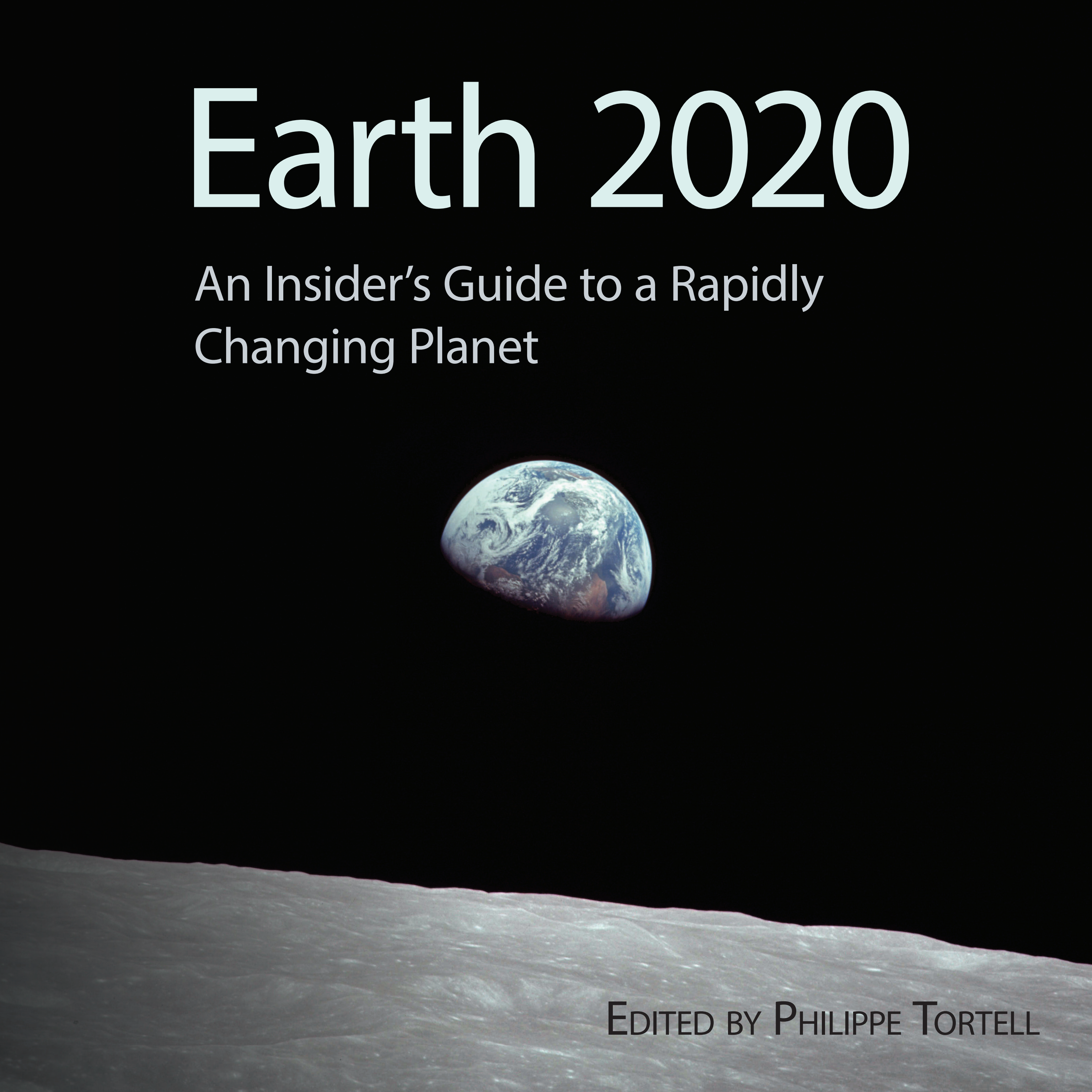
Earth 2020

An Insider's Guide to a Rapidly Changing Planet



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Climate 1970–2020

Tapio Schneider

I grew up in Germany in the 1970s and 80s, where I became a competitive cross-country skier in my teenage years. Back then, the sport was popular in the Harz Mountains near my home, and we could count on 120 days per year with snow on the ground. Today, four decades later, skiing in the Harz Mountains has lost its wide appeal. Winters now average just 65 days per year with snow cover, tendency falling.

