SIMPLER PRESENTATIONS OF CLIMATE CHANGE

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and
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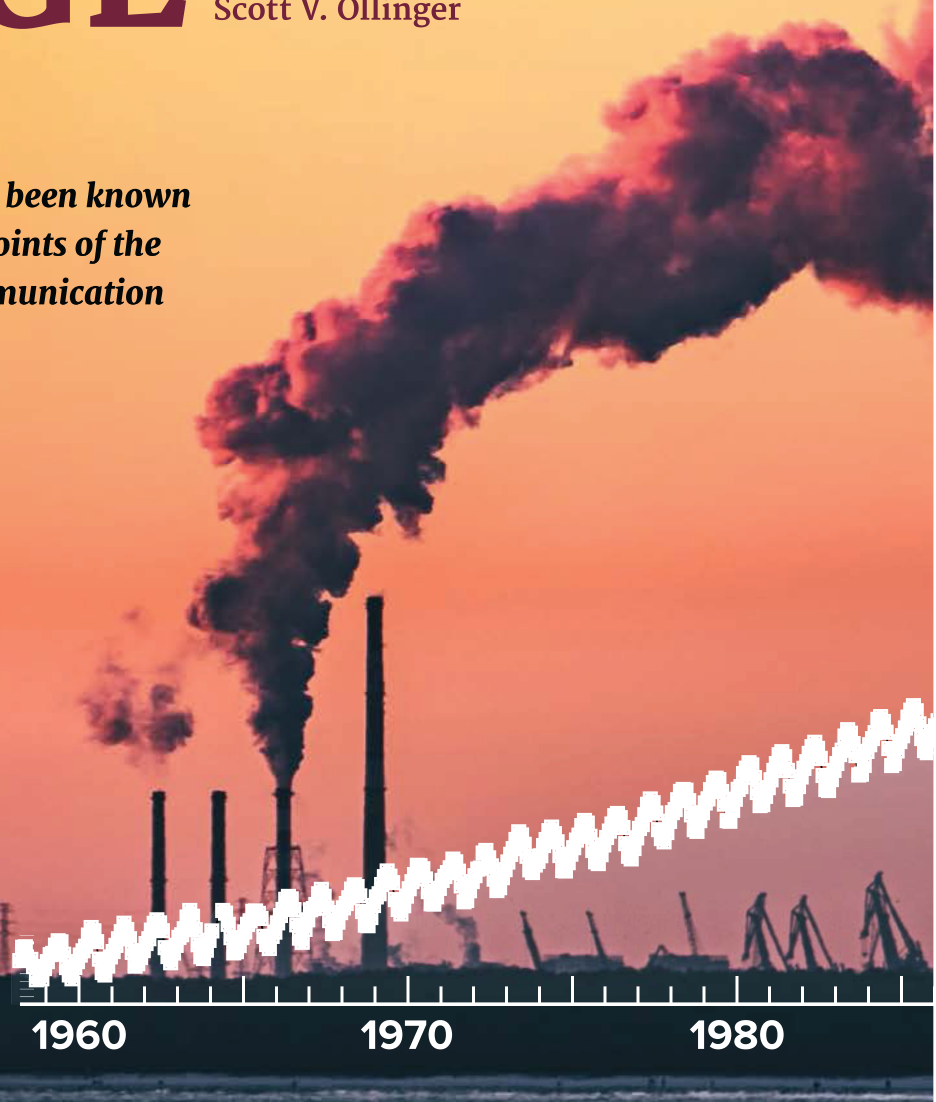
