Climate change

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Stratospheric cooling explained

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Models have long predicted, and satellites have observed, stratospheric cooling from rising anthropogenic carbon dioxide, yet its magnitude and structure have lacked a robust theoretical explanation — until now.

When Manabe and Wetherald conducted the first computer simulations of global warming in the 1960s, they found that rising carbon dioxide concentrations not only warmed Earth's surface, as expected, but also cooled the stratosphere — the layer of the atmosphere extending from roughly 15 to 50 kilometres above the surface[1] (Fig. 1). This initially surprising result has proven remarkably robust, appearing consistently in every generation of climate models, and has been confirmed by decades of satellite observations, making stratospheric cooling one of the most salient fingerprints of global warming driven by anthropogenic carbon dioxide[2]. Yet, despite its importance, our theoretical understanding of this cooling — particularly what sets its magnitude or vertical structure — has remained incomplete. Writing in *Nature Geoscience*, Cohen et al.[3] have now closed this long-standing gap by introducing an elegant theoretical approach that builds on recent advances in greenhouse-effect physics and provides a principled, quantitative explanation of stratospheric cooling.

The troposphere — the lowest 10–15 kilometres of the atmosphere — is the region where energy from Earth's surface is carried upwards through convection and large-scale midlatitude storm systems, the processes we know collectively as weather. The stratosphere, which lies directly above the troposphere, is, by contrast, almost weatherless (which is why commercial planes typically fly in its lower layer), and its temperature is largely decoupled from surface conditions. Instead, it is governed by a delicate balance between two key processes: the absorption of ultraviolet radiation by ozone and the emission of infrared radiation to space by carbon dioxide. When atmospheric carbon dioxide increases, it traps more heat near the surface, leading to surface warming. But in the stratosphere, the same increase in carbon dioxide enhances the emission of infrared radiation to space, causing the stratosphere to cool even as the surface warms.

The role of carbon dioxide in determining stratospheric temperatures was reasonably well understood following Manabe and Wetherald's early simulations and helped explain why stratospheric cooling appeared so consistently in model simulations[4,5]. Furthermore, models largely agreed on both the magnitude and vertical structure of the cooling. The cooling strengthens with altitude, rising from nearly zero near the base of the stratosphere to about −10 °C per doubling of carbon dioxide at its upper boundary (Fig. 1). Yet, reproducing a pattern in a simulation is not the same as fully explaining it. The main question — what physical processes determine the vertical structure of stratospheric cooling — remained unanswered. Much of the research at the time focused instead on more practical questions, such as how stratospheric cooling modulates or adjusts the net heat trapped in the troposphere below[4]. The discovery of the ozone hole in 1985 redirected focus even further. Research concentrated on stratospheric ozone rather than carbon dioxide, and attempts to detect cooling from carbon dioxide in the lower stratosphere were obscured by the concurrent cooling from ozone loss[6].

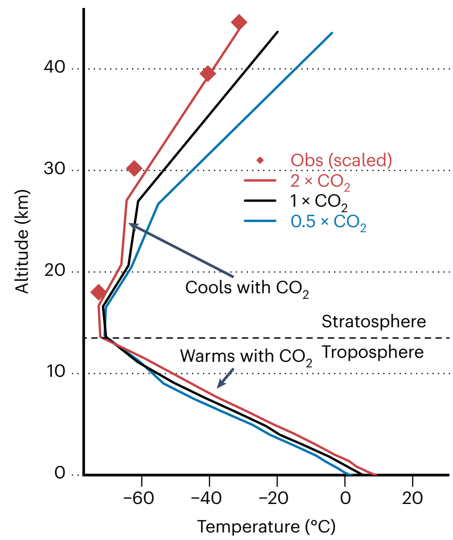

Fig. 1 | Warming of the troposphere and cooling of the stratosphere with increased carbon dioxide concentrations. Vertical profiles are taken from ref. 1. Observational data (diamonds) are central estimates of satellite observed trends taken from Cohen et al. and extrapolated to a doubling of carbon dioxide (2 x CO_2) perturbation, and compare favourably with ref. 1's 2 x CO_2 profile.

In recent years, however, the stratospheric research landscape has changed. With signs of ozone-layer recovery and the availability of reliable satellite observations of the upper stratosphere — where ozone plays a smaller role and carbon dioxide's influence is stronger — we can now clearly attribute cooling in the upper stratosphere to rising carbon dioxide[2]. Satellite remote sensing observations thus now provide firm empirical confirmation of Manabe and Wetherald's early prediction that rising carbon dioxide levels cool the stratosphere[1] (Fig. 1). At the same time, advances in climate physics have led to analytical theories of carbon dioxide emission and radiative forcing that encapsulate the quantum-mechanical variations in the carbon dioxide absorption spectrum into a few key parameters[7–9]. This new analytical approach reveals the key role of carbon dioxide emission from the stratosphere[8], and offers a more intuitive understanding of the greenhouse effect and how it shapes temperature changes throughout the atmosphere.

These empirical and theoretical developments set the stage for the Cohen et al. study. Building on the analytic theory of carbon dioxide radiative forcing, the authors incorporated an additional effect: the narrowing of the carbon dioxide absorption spectrum in the stratosphere. This refinement turns out to be crucial for understanding both the magnitude and the structure of stratospheric cooling. They also introduced a streamlined way to express the relative contributions of carbon dioxide, water vapour and ozone to the greenhouse effect – recognizing that ozone, in addition to absorbing ultraviolet sunlight, also emits infrared radiation. Bringing these components together, Cohen et al. developed an elegant approach for describing stratospheric cooling. It is simple yet accurate enough to quantitatively reproduce patterns from climate simulations and satellite observations. The authors then extended this approach to quantify how stratospheric cooling adjusts the greenhouse effect experienced by the surface and troposphere, and therefore how it ultimately impacts global warming.

The upshot of this work is clear: first and foremost, insight. The ability to reproduce the magnitude and vertical structure of stratospheric cooling using only a small set of equations –rather than a complex numerical model – clarifies which physical processes matter most. It highlights two central drivers: the shape of the carbon dioxide absorption spectrum and the relative contributions of greenhouse gases to stratospheric temperature changes. Such insight also opens the door to new research directions. For instance, as global warming continues and the ozone layer recovers, shifts in the balance between carbon dioxide and ozone greenhouse effects may influence future patterns of stratospheric cooling. This framework could also help elucidate the impact of proposed stratospheric aerosol geoengineering schemes on stratospheric temperatures and circulation[10].

But more broadly, Cohen et al.'s work strengthens the foundations of climate science by demonstrating that our understanding is not just empirical or numerical but rooted in physical first principles. When a simple analytical framework can reproduce the same cooling patterns seen in both models and satellite observations, it shows that the behaviour of the stratosphere emerges from well understood physics – not from the quirks or complexity of climate models. This matters. It increases confidence in climate model projections, exposes the mechanisms that drive them, and provides a transparent benchmark against which model performance can be assessed. It also sends a clear message beyond the scientific community: the large-scale effects of rising anthropogenic carbon dioxide are well understood. In the current landscape where aspects of climate physics – including stratospheric cooling – are still questioned in some circles[11], this message is timely indeed.

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Competing interests

The author declares no competing interests.