Meanwhile, in my current home in Los Angeles, the average number of days with temperatures exceeding 32°C has increased from 53 in 1970 to 67 today. This is two extra weeks' worth of very hot days that desiccate California's landscape, priming it for ferocious wildfires, and days that put vulnerable populations at risk — days when children cannot play sports or have school recess outside, when heat-related emergency room visits by outdoor workers soar, and when deaths among the elderly spike because they are susceptible to heat stroke and heat stress-induced heart attacks.

From 1970 to now, global warming has gone from an abstract threat discussed by scientists to a fact that cannot be ignored. It is here. We feel it. We see it.

The global warming we experience now was predicted long ago. In an 1896 paper that marked the birth of modern climate science, Swedish chemist and Nobel Laureate Svante Arrhenius connected rising and falling CO_2 levels to global warming and cooling in an attempt to explain the waxing and waning of ice ages over Earth's history.[1] From earlier

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measurements by others, such as the American astronomer Samuel Langley, Arrhenius knew that CO_2 and water vapor are what we now call greenhouse gases: gases that selectively absorb the infrared radiation emitted by heated bodies (the radiation that warms your hand next to a stove or radiator). Arrhenius demonstrated how rising CO_2 levels would lead to warming by trapping heat near Earth's surface. He also recognized that water vapor exerts an important amplifying feedback, since a warmer atmosphere holds more water vapor, which itself is a greenhouse gas that traps heat.

Arrhenius' model was simple, and the measurements he used were inaccurate. Fortuitously, errors from the simplification and in the measurements largely canceled each other, and he was able to get what is now considered not far from the correct result. Arrhenius predicted that doubling atmospheric CO_2 levels would raise Earth's temperature by 5–6°C. But more important than the precise degree of warming Arrhenius predicted was the fundamental physical insight he delivered: there is a close link between greenhouse gas concentrations and global temperatures. In later work, he observed that burning coal could lead to a significant rise in atmospheric CO_2 levels and appreciable global warming within a few centuries to millennia, a prospect entirely desirable from his Nordic vantage point: 'We would then have some right to indulge in the pleasant belief that our descendants, albeit after many generations, might live under a milder sky and in less barren natural surroundings than is our lot at present'.[2]

Arrhenius' insights proved prescient about what the future would hold, though he and generations of scientists after him severely underestimated the rate at which CO_2 would accumulate in the atmosphere and change the climate.

We now know from historic air preserved in bubbles in the ice sheets of Antarctica and Greenland that atmospheric CO_2 levels hovered around 270 ppm for 10,000 years, following the end of the last ice age. By the late 1800s, however, industrial activities began to increase atmospheric CO_2 levels, which reached 295 ppm by the turn of the twentieth century. Modern measurements of atmospheric CO_2 levels were started in the late 1950s by Charles David Keeling from the Scripps Institution of Oceanography and brought an almost immediate surprise: concentrations were rising more rapidly than anticipated, implying that the oceans were taking up less of the CO_2 emitted by human activities than scientists had previously believed.

By the first Earth Day in 1970, CO_2 levels had reached 320 ppm, 20% above pre-industrial levels. The current value, half a century later, is around 415 ppm, more than 50% more than pre-industrial levels.[3] These values imply that we have added about twice as much carbon dioxide to the atmosphere since 1970 as in all of previous human history before. Worldwide emissions of carbon dioxide from all human sources, including fossil fuels and deforestation, have steadily climbed from 20 billion metric tons per year in 1970 to 42 billion tons now, with no peak in sight. Today, the average North American loads the atmosphere every year with an amount of carbon dioxide weighing about the same as ten midsize-passenger cars. We are releasing CO_2 into the atmosphere far more rapidly than Arrhenius could have possibly imagined.

