A Physicist's Journey

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The Physics of Climate Change
by Lawrence Krauss
Post Hill Press, 208 pp., $27.39.

If physicists are skeptical about climate science it is because they believe that the earth is too complex a system to be understood using the tools and data currently available. In this, they represent an anomaly in the broader scientific community.[1] Granted, none of the sources of evidence being marshaled today is unassailable: trends in data are confounded by internal variability, models cannot be confidently extrapolated into new regimes, and reconstructions of the past are partial at best. Climate scientists are aware of these shortcomings, and Lawrence Krauss, to his credit, presents these concerns in a clear and comprehensible manner in his latest book, *The Physics of Climate Change*. He also explains why progress toward improved predictive capacity is bound to be slow, even though certain features of the climate system are clear, such as the direct role of CO_2 in climate change.

Krauss is a serious physicist, as well as one of the most adept communicators of physics to a general audience. The book's key message is that climate science is being done well and its major conclusions are correct. Krauss writes with respect for both climate science and climate scientists. *The Physics of Climate Change* is the only book I am aware of that seeks to bridge the physics–climate science chasm and should be valued for this reason alone.

Aside from concerns about the intrinsic limitations of climate science research, the mistrust among physicists is also a consequence of how climate science is packaged by activists. It is unsettling for a physicist to be informed that 97% of climate scientists believe that climate change is already underway and is being driven by human action.[2] Science does not proceed by voting, and science is not something a scientist believes, but rather finds persuasive. This packaging is well-intentioned and apparently makes climate science more convincing to a lay audience, but it also greatly impedes the communication of climate science among scientists. Krauss is not concerned with packaging; his objective is to explain what climate science has figured out so far and what it means.

> This book, and all my others for that matter, aim to demonstrate how an explanation of fundamental physics arguments can give interested laypeople the tools to: (a) address questions they may have about the world and their place within it, (b) assess claims about the world they may read about, and (c) make decisions about their own actions and about public policy questions. With this in mind, I have concentrated on the general physical principles and tools that give some basic perspective on how a predictive understanding of the causes and various effects of radiative forcing on climate can be obtained and how reliable it might be.[3]

Elsewhere in *The Physics of Climate Change*, Krauss displays a fine grasp of the early history of climate science. These first stages in our understanding of climate change are presented in a level of detail not often seen in popular literature. Rather than mentioning in passing figures such as Svante Arrhenius, Joseph Fourier, and John Tyndall, Krauss takes readers inside their laboratories. A good example is his explanation of two tables from Arrhenius's late nineteenth-century work which predict the effect on the earth's surface temperature of various atmospheric concentrations of water vapor and CO_2.

The book begins with a discussion of the earth-atmosphere energy balance—the relationship between energy received from the sun and energy radiated back into space—before moving on to the perturbation of this balance by rising levels of atmospheric CO_2, and the effects of a lingering imbalance in this energy exchange, especially in relation to rising sea levels.

Krauss's explanation of the connection between atmospheric CO_2 buildup and surface warming is as good as any I have seen.[4] From what I gather, this discussion is his own adaptation of the approach taken in college-level atmospheric science textbooks.[5] Observed from space, the earth's infrared radiation emissions emerge from a layer in the atmosphere above which little incoming energy absorption takes place. Increases in atmospheric CO_2 concentration serve to increase the altitude of this layer, elevating it higher and higher above the surface below.

Due to decreases in atmospheric temperature with height at these altitudes, radiation emissions actually grow weaker during this process. As a result, the approximate equilibrium in energy exchanges maintained across many centuries prior to the industrial revolution is gradually lost and the surface becomes warmer. In this simplified model, equilibrium is eventually restored—for a constant but elevated CO_2 concentration—when the temperature of the emitting layer matches the temperature at its previous elevation.

The book's longest chapter discusses rising sea levels. Krauss includes a wealth of details about ice-loss rates, past and future, in both Greenland and Antarctica. It is a topic that he clearly finds sobering.

> For those who doubt significant sea-level change is possible, or who doubted predicted relatively direct connection between CO_2 levels, global temperatures, and sea-level rise, I now finally turn to the figure that first shook me out of my own complacency in this regard.[6]

The figure referred to by Krauss is James Hansen's reconstruction of sea levels over the past 400,000 years—a period which includes three 100-meter peak-to-trough swings. A rise of that magnitude had different implications 20,000 years ago when the earth was emerging from the last ice age. At that time, the sea level was 100 meters lower than the present day. Today, a sea-level rise of one meter will be highly problematic for the world's coastal cities, and five meters will mean relocating them.

The book is not without its flaws. The question of what effect an end to greenhouse gas emissions might have on average surface temperature is a controversial topic among climate scientists. The ongoing debate concerning heat redistribution is examined by Krauss in chapter eight. This section is somewhat disappointing and would benefit from an overhaul.

Consider a simplified version focused on the two roles played by the deep ocean after atmospheric emissions cease. Assume also that the flows of carbon among the three carbon reservoirs nearest to the earth's surface—the atmosphere, the surface ocean, and the earth's vegetation—remain approximately in equilibrium throughout that period. After emissions stop, the deep ocean absorbs CO_2 from these reservoirs leading to a decrease in the level of atmospheric CO_2 concentration. From this effect alone, the earth's average surface temperature would fall. As heat flows into the deep ocean from the surface ocean—the so-called mixed layer—the temperature difference between the two layers will also fall. Over time, less heat would flow to the deep ocean than when atmospheric emissions first stopped. From *this* effect alone, the average temperature at the surface of the earth would rise. As it turns out, these effects roughly cancel each other.