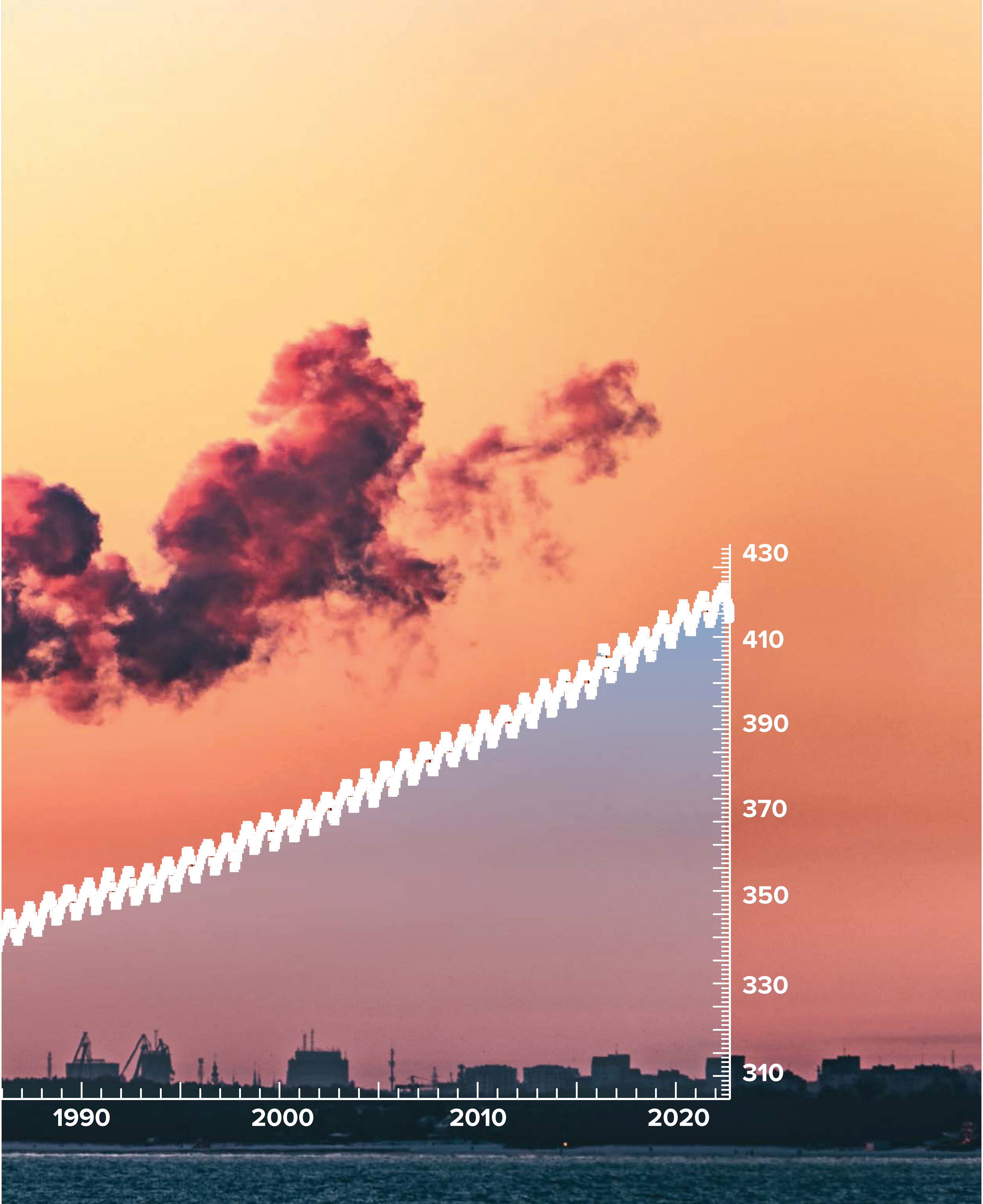
The basics of climate change have been known for a long time. Focusing on key points of the settled science provides clear communication and a platform for further inquiry.