Along with a growing global network of CO_2 measurements, we have also amassed a large instrumental record of temperature measurements from the nineteenth into the twentieth centuries. In the late 1930s, English engineer Guy Callendar first demonstrated a global warming trend, which he linked to the 10% rise in CO_2 levels that had already occurred by that date. Modern temperature data compiled from all over the world have demonstrated that the average land temperature has increased by 1.4°C since 1900.[4] The vast majority of this increase (1.2°C) has happened since 1970, with a rate of increase in the Arctic (2°C since 1970) that is almost twice the global average. These seemingly small temperature increases hide large changes, leading, in the case of the Arctic, to thawing permafrost and the collapse of structures built on formerly frozen ground.

In response to this warming, the Arctic's summer sea ice cover has plummeted 40% and is approaching its demise.[5] Arctic summers without sea ice will soon be a reality, with enormous implications for human livelihoods and regional ecology.[6] Across the globe, increasing temperatures are associated with a wide range of climate concerns, including stronger rain storms, prolonged droughts and sea level rise.[7]

Even worse, we have yet to see the full extent of the warming to which we have already committed our planet. At least some of the warming associated with increased greenhouse gas levels is masked by air pollution. Over much of the middle to late twentieth century, smog blanketed industrialized areas such as London, Los Angeles and Central and Eastern Europe.[8] Smog consists of tiny aerosol particles, which reflect sunlight back to space, shading and cooling Earth. The added aerosol particles can also increase the number of droplets and ice crystals in clouds, which increases their reflectivity and adds to the cooling effect of air pollution.

Although air quality in the west has improved over the past fifty years (thanks to amendments to the Clean Air Act in the US in 1970, and similar legislation in other western countries that followed), air pollution has worsened in much of the rapidly industrializing world, especially in China and India. The persistence of smog in Earth's atmosphere has thus masked some of the warming that rising greenhouse gas levels otherwise would have caused. As countries improve their air quality, the cooling effects of smog will be reduced, leading to more warming.

Today, we know there's more to climate change and the ways it affects humans than how greenhouse gases regulate the transfer of radiation through the atmosphere. Other processes are also important, including changes in cloud cover, effects of air pollution on clouds, uptake of heat by turbulent ocean circulations and uptake of CO_2 by the ocean and land biosphere. Understanding this complex web of interlinked processes requires more than the calculations Arrhenius performed by hand — it requires computer models.

The first computer-based global climate models were developed in the 1960s and 1970s by pioneers Joseph Smagorinsky and Syukuro Manabe at the US Government's Geophysical Fluid Dynamics Laboratory, Akio Arakawa and Yale Mintz at the University of California, Los Angeles, and Warren Washington and Akira Kasahara at the National Center for Atmospheric Research in Boulder. From these early beginnings more than half a century ago, climate models have steadily become more complex, tracking the exponential increase in computer performance since then.

Current climate models follow the path of solar radiation through the atmosphere to the surface, accounting for what is reflected back out into space and what is absorbed by Earth's atmosphere and surface. They calculate how the heated atmosphere and surface emit thermal infrared radiation, how the radiative heating and cooling drive the motion of the atmosphere and ocean and how air and water transport energy from low to high latitudes, cooling the tropics, warming the poles and enabling life as we know it. Capturing the full complexity of the atmosphere alone is a daunting task, even without including the oceans, biosphere and frozen cryosphere. It is a task far beyond the capabilities of the largest supercomputers today or those of the foreseeable future. Describing just the turbulent motions of the atmosphere requires around 10^{22} numbers characterizing temperature, velocity and humidity at different locations — about the number of molecules in a computer chip, and far beyond what a computer can hold in memory.

