Earth 2020

An Insider's Guide to a Rapidly Changing Planet

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Carbon

David Archer

Carbon is the backbone of all life on Earth. This element is able to accommodate up to four molecular bonds, giving it great chemical versatility and the ability to assemble into a wide variety of molecules, from sugars, fats and proteins (the building blocks of life), to the complex hydrocarbons that fueled the industrial revolution. By weight, carbon makes up only about 0.03% of our planet, yet this element exerts a profound influence on virtually every aspect of the Earth System. And perhaps more than any other element, carbon has been the subject of intensive debate over humanity's impact on the global environment.

On Earth, carbon is partitioned among a number of different reservoirs, including the crust and mantle (99.95%), dissolved and particulate forms of inorganic carbon (0.049%), living organic material in the terrestrial and marine biospheres (0.00064%), and atmospheric trace gases (another 0.00064%), including carbon dioxide (CO_2) and methane (CH_4). These 'greenhouse' gases absorb out-going infra-red radiation from Earth's surface, trapping heat within the planetary system like a thermal blanket. Of all the forms of carbon, most recent attention has been focused on CO_2, whose atmospheric concentrations have been significantly altered by human activities, with profound impacts on Earth's climate. Understanding how the concentration of atmospheric CO_2 is controlled requires an

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appreciation of complex processes that act to regulate the distribution of carbon among its different global reservoirs.

On long-term geologic time scales, carbon flowing into and out of the solid Earth (primarily continental and oceanic crust) acts to stabilize climate, in a negative feedback loop known as the CO_2 weathering thermostat.[1] When dissolved in water (including rain), carbon dioxide acts as an acid, reacting with continental igneous rocks to release minerals that are eventually transported to the oceans, where they regulate seawater chemistry and pH. The calcium that is released from this 'weathering' process reacts with dissolved carbon in seawater to produce the mineral calcium carbonate ($CaCO_3$), which sinks through the water column and is buried in ocean sediments for hundreds of thousands of years or longer. This burial of carbonate minerals is the main pathway for pulling carbon out of the atmosphere and storing it in long-term geological reservoirs. The rate of this carbon storage process depends on the climate (temperature and especially rainfall), which itself depends on the concentration of CO_2 in the air. As atmospheric CO_2 concentrations increase, so too does the rate of CO_2 removal through weathering reactions. Hence the thermostat.

The co-evolution of Earth's climate and biosphere has not always gone entirely smoothly.[2] The weathering CO_2 thermostat sometimes lurches toward warmer or colder set points for a period, challenging the biosphere to adapt. Take, for example, those episodes in Earth history when huge floods of volcanic lava released world-changing amounts of CO_2 into the atmosphere. Volcanic gases become greatly enriched in CO_2 when hot magma rapidly heats sedimentary rocks, causing them to explode with CO_2, methane and other gases. In the present day, a large fraction of Earth's volcanic CO_2 emissions comes from just a few volcanoes, which are mostly located in the tropics and associated with sedimentary calcium carbonate deposits. But the CO_2 emissions from these modern volcanos are tiny compared to the massive volcanic sources of the distant geological past. The largest of the mass extinctions, at the end of the Permian period 250 million years ago, was driven by one of the largest volcanic floods in Earth history, in present-day Siberia.[3] This huge CO_2 release to the atmosphere overwhelmed the capacity of the CO_2 thermostat to adjust, leading to a large spike in global temperatures that radically changed environmental conditions on Earth, resulting in wide-spread species extinction.

