system is considerably more complex than the simple greenhouse paradigm described above. System feedbacks include changes in the circulation of the atmosphere and ocean (redistributing heat around the globe), the melting of snow and ice (altering albedo: the reflection of solar radiation from the Earth's surface), sequestration of CO_2 by plants, changes to the amount and types of clouds, and altered atmospheric water vapour (a warmer atmosphere holds more water), among others. The need to include all these processes, as well as the fact that objective quantification of associated uncertainties is problematic,[3] provides an easy opportunity for misinformation and disharmony. The media struggle to accurately communicate climate science, often leading to an emphasis on confusion and uncertainty when presenting the climate change debate.[4]

In some instances, there has been direct criticism of the trustworthiness of the ESMs within the peer-reviewed literature. Gregor Betz, for example, remarks that "it's not even clear that discrete simulations yield individually plausible or relevant projections."[5]

In this article, we delve into the history of climate science, notably the early "pen-and-paper" models of planetary energy budget by Svante Arrhenius (1859–1927) and Guy Stewart Callendar (1898–1964).[6] Arrhenius was primarily interested in the causes of the ice ages, whereas Callendar is remembered for his work linking warming to human-made burning of fossil fuels, the so-called "Callendar Effect."[7] Both models illustrate the role of the "greenhouse" physics of radiative transfer (the passage and attenuation of radiation in the atmosphere by absorption and scattering) in global warming, in the absence of feedbacks (with the exception of water vapour). We construct an empirical approximation of Callendar's model and show that it successfully generates a retrospective forecast of warming during the twentieth century. The same model is then used to make projections of warming to the end of the current century and compared with equivalent simulations made by today's ESMs (which include a range of system feedbacks), as presented in the latest IPCC assessment report.[8] Based on this comparison, we will conclude by presenting the case for the trustworthiness of ESMs as regards their projection of global warming during the twenty-first century.

Arrhenius: CO_2 and the ice ages

During the eighteenth century, early geologists noticed that giant boulders, today known as "erratics," were scattered across much of Europe, far beyond the Alpine mountains from which they originated. How did they get there? Noah's flood was one obvious suggestion. Or maybe they were the result of cataclysmic volcanic activity. The actual cause turned out to be as remarkable as it was profound. Jean de Charpentier, a mining engineer, travelled to the Rhône Valley in the 1830s and suggested that the huge blocks of granite he saw there had been transported from afar by glaciers. Soon afterwards, Louis Agassiz, the famous Swiss-born naturalist and geologist, proposed that great ice ages had gripped the Earth during the previous millions of years of its history.[9] Deep valleys were carved into the landscape as large parts of Europe, North America, and South America were covered by expanding ice sheets and glaciers, carrying with them the mysterious boulders. Woolly mammoths, mastodons, and other wild animals roamed the surrounding areas, experiencing temperatures some five degrees colder than today.[10]

What, then, was the cause of changes in the temperature of the Earth sufficient to drive the ice ages? Even today, we

[2] IPCC, *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press, 2013). Warming is specified relative to the reference period, 1986–2005, and the figures represent ensemble-mean results of the ESMs.

[3] D. A. Stainforth, M. R. Allen, E. R. Tredge, and L. A. Smith, "Confidence, Uncertainty and Decision-Support Relevance in Climate Predictions," *Philosophical Transactions of the Royal Society A* 365 (2007): 2145–61.

[4] Liisa Antilla, "Climate of Scepticism: US Newspaper Coverage of the Science of Climate Change," *Global Environmental. Change* 15 (2005): 338–52; Maxwell T. Boykoff, "Lost in Translation? United States Television News Coverage of Anthropogenic Climate Change, 1995–2004," *Climate Change* 86 (2008): 1–11.

[5] Gregor Betz, "Are Climate Models Credible Worlds? Prospects and Limitations of Possibilistic Climate Prediction," *European Journal for Philosophy of Science* 5 (2015): 191–215.

[6] We use the word "model" to describe any set of equations used to estimate climate, ranging from simple to very complex.

[7] James R. Fleming, *The Callendar Effect* (Boston: American Meteorological Society, 2007).

[8] IPCC, *Climate Change 2013* (ref. 2).

[9] Louis Agassiz, *Études sur les glaciers* (Neuchatel: Jent et Gassmann, 1840).

[10] J. D. Annan and J. C. Hargreaves, "A New Global Reconstruction of Temperature Changes at the Last Glacial Maximum," *Climate of the Past* 9 (2013): 367–76.