To approach the monumental challenge of simulating a coupled Earth system, climate models break down the complexity of the system into coarser chunks. This is achieved by dividing the globe into a grid and then performing computations separately for each box of the grid. The size of the grid's boxes — the resolution at which the model can view Earth — controls the accuracy of its calculations. Early climate models in the 1970s had a grid size of about a thousand kilometers, meaning that a slice across the Atlantic Ocean might span just four or five boxes. Current models with much smaller grid sizes can resolve processes down to scales of tens of kilometers. The most sophisticated models today capture radiative processes and larger-scale turbulence in the atmosphere and oceans, and they include models of the land and ocean biosphere. They have allowed us to explore complex processes, such as the link between global warming and intensification of rainstorms.

But despite significant advances in climate models since the 1970s, some critical processes remain difficult to resolve. The small-scale turbulence that sustains clouds, and processes occurring on tiny scales, such as the microphysical processes shaping droplets and ice crystals in clouds, cannot be accurately represented in current models. Yet even these small-scale processes matter for climate. A cloudy night is warmer than a clear night because clouds are good absorbers of Earth's emitted infrared radiation. Clouds can also make for a cool day at the beach because they reflect sunlight back to space, shading Earth. These small-scale processes affect the trajectory of longer-term climate change, and therein lies the rub — without resolving these processes in climate models, it is difficult to predict precisely how much more warming, extreme storms and sea level rise we should plan for, even if we know how much greenhouse gases will be emitted.

Despite the uncertainty of climate predictions, some things are clear. If greenhouse gas emissions were immediately cut to zero, the level of these gases in the atmosphere would stabilize, before starting a slow decline to a new baseline level over centuries to millennia. But the air would also be cleared of the polluting and cooling aerosols produced by fossil-fuel burning. The result would be more warming in the short term, despite stabilization of greenhouse gas levels. The climate effects of air pollution have not been precisely quantified, but current models suggest that we would see an additional global average warming of 0.4–1.7°C within years of eliminating all greenhouse gas emissions.[9]

We cannot stop CO_2 emissions suddenly; our energy economy has the agility of an oil tanker. Over the past fifty years, growth in global energy demand has outpaced growth in energy production from renewables. Greenhouse gas emissions are growing with no peak in sight, much less a reduction to zero. There is virtually no chance that we can avoid the 1.5°C global-average warming above pre-industrial temperatures aimed for by the Paris Agreement in 2015 (signed in 2016).[10] If we consider the 1.1°C global-average warming that has already occurred since the nineteenth century, and the time-delays in our energy economy and in the climate system, the inescapable conclusion is that we are on track to exceed 1.5°C and perhaps even 2°C global-average warming above pre-industrial temperatures.

While not physically impossible, limiting global warming to 1.5°C requires an implausibly short-term turnaround of greenhouse gas emissions, and staying within a 2°C warming target requires an economic restructuring at a pace not previously seen in history. Just to have a fighting chance of avoiding more than 2°C warming, we would have to drop greenhouse gas emissions down to zero within about 30–40 years — the lifetime of today's fossil-fuel power plants. Even achieving zero emissions in that timeframe would give us only a two-thirds chance of limiting global warming to 2°C above pre-industrial levels, according to the generation of climate models that came out in the early 2010s.[11]

Worse still, many of the most recent climate models are running hotter, indicating a higher sensitivity of the climate system to greenhouse gases than previously considered likely. This result stems in part from recent findings that the cooling effect of polluting aerosols may be stronger than previously thought. But if cooling by air pollution in the past was stronger than previously estimated, the sensitivity of the climate system to increases in greenhouse gases must be larger than previously estimated, or else we would not be able to account for the twentieth-century temperature rise. If the new models are more accurate than the previous generation — which is unclear at present — we may have underestimated the warming response to greenhouse gases. In that case, limiting global warming to 2°C above pre-industrial levels will be extremely challenging, if not impossible.