Sometimes, the biosphere itself lurches suddenly in a new direction, impacting the carbon cycle and global climate. For example, at the end of the Devonian period, about 350 million years ago, plants began to colonize Earth's land surface, with the evolution of roots, leaves and seeds that allowed them to extract water from the ground and disperse their offspring. These early terrestrial plants enhanced the weathering reaction on land by chemically attacking the rocks and forming soils as a by-product. The faster rates of weathering also removed a huge amount of CO_2 from the atmosphere, sending the planet into an ice age. Moreover, the colonization of land by plants led to a massive release of phosphorus into the ocean, which fertilized marine algae, resulting in oxygen depletion and extinction in the deep ocean.[4]

Fast forward several hundred million years or so, and CO_2 still seems to be the mother of all environmental problems.[5] Humans first exerted a significant impact on the atmospheric CO_2 concentration by clearing land for agriculture or game management. A century of deforestation in North America and Europe, from 1800–1900, caused the land surface to become a source of carbon to the atmosphere. Around the same time, humanity's first substantial use of fossil carbon arose with the invention of the steam engine by James Watt, giving our species the means to generate mechanical power on a large scale. Invention and ingenuity took hold quickly, pushing forward an unprecedented revolution of technology that transformed life on Earth over a mere two centuries. In a geological heartbeat, humanity consumed vast amounts of organic carbon deposits that had formed over hundreds of millions of years.

Since 1750, humans have released about 330 billion metric tons of carbon. Approximately half of all these emissions have occurred over the last half-century, since the first Earth Day in 1970. Additional human impacts on the carbon cycle have come from continued land use changes and cement production at massive scales (cement fabrication can be considered as a 'reverse weathering' process that liberates CO_2). While the land surface of Europe and North America may now, fortuitously, be re-absorbing CO_2 through the regrowth of trees, deforestation in other regions continues to provide a source of CO_2 to the atmosphere.[6] The future of the land carbon pool depends significantly on human land use practices, but also on the stability of huge deposits of frozen organic carbon in northern permafrost soils. Warming tundra and Arctic soils are accelerating the melting of these frozen deposits, which will likely release more CO_2 than any other part of the land surface could match.[7] Taken together, these human perturbations of the global carbon cycle are analogous to the volcanic CO_2 releases in the 'greenhouse extinctions' of the geological past. The total quantities of CO_2 liberated naturally by volcanos were probably larger than humans could muster by burning fossil fuels, but the rate of our CO_2 emissions are likely unprecedented in Earth history.

What happens to all of the CO_2 released by human activities? About half of it is still in the atmosphere, with the concentration rising from around 320 parts per million (ppm) in 1970 to around 415 ppm today (a roughly 30% increase). The rest of the anthropogenic carbon has mostly been absorbed into a giant oceanic pool, which has helped to stabilize both the atmospheric CO_2 concentration and the temperature of Earth's surface (and thus global climate). Over the past fifty years alone, the oceans have absorbed about 150 billion metric tons of CO_2 from the atmosphere, while also absorbing significant amounts of heat. In the short-term, oceanic uptake of CO_2 and heat are mitigating the greenhouse effect. Over the longer-term, however, CO_2 and heat pollution stored in the ocean will eventually be re-released to the atmosphere, slowing down any future recovery. In addition, CO_2 uptake by the oceans has a significant effect on seawater chemistry, resulting in increasing acidity (decreased pH) as hydrated CO_2 becomes carbonic acid. The global-scale response of the ocean carbon cycle to a shift toward greater acidity is difficult to predict, but we do know that ocean acidification was a prominent feature of previous mass extinction events on Earth.

The time it takes for ocean pH to recover from an abrupt increase in CO_2 concentrations is on the order of thousands of years — long by human standards, but short geologically. And herein lies a critical distinction between human-derived fossil fuel carbon and natural volcanic CO_2 sources. Whereas volcanic CO_2 was released into the atmosphere over millions of years, fossil-fuel carbon has been released over the last couple of centuries at a rate that overwhelms the capacity of natural chemical buffering processes. Our rapid CO_2 emissions will thus lead to larger spike in ocean acidity than any previous disturbance of the carbon cycle.[8]

