Science Fact

Evolving Brainy Brains Takes More Than Living on a Lucky Planet

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One question that keeps Earth scientists up at night is how has the Earth managed to remain continuously habitable for the four-ish billion years that it took for intelligent life to evolve. Of course, there are many aspects to habitability and additional requirements for the evolution of intelligent life, but with respect to climate, the simple answer is that, in addition to the Earth having a reasonable orbit a reasonable distance from a reasonable star within a reasonable neighborhood of a reasonable galaxy, ever since that point at which life managed to organize itself into existence, buffers and feedback loops in Earth's climate system have kept global average temperatures from ever straying far enough from balmy to wipe life out. A slightly longer answer would acknowledge that there have been a few close calls (see, for example, the Proterozoic Snowball glaciations that appear to have covered the Earth, from the poles to the equator, with ice for millions of years).

It's a situation as profound as it is easy to ignore: evolution managed to get as far as us because of processes that stabilize Earth's climate that are powerful but have their breaking points. So, while the Earth would not have achieved its continuous four-ish-billion-year habitability streak without some serious bumpers in the gutters of climate's bowling lane, even with them, there were never any guarantees.

And there still aren't guarantees.

Earth's long lucky streak could end tomorrow. Or it could be some day sometime next century that the Earth encounters the perturbation severe enough to tip its climate into the runaway icehouse cooling or runaway greenhouse warming that exterminates its inhabitants. Or maybe Earth's luck will endure for several hundred million more years.

In the meantime, here's a crash course on how the climate system keeps itself in line because it's fun to know at least a little bit about this. Also, it ought to be every Earth citizen's duty to learn at least the basics, because what we have here is both precious and breakable, and we seem to be actively failing to appreciate those last two points.

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What Sets Earth's Average Annual Global Surface Temperature?

A smart aleck reply to the question *why is the Earth habitable* is that its current average annual global surface temperature is more like 15°C (59°F) than -200°C (-328°F) or 505°C (941°F). A more interesting answer would delve into why, and that's where the simple energy balance model of average annual global surface temperature comes in.

If the Earth's annual average global surface temperature is at steady state (meaning that it is not notably changing over the time frame of interest), the amount of energy received by the Earth from the Sun has to equal the amount the Earth is emitting back to space. The field of physics long ago worked out how to describe such things mathematically, and when you set the equations equal to each other, rearrange, and then improve the model by testing it against data, what pops out is that Earth's annual average surface temperature is controlled by three variables. The first, known as the solar constant (even though it isn't constant), is how much energy reaches Earth from the Sun. The second, known as albedo, is what fraction of that energy is reflected back to space instead of absorbed by the Earth's surface system. The third is the emissivity of the atmosphere, which is the degree to which the atmosphere *doesn't* impede the Earth's loss of heat to space. The Earth's atmosphere, of course, is not perfectly emissive, but contains greenhouse gases that slow the escape of heat to space by absorbing some of the infrared radiation that's trying to hustle that energy out to the void.

That's really it. Anything else you want to bring up—sunspot cycles, melting of ice sheets, changes in ocean circulation, variations in cloud cover, everyone deciding to paint their rooftop white—is just something that has an effect on the solar constant, Earth's albedo, or the atmosphere's emissivity.

At the moment, because the Sun's energy spreads outward in all directions as it travels away from the Sun, by the time sunlight reaches one astronomical unit away from the Sun, it is packing a punch of 1.361 kilowatts of energy per square meter. What a sun-facing disk of Earth's radius intercepts sums to 1.73×10^{17} watts, or 173,000 terawatts. A disk is used in this calculation not because the Earth is flat, but because the essentially spherical Earth intercepts a disk's worth of sunlight, or, to put it another way, you, too, cast a two-dimensional shadow. This is enough to raise Earth's average annual global surface temperature to 122°C (251°F), which would be warm enough to slowly roasted meat. But Earth's current layout of ocean and continents with deserts, forests, grasslands, cities, and polar ice caps, and the complication of clouds, reflects 29% of this incoming energy before it heats the planet at all. If Earth's atmosphere were perfectly emissive, the 71% of 1.73×10^{17} watts of arriving solar energy that Earth absorbs would heat the surface of the Earth to an average of 18°C (0.4°F), which is the temperature of your freezer. So, three cheers for greenhouse gases like water vapor, carbon dioxide (CO_2), and methane (CH_4), because they enable this insufficiency of absorbed solar energy to warm Earth's surface up to today's entirely reasonable 15°C (59°F), an average that is currently increasing thanks to our enthusiastic packing of additional greenhouse gas into the atmosphere.