Since 1958, the "Keeling curve" has charted steadily rising atmospheric carbon dioxide concentrations on the basis of measurements at an observatory on Mauna Loa, Hawaii. Photo credit: Marek Piwnicki/Unsplash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Has this happened to you? You are presenting the latest research about climate change to a general audience, maybe at the town library, to a local journalist, or even in an introductory science class. After presenting the solid science about greenhouse gases, how they work, and how we are changing them, you conclude with "and this is what the models predict about our climate future…"

At that point, your audience may feel they are being asked to make a leap of faith. Having no idea how the models work or what they contain and leave out, this final and crucial step becomes to them a "trust me" moment, which can be easy to deny.

This problem has not been made easier by a recent expansion in the number of models and the range of predictions presented in the literature. One recent study making this point is that of *Hausfather et al.* [2022], which presents the "hot model" problem: Some of the newer additions to the Coupled Model Intercomparison Project Phase 6 (CMIP6) predict global temperatures above the range presented in the Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (AR6). The authors present a number of reasons for, and solutions to, the hot model problem.

Models are crucial in advancing any field of science. They represent a state-of-the-art summary of what the community understands about its subject. Differences among models highlight unknowns on which new research can be focused.

As questions are answered and models evolve, they should not only reproduce past measurements but also begin to produce similar projections into the future.

But Hausfather and colleagues make another point: As questions are answered and models evolve, they should also converge. That is, they should not only reproduce past measurements but also begin to produce similar projections into the future. When that does not happen, it can make "trust me" moments even less convincing.

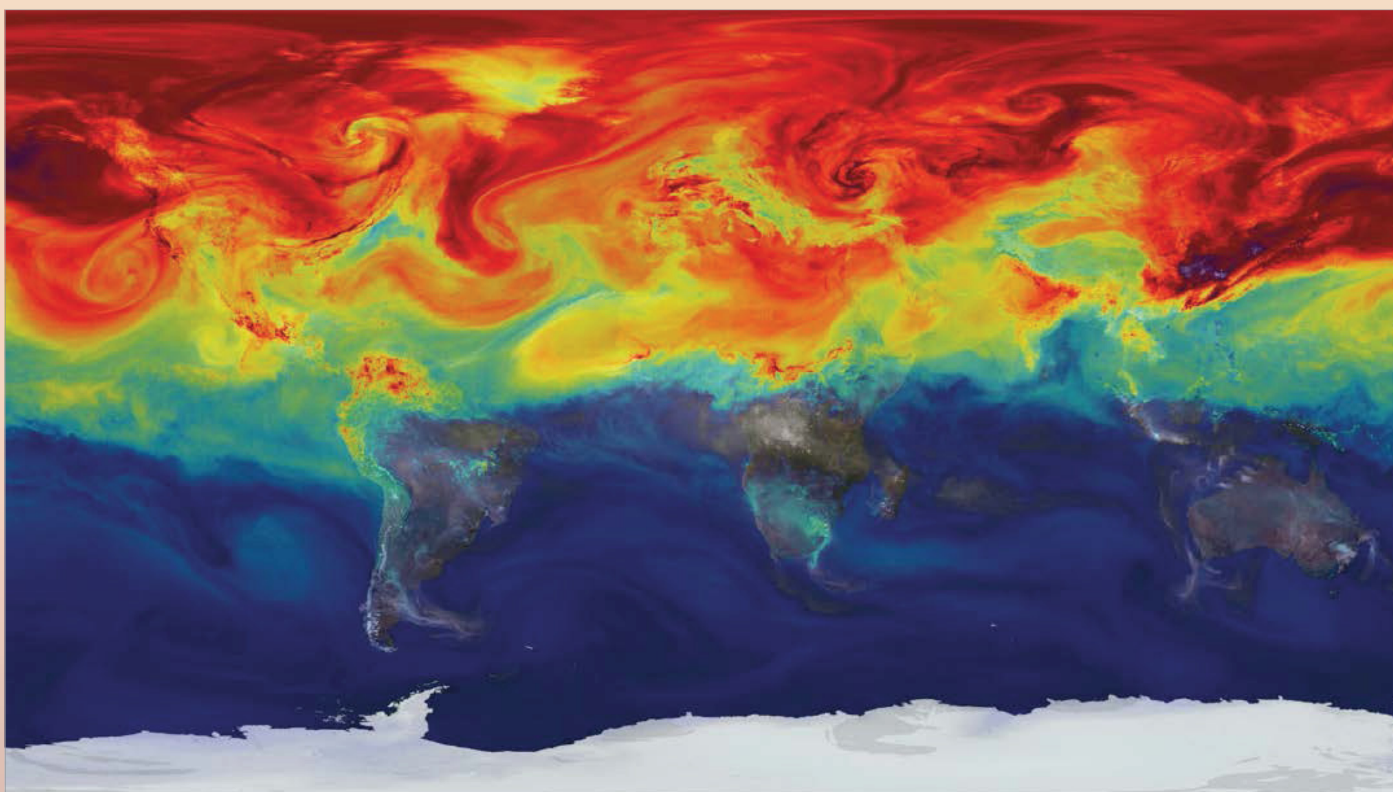
Are there simpler ways to make the major points about climate change, especially to general audiences, without relying on complex models?