Political negotiation on the climate issue has focused on trying to limit peak global temperature rise to 1.5°C.[9] This much warming would make the planet warmer than it has been in millions of years, since long before the development of humans as a civilized species. Warming of 2°C or more would almost certainly be worse, but the choice of 1.5°C itself is somewhat arbitrary. A true 'safety' boundary could be defined in terms of the energy balance of the planet. Today, due to the rising CO_2 concentration, the amount of solar energy delivered to Earth from sunlight, exceeds the energy lost from the planet. This energy imbalance is causing the planet to warm, with most of the excess heat going into the ocean. The concentration of CO_2 in the air that would balance Earth's energy budget, and thereby stop the buildup of this heat pollution, is about 350 ppm. This threshold was crossed about thirty years ago. The current atmospheric CO_2 concentration, 410 ppm, is rising by a few ppm per year.

Even if human CO_2 emission stopped today, cold turkey, the CO_2 concentration in the air would remain above 350 ppm for thousands of years; essentially forever, from our perspective. Engineering a return to a stable, optimal climate state may thus require actively removing CO_2 from the atmosphere. There are multiple possible strategies for doing this, including stimulating the growth of plants (we would have to bury the resulting carbon), using chemical scrubbers (as is done on submarines and spaceships), and artificially increasing weathering rates (by grinding up certain kinds of rocks that react with CO_2).[10] But whatever approach we take, limiting atmospheric CO_2 levels will be extremely difficult and costly. Getting back to 350 ppm within a few decades would require removing about 440 billion metric tons of carbon from the atmosphere. Optimistically, if it costs $360 to remove one metric ton of carbon from the atmosphere,[11] the total bill would be $160 trillion, about 1.6 year's worth of global world economic activity.

In Earth history, innovations such as the development of mining — whether by dirt-eating worms, rock-cracking roots, or fracking oil drillers — are able to upend Earth's chemical metabolism and alter its climate. Today, humanity is gorging on the energy of fossil fuels, eating the fat of the land, like a giant mold thriving on an old crust of bread. In a world of biological opportunism and growth, the conclusion would be foregone: exponential growth of the consumer population followed by collapse when the nourishment is gone. However, of all of the climate episodes and extinctions in the history of the carbon cycle, this is the first in which the agent of the event is at least beginning to *understand* the consequences of its actions.

Our perturbation of the carbon cycle is primarily an energy problem, so fundamental to our lives that it is challenging to imagine changing it quickly enough. But there is plenty of energy all around us, from the sun, and in the wind. If we were simply running out of fossil fuel now, would our civilization really collapse? Much of the human activity on planet Earth is driven and guided by our financial system; when there is immediate money to be made, we are extremely clever and adaptable.

Fossil CO_2 can be seen as a waste-management problem, like that of Shel Silverstein's Sarah Cynthia Sylvia Stout, who would not take the garbage out.[12] The poem describes how Sarah's house filled up with all manner of solid waste. If Sarah's consumption habits were typical of a North American child, it might take a few years for her house to fill completely with garbage. By comparison, the mass of invisible waste CO_2 from her fossil energy use would be about thirty times that of the visible solid waste. If her CO_2 waste also remained in the house, it would flush out all of the air within about a month, killing Sarah like a gawping fish.

Before the Great Stink in 1858, the sewers of London emptied directly into the Thames River. Massive overhauls of the rudimentary sewer system must have been controversial at the time, but business as usual was no longer an option. Neither is it a viable option now, as we come to understand that our waste CO_2 is not so different from the chamber pots of Victorian Londoners. The challenge lies in making the decision. The global scope of CO_2 emissions means that everyone has to cooperate in the eventual solution, even if the benefits of cleaning up are far less immediate to individuals. It is a question of ethics versus finance, analogous to the institution of slavery, which has been largely eliminated multiple times in human history. In many ways, things are going in the right direction, with costs of carbon-free energy becoming competitive with existing coal power, for example. At present, however, our progress — driven by our money-oriented decision-making system — is too slow.

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