Climate Change’s Fingerprints Came Early, a Thought Experiment Reveals

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July 4, 2025

Opinion
5 min read

Climate change left its signature on the atmosphere early in the industrial revolution, reveals a thought experiment investigation

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Physicists are fond of *Gedankenexperimente*—thought experiments that are difficult or impossible to perform in the real world. Schrödinger’s cat is a well-known example of a thought experiment, used to illustrate the complexities of quantum mechanics. This puzzle occupied some of the best and brightest physicists of the early 20th century.
We tried the same thing recently, only with climate change. Given today’s network of satellites and temperature sensors, when could scientists have first known, beyond a

reasonable doubt, that increases in atmospheric CO_2 from fossil fuel burning and land use change were altering our global climate? The results might surprise you, and they help to illustrate why it's critically important to continue long-term monitoring of Earth's climate. Our thought experiment used simulations of historical climate change from nine different state-of-the-art computer models. We made three key assumptions. The first was that back in 1860, scientists in our "Gedanken world" had the technology to monitor global temperature changes in both the troposphere (the atmospheric layer extending from the surface up to about 15 kilometers) and the stratosphere (ranging from roughly 15 km to 50 km). Historically, global monitoring didn't happen until the 1940s using early weather balloon networks. More recently, since the late 1970s, we've monitored global atmospheric temperature changes with satellites.

Second, we assumed that over the period 1860 to 2024, the model simulations used reliable estimates of human-caused changes in greenhouse gases, particulate pollution and land use, as well as accurate estimates of natural changes in external factors like volcanic activity and the sun's energy output. All of these inputs to the model simulations are primarily derived from observational data.

Third, we assumed the model-simulated responses to human and natural factors were realistic, and that the size of modeled "climate noise" associated with natural phenomena like El Niño and La Niña was in reasonable agreement with observations. We tested the third assumption by comparing modeled and observed climate change and variability and found no evidence of model errors that would negate our bottom-line findings.

The work of Syukuro ("Suki") Manabe helped inspire this investigation. Back in 1967, Manabe—who would later go on to receive the 2021 Nobel Prize for Physics—published one of the most famous papers in climate science. Together with his colleague Richard Wetherald at the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, N.J., Manabe used a simple climate model to show that increasing levels of atmospheric CO_2 would lead to more efficient trapping of heat in the troposphere. The consequence? Warming of the troposphere *and* cooling of the stratosphere. The former has captivated most of the world's attention for good reason—it is where we humans live—but the latter turns out to be particularly useful in our thought experiment.
The 1967 Manabe and Wetherald paper made a testable prediction: if humans continue to burn fossil fuels and ramp up levels of CO_2 in the atmosphere, the vertical structure of atmospheric temperature will change not only in the troposphere but also in the stratosphere. But back in 1967, scientists lacked the long-term records necessary to test this prediction, particularly for the mid- to upper stratosphere, between approximately 25 and 50 km above Earth's surface.

Decades after 1967, weather balloon and satellite temperature records revealed that Manabe and Wetherald were right. Their predicted pattern of change in the thermal structure of the atmosphere was observable. Importantly, this pattern of human influence—showing long-term, global-scale warming of the troposphere and cooling of the stratosphere—couldn't be confused with natural patterns of temperature change. The human "fingerprint" on atmospheric temperature was distinctly different from the natural temperature fingerprints caused by the sun, volcanoes and internal climate noise. When climate scientists say we know people cause climate change, this fingerprint is one defining reason why.

Which brings us back to our "When could we have known?" thought experiment.

Although the question is simple, the answer isn't obvious. The first 40 years of the thought experiment (from 1860 until 1899) were a time when large-scale fossil fuel burning and deforestation were just beginning to ratchet up during the industrial revolution. The resulting increase in atmospheric CO_2 over this time, which we can estimate from Antarctic ice cores, was only 10 parts per million. This is small relative to the recent CO_2 increase of roughly 54 parts per million over the 25 years from 2000 to 2024. Nevertheless, this modest 10 parts per million early CO_2 increase is still large enough to lead to significant cooling of the stratosphere over 1860 to 1899. The size and pattern of this stratospheric cooling is very different than what we would expect from natural forces affecting temperature: the solar variability at the time, the eruption of Krakatoa in 1883, and internal climate noise.

Because of these differences between signal and noise, our thought experiment shows that even the relatively small human-caused signal of stratospheric cooling could have been identified in 1885. Put differently, given today's measurement capabilities, humans could have known that our actions were significantly changing global climate even before Carl Benz patented the first gasoline-powered car. The human-caused signal of tropospheric warming emerges later, in the second half of the 20th century, partly because human and natural patterns of climate change are more similar in the troposphere than in the stratosphere.

Would this advance knowledge have made a difference? Would humanity have followed a different energy use pathway given the understanding that fossil fuel burning eventually leads to large, global-scale changes in climate? That's outside of our sandbox as climate scientists—it's a question for philosophers, social scientists, and historians of science. But in our opinion, based on the history of other global environmental problems, it's certainly conceivable that early knowledge of the reality and seriousness of climate change could have spurred earlier global action to reduce greenhouse gas emissions.

It's worth noting that our identification of the atmospheric "fingerprints" predicted by Manabe and Wetherald was enabled by NOAA and NASA satellite remote sensing. The work of these agencies is an essential part of our research, and of the national and international climate science enterprise.

But in the United States in 2025, federally funded climate science, including observation and modeling work, is being systematically dismantled. This is not a thought experiment. It is all too real. We are now observing what happens when decades of work to understand the nature and causes of climate changes are rejected, and are replaced by ideology, conspiracy theories and disinformation. Stopping climate work will lead to a data vacuum that could last years or even decades. This experiment in willful ignorance can only end poorly.

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