We think there are.

Old Predictions That Still Hold True

In a recent article in *Eos*, Andrei Lapenis retells the story of Mikhail Budyko's 1972 predictions about global temperature and sea ice extent [*Budyko*, 1972]. Lapenis notes that those predictions have proven to be remarkably accurate (bit.ly/Eos-global-warming-forecast). This is a good example of effective, long-term predictions of climate change that are based on simple physical mechanisms that are relatively easy to explain.

Many other examples go back more than a century. These simpler formulations don't attempt to capture the spatial or temporal detail of the full models, but their success at predicting the overall influence of



Atmospheric carbon dioxide concentrations in April 2006, with warmer colors representing higher concentrations, are depicted in this snapshot from a simulation of the gas's movement through the atmosphere performed using NASA's Goddard Earth Observing System model, version 5. Credit: William Putman/NASA Goddard Space Flight Center rising carbon dioxide (CO_2) on global temperatures makes them a still-relevant, albeit mostly overlooked, resource in climate communication and even climate prediction.

One way to make use of this historical record is to present the relative consistency over time in estimates of equilibrium carbon sensitivity (ECS), the predicted change in mean global temperature expected from a doubling of atmospheric CO_2. ECS can be presented in straightforward language, maybe even without the name and acronym, and is an understandable concept.

Estimates of ECS can be traced back for more than a century (Table 1), showing that the relationship between CO_2 in the atmosphere and Earth's radiation and heat balance, as an expression of a simple and straightforward physical process, has been understood for a very long time. We can now measure that balance with precision [e.g., *Loeb et al.*, 2021], and measurements and modeling using improved technological expertise have all affirmed this scientific consistency.

Table 1. Selected Historical Estimates of Equilibrium Carbon Sensitivity (ECS)

DATE	AUTHOR	ECS (°C)	NOTES
1908	Svante Arrhenius	4	In *Worlds in the Making*, Arrhenius also described a nonlinear relationship between carbon dioxide (CO_2) and temperature.
1938	Guy Callendar	2	Predictions were based on infrared absorption by CO_2, but in the absence of feedbacks involving water vapor.
1956	Gilbert Plass	3.6	A simple climate model was used to estimate ECS. Plass also accurately predicted changes by 2000 in both CO_2 concentration and global temperature.
1967	Syukuro Manabe and Richard T. Wetherald	2.3	Predictions were derived from the first climate model to incorporate convection.
1979	U.S. National Research Council	2–3.5	The results were based on a summary of the state of research on climate change. The authors also concluded that they could not find any overlooked or underestimated physical effects that could alter that range.
1990 to present	Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report	3 (2.5–4)	Numerous IPCC reports have generated estimates of ECS that have not changed significantly across the 30-year IPCC history.
2022	Hausfather et al.	2.5–4	ECS was derived by weighting models based on their historical accuracy when calculating multimodel averages.
2022	Aber and Ollinger	2.8	A simple equation derived from Arrhenius [1908] was applied to the Keeling curve and Goddard Institute for Space Studies temperature data set.