Any change in global mean temperature when these effects are taken into account is referred to as the zero-emissions commitment. The assumption that the zero-emissions commitment is zero plays a crucial role in the carbon budget concept that has been embraced by policymakers. The carbon budget is the sum of all global emissions from the present moment until net emissions reach zero—and, by assumption, stay there. The zero-emissions commitment is a "key component of estimating the remaining carbon budget to stay within global warming targets as well as an important metric to understand impacts and reversibility of climate change."[7] According to this framing, Earth's ultimate surface temperature does not depend on where or when emissions occur, only on the time-integrated total.

The explanation and discussion in the chapter lack the accessibility and rigor that Krauss brings to other topics in the book. All of this might have been presented much better using a two-box model, where one box encompasses the deep ocean and the other includes the atmosphere, the land, and the ocean's mixed layer. These are not easy topics for a lay audience, but their importance for understanding the terms of the current debate cannot be overstated.

Immense costs will inevitably be incurred as the world enacts new measures to mitigate and adapt to the consequences of climate change. These costs are likely to be felt most severely in countries at the early or middle stages of industrialization. Widespread resistance to these measures is not inconceivable. For all these reasons, understanding the real threat posed by climate change should be accorded a far higher priority than is currently the case. Accelerating the learning process has enormous positive benefits, whether the consequence is discovering that certain investments are unnecessary, or that they are more urgent than had been envisaged. Risk aversion elevates bad outcomes over good ones. This makes learning about bad outcomes especially important. Efforts to reduce the uncertainty in estimates associated with a particular outcome should allow for more cost-effective mitigation of its consequences. Learning more about climate change is both important and cost-effective.[8]

As part of the broad structural change required to advance climate science, the field urgently needs to recruit mid-career scientists from neighboring disciplines and to welcome graduate students from these disciplines who have not yet chosen their research areas. This is starting to happen.[9] Within the American Physical Society, there is a fledgling Topical Group on the Physics of Climate. But there is yet little sign that climate science might soon be incorporated into high-school and college physics courses. Textbooks that address this challenge are yet to be written; perhaps Krauss's book will help inspire similarly skilled and knowledgeable writers. In the energy field, the recent book by Robert Jaffe and Washington Taylor, *The Physics of Energy*, provides resources for a new set of courses at this margin of physics; an equivalent text for climate science would be invaluable.

In the latter chapters of *The Physics of Climate Change*, Krauss sums up the case for action on climate change.

> [N]ature doesn't care about the happiness of modelers or the utility of their modeling techniques. There are undoubtedly feedback mechanisms that affect climate that can be difficult to model because of the sudden changes they may bring about. … The future is charging at us like a freight train, but it is doing so on tracks we have built. We may have time to divert the train, or perhaps build a bridge so it safely bypasses us. We will never know unless we try.[11]

This is good advice. We ought to follow it.

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1. The American Physical Society's Panel on Public Affairs (POPA) is responsible for writing and periodically updating the society's official statements on public issues. POPA was engaged for more than a decade as the society's statement on climate change was produced, challenged, reviewed, rechallenged, and rereviewed. All society members were invited to comment, and hundreds did. The process was neither convergent nor satisfying. Many physicists remained unconvinced that climate science was trustworthy. A good number of leading climate scientists are physicists, but that has not placated the doubters.
2. Robert Socolow, "Witnessing for the Middle to Depolarize the Climate Change Conversation," *Daedalus* 149, no. 4 (2020): 46–66.
3. Lawrence Krauss, *The Physics of Climate Change* (New York: Post Hill Press, 2021), 14. Here, "radiative forcing" is the additional downward radiation at the top of the troposphere, primarily due to greenhouse gases, which has created a departure from thermal equilibrium and is warming the planet.
4. See Chapter 6, "Forcing the Issue," in Krauss, *Physics of Climate Change*.
5. This approach is not without some drawbacks. The contribution of atmospheric dynamics, for example, is not taken into account.
6. Krauss, *Physics of Climate Change*, 128.
7. Chris Jones et al., "The Zero Emissions Commitment Model Intercomparison Project (ZECMIP) Contribution to C4MIP: Quantifying Committed Climate Changes Following Zero Carbon Emissions," *Geoscientific Model Development* 12, no. 10 (2019), doi:10.5194/gmd-12-4375-2019.
8. Robert Socolow, "Contending with Climate Change: The Next 25 Years," *Bulletin of the Atomic Scientists* 76, no. 6 (2020): 294–301, doi:10.1080/00963402.2020.1846410.
9. Personally, I was able to persuade two prominent physicists already working in climate science, Tapio Schneider and Nadir Jeevanjee, to coauthor an article with me, "Accelerating Progress in Climate Science" (*Physics Today* 74, no. 6 (2021): 44, doi:10.1063/PT.3.4772). The paper sets forth an ambitious climate science agenda that blends theory, data harvesting, and advanced computation, revealing many avenues of entry.
10. Krauss, *Physics of Climate Change*, 141, 167.

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