From the first Earth Day in 1970 to today, global warming has moved from an abstract scientific prediction to a reality we must contend with. At the same time, the discussion of global warming has moved from an exclusive focus on mitigation to the deepening realization that adaption is also critical. Mitigation was the focus of the 1992 United Nations Framework Convention on Climate Change, in which countries around the world committed to 'stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system'.[12] Follow-on treaties such as the Kyoto Protocol (1997) and the Paris Agreement were attempts to make this specific and enforceable. What 'dangerous anthropogenic interference with the climate system' means remains unclear. Nonetheless, we do have an idea of where we are headed.

The last time carbon dioxide levels were sustained at today's levels (around 415 ppm) was three million years ago, during the mid-Pliocene. At that time, Earth's global mean temperature was 2–3°C warmer than today, and sea level was about 17 m higher. The Greenland ice sheet was ephemeral and the Antarctic ice sheets were smaller; the water locked up in them now was part of the oceans. Mammalian life on Earth was thriving, but Homo sapiens did not yet exist, and neither did currently low-lying cities such as Alexandria, Amsterdam, Cape Town, Guangzhou, London, Miami, Mumbai, New York, Osaka, Rio de Janeiro or Shanghai. Even today's greenhouse gas levels, if sustained for centuries, must be considered dangerous for human civilizations that are adapted to the relatively stable climate and coast lines that existed for the 10,000 years before the industrial revolution.

Mitigating global warming to the greatest extent possible remains essential to prevent the cataclysms that await when current greenhouse gas levels are sustained for centuries, or increase even further. After decades of failures, efforts to stem rising tides and temperatures are much more urgent now than in 1970 or 1992, when snow and skiing were still common in the Harz Mountains of my childhood. But mitigation alone no longer suffices. Climate change will leave no one untouched. We have no choice but to adapt.

Endnotes

1. For a reprint of Arrhenius' paper and a discussion of its context and reception, see D. Archer and R. Pierrehumbert (eds.), *The Warming Papers: The Scientific Foundation for the Climate Change Forecast*, Chichester, UK: Wiley-Blackwell, 2011, https://doi.org/10.1002/met.1289
2. Quoted in H. Rodhe, R. Charlson and E. Crawford, 'Svante Arrhenius and the greenhouse effect', *Ambio*, 1997, 26, 2–5, at 4.
3. For historical and current concentrations of CO_2 in the atmosphere, see https://www.esrl.noaa.gov/gmd/ccgg/trends/
4. For a modern compilation of Earth temperature data on which these figures are based, see http://berkeleyearth.org
5. For sea ice data, see https://nsidc.org/cryosphere/sotc/sea_ice.html
6. See also 'Ice' by Julian Dowdeswell in this volume.
7. See also 'Weather' by Neville Nicholls and 'Sea Level Rise, 1970–2070: A View from the Future' by Robert E. Kopp in this volume.
8. See also 'Air' by Jon Abbatt in this volume.
9. The short-term committed warming estimates here indicate the warming that results from eliminating aerosols and short-lived greenhouse gases associated with fossil-fuel burning. The estimates are based on the simple model put forward by T. Mauritsen and R. Pincus ('Committed warming inferred from observation,' *Nature Climate Change*, 2017, 7, 652–55, https://doi.org/10.1038/nclimate3357), updated using recent modeling results. For more discussion of the challenges posed by committed warming, see V. Ramanathan and Y. Feng ('On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead', *Proceedings of the National Academy of Sciences of the United States of America*, 2008, 105, 14245–50, https://doi.org/10.1073/pnas.0803838105).
10. Available at https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

11. These estimates are based on the carbon budgets in Table 2.2 of R. K. Pachauri and L. A. Meyer, eds., *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Geneva: IPCC, 2014, https://www.ipcc.ch/report/ar5/syr/). They include cumulative carbon dioxide emissions since the reference year in the report and assume an immediately starting and approximately linear ramp down of emissions to zero.
12. Available at https://unfccc.int/resource/docs/convkp/conveng.pdf