Settled Science

Another approach for communicating with general audiences is to present an abbreviated history demonstrating that we have known the essentials of climate change for a very long time—that the basics are settled science.

The following list is a vastly oversimplified set of four milestones in the history of climate science that we have found to be effective. In a presentation setting, this four-step outline also provides a platform for a more detailed discussion if an audience wants to go there.

• 1850s: Eunice Foote observes that, when warmed by sunlight, a cylinder filled with CO_2 attained higher temperatures and cooled more slowly than one filled with ambient air, leading her to conclude that higher concentrations of CO_2 in the atmosphere should increase Earth's surface temperature [*Foote*, 1856]. While not identifying the greenhouse effect mechanism, this may be the first statement in the scientific literature linking CO_2 to global temperature. Three years later, John Tyndall separately develops a method for measuring the absorbance of infrared radiation and demonstrates that CO_2 is an effective absorber (acts as a greenhouse gas) [*Tyndall*, 1859; 1861].

• 1908: Svante Arrhenius describes a nonlinear response to increased CO_2 based on a year of excruciating hand calculations actually performed in 1896 [*Arrhenius*, 1896]. His value for ECS is 4°C (Table 1), and the nonlinear response is summarized in a simple one-parameter model.

• 1958: Charles Keeling establishes an observatory on Mauna Loa in Hawaii. He begins to construct the "Keeling curve" based on measurements of atmospheric CO_2 concentration over time. It is amazing how few people in any audience will have seen this curve.

• Today: A data set of global mean temperature from NASA's Goddard Institute for Space Studies (GISS) records the trajectory of change going back decades to centuries using both direct measurements and environmental proxies.

One way to make use of the historical record is to present the relative consistency over time in estimates of equilibrium carbon sensitivity (ECS), the predicted change in mean global temperature expected from a doubling of atmospheric CO_2. ECS is an understandable concept.

The last three of these steps can be combined graphically to show how well the simple relationship derived from *Arrhenius*'s [1908] projections, driven by CO_2 data from the Keeling curve, predicts the modern trend in global average temperature (Figure 1). The average error in this prediction is only 0.081°C, or 8.1 hundredths of a degree.

A surprise to us was that this relationship can be made even more precise by adding the El Niño index (November–January (NDJ) from the previous year) as a second predictor. The El Niño–Southern Oscillation (ENSO) system has been known to affect global mean temperature as well as regional weather patterns. With this second term added, the average error in the prediction drops to just over 0.06°C, or 6 hundredths of a degree.

It is also possible to extend this simple analysis into the future using

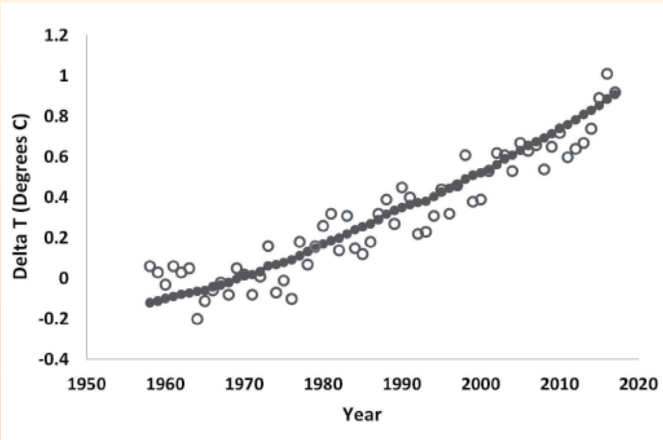


Fig. 1. Measured changes in global mean temperature (Delta T) from Goddard Institute for Space Studies data (open circles) are compared here with predictions (solid circles) from a one-parameter model derived from calculations performed by Svante Arrhenius in 1896 and driven by Keeling curve carbon dioxide (CO_2) data. Temperature changes are relative to the baseline average temperature for the period 1951–1980.

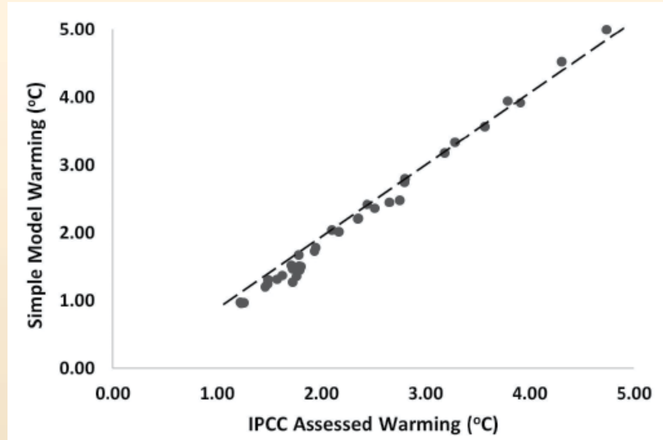


Fig. 2. Values of assessed global mean warming through the year 2100 from four frequently cited scenarios included in the Intergovernmental Panel on Climate Change's Sixth Assessment Report are compared here with predictions from the simple model used in Figure 1 driven by the projected CO_2 concentrations from the same four scenarios. The dashed line indicates a 1:1 relationship, showing close agreement between the two estimates.

the same relationship and IPCC AR6 projections for CO_2 and "assessed warming" (results from four scenarios combined; Figure 2).

Although CO_2 is certainly not the only cause of increased warming, it provides a powerful index of the cumulative changes we are making to Earth's climate system.

In this regard, it is interesting that the "Summary for Policymakers" [*Intergovernmental Panel on Climate Change*, 2021] from the most recent IPCC science report also includes a figure (Figure SPM.10, p. 28) that captures both measured past and predicted future global temperature change as a function of cumulative CO_2 emissions alone. Given that the fraction of emissions remaining in the atmosphere over time has been relatively constant, this is equivalent to the relationship with concentration presented here.

That figure also presents the variation among the models in predicted future temperatures, which is much greater than the measurement errors in the GISS and Keeling data sets that underlie the relationship in Figure 1.

A presentation built around the consistency of ECS estimates and the four steps clearly does not deliver a complete understanding of the changes we are causing in the climate system, but the relatively simple, long-term historical perspective can be an effective way to tell the story of those changes.

Past Performance and Future Results

Projecting the simple model used in Figure 1 into the future (Figure 2) assumes that the same factors that have made CO_2 alone such

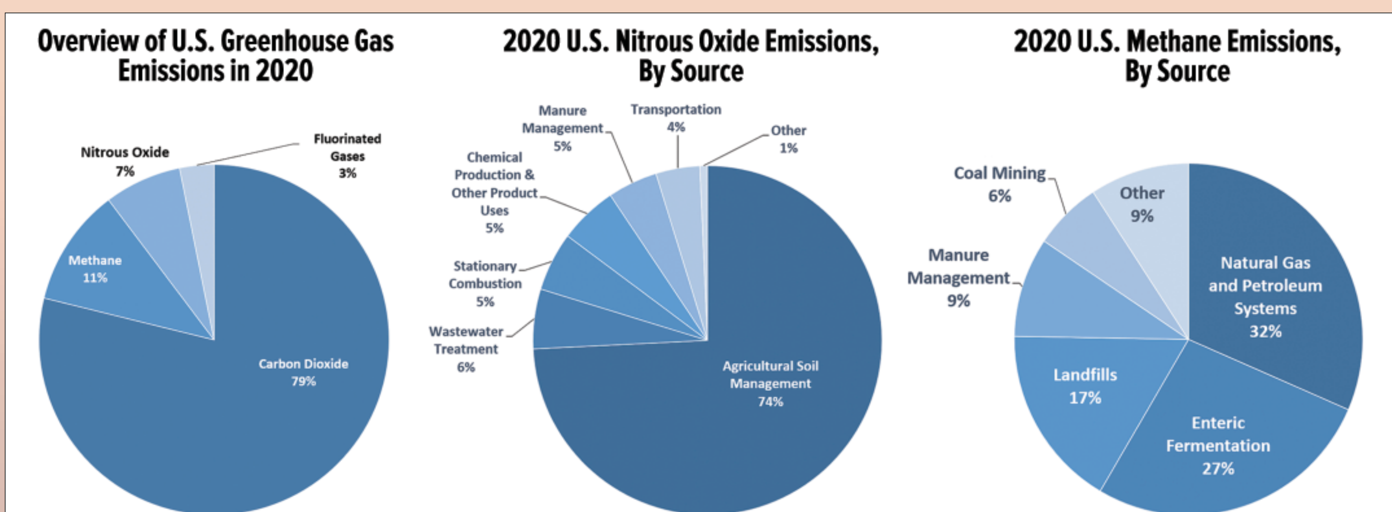


Fig. 3. EPA-reported total U.S. greenhouse gas emissions in 2020 (left) amounted to 5,981 million metric tons of CO_2 equivalent, led by emissions of CO_2, methane (CH_4), and nitrous oxide (N_2O). Major sources of N_2O (center) and CH_4 (right) emissions are also shown. Credit: EPA

a good index of climate change to date will remain in place. But we know there are processes at work in the world that could break this relationship.

For example, some sources now see the electrification of the economic system, including transportation, production, and space heating and cooling, as part of the path to a zero-carbon economy [e.g., *Gates*, 2021]. But in one major economic sector, energy production is not the dominant process for greenhouse gas emissions, and carbon dioxide is not the major greenhouse gas. That sector is agriculture.

The U.S. Department of Agriculture has estimated that agriculture currently accounts for about 10% of total U.S. greenhouse gas emissions, with nitrous oxide (N_2O) and methane (CH_4) being major contributors to that total. According to the EPA (Figure 3), agriculture contributes 79% of N_2O emissions in the United States, largely from the production and application of fertilizers (agricultural soil management) as well as from manure management, and 36% of CH_4 emissions (enteric fermentation and manure management—one might add some of the landfill emissions to that total as well).

If we succeed in moving nonagricultural sectors of the economy toward a zero-carbon state, the relationships in Figures 1 and 2 will be broken. The rate of overall climate warming would be reduced significantly, but N_2O and CH_4 would begin to play a more dominant role in driving continued greenhouse gas warming of the planet. We would then need more complex models than the one used for Figures 1 and 2. But just how complex?

In his recent book *Life Is Simple*, biologist Johnjoe McFadden traced the influence across the centuries of William of Occam (~1287–1347) and Occam's razor as a concept in the development of our physical understanding of everything from the cosmos to the subatomic structure of matter [*McFadden*, 2021]. One simple statement of Occam's razor is, Entities should not be multiplied without necessity.

This is a simple and powerful statement: Explain a set of measurements with as few parameters, or entities, as possible. But the definition of necessity can change when the goals of a model or presentation change. The simple model used in Figures 1 and 2 tells us nothing about tomorrow's weather or the rate of sea level rise or the rate of glacial melt. But for as long as the relationship serves to capture the role of CO_2 as an accurate index of changes in mean global temperature, it can serve the goal of making plain to general audiences that there are solid, undeniable scientific reasons climate change is happening.

When and if the simple relationship derived from Arrhenius's calculations does fail as an accurate index of changes in mean global temperature, it will still provide a useful platform for explaining what has happened and why.

Getting the Message Across

If we move toward an electrified economy and toward zero-carbon sources of electricity, the simple relationship derived from Arrhenius's calculations will no longer serve that function. But when and if it does fail, it will still provide a useful platform for explaining what has happened and why. Perhaps another, slightly more complex model will be created for predicting and explaining climate change that involves three gases.

No matter how our climate future evolves, simpler and more accessible presentations of climate change science will always rely on and begin with our current understanding of the climate system. Complex, detailed models will be central to predicting our climate future (Figure 2 here would not be possible without them), but we will be more effective communicators if we can discern how best to simplify that complexity when presenting the essentials of climate science to general audiences.

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