This simple model means there is also a simple answer for how the Earth has managed to maintained a survivable surface temperature for the billions of years it took for intelligent life to develop: Earth's reflectivity and its greenhouse effect managed to strike a reasonable balance pretty much that entire time. But how they managed it is where the simple answers end.

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To Begin With, Say Thank You to the Ocean

That we of the brainy brains are here is that, on top of the luck of having not yet run into a habitability-ending perturbation, the Earth's climate system has three great things lending it a tendency to remain conducive to the survival of life. The first of these is an ocean that is large enough to hold a lot of solutes and to impart considerable thermal inertia to the climate system.

Presently, Earth's ocean is 1.3 sextillion liters of water large (or, if you prefer, 0.35 sextillion U.S. gallons full). Not only does this provide a robust supply of the water vapor responsible for most of the atmosphere's greenhouse effect, such a volume of water can contain the current 46,000 billion tons of carbon that it does mainly in the form of the antacids (better known as alkalinity) carbonate ($CO_3^{=}$) and bicarbonate (HCO_3^{-}) ions and, to a lesser extent, dissolved CO_2 gas. These 46,000 gigatons of carbon represent 89% of the reactive carbon in the surface Earth-ocean-atmosphere system, leaving the biosphere, atmosphere, and young, reactive sediments to duke it out for the remaining 11%. This in turn means that only 1% of the carbon that could easily be in the atmosphere is in the atmosphere in the form of the greenhouse gases CO_2 and CH_4, which, when you consider how much warming that mere 1% does, is a pretty darned good thing.

The ocean being such a storehouse of reactive carbon also means it serves as a buffer, putting the brakes on large changes in atmospheric CO_2 concentrations. The basic physics of gas exchange mean that the surface ocean and atmosphere tend toward being in equilibrium with each other in terms of their CO_2 concentrations. When CO_2 is added to the atmosphere, some portion of it will be soaked up by the ocean, until the balance is restored, which is why, so far, the ocean has absorbed a third of the CO_2 released by bipeds burning fossil fuels and felling forests, and this absorption has severely dented the speed and extent of anthropogenic global warming. Likewise, were atmospheric CO_2 concentrations to catastrophically diminish, the resulting disequilibrium between surface ocean and atmosphere would draw CO_2 out of the ocean, preventing too great a loss from the atmosphere.

But 1.3 sextillion liters of water is also a lot of liters of a material that is second to almost nothing in its reluctance to change its temperature as well as in terms of the amount of energy you have to put into it or remove from it to change its phase. Ask anybody who has lived along a coast or on the receiving end of the Gulf Stream's warm flow; a huge mass of water, by being able to absorb and release great quantities of heat, does a great job of keeping a climate from swinging to extremes. Furthermore, if you want to heat Earth's climate up above 100°C (212°F), you have to boil off the ocean first, which is doable, but requires enormously more work than if there were no ocean at all. Likewise, to cool global climate down below the freezing point of water, you'd have to freeze the entire ocean over first and that is also quite a task. Thus the ocean acts as a huge drag on the climate system, giving it a natural tendency to remain, on global average, somewhere between 0°C (32°F) and 100°C (212°F), a range a good chunk of which is survivable, even if you're not an extremophilic microorganism.

As an added bonus, water is weird. Its solid is less dense than its liquid, and its liquid attains its maximum density at a temperature higher than its freezing point. If these things weren't true, bodies of water would easily freeze solid, rather than just at the surface. By acting as insulation that hinders further cooling of the water below by the freezing cold air above, floating ice create refuges for aquatic organisms. Without such refuges, life might have been entirely wiped out by the fully (or nearly fully) global Snowball glaciations of the Proterozoic during those millions to tens of millions of years it took the climate system to dig itself out of the mess it had gotten itself into.

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Also Thank the Carbon Cycle(s)

The next great thing Earth's climate system has going for its tendency to remain reasonable is the cycling of carbon between various surface and deep Earth reservoirs.

To get into that, we need to speed through day one of Geology 101: At the center of the Earth is the Earth's iron- and nickel-rich core. Next comes the mantle, which consists of very hot silicate rock under a lot of pressure. Above the mantle floats the lithosphere, which includes the continental and oceanic crust that has formed over the mantle, the tiny bit of mantle in contact with the crust, and the sediments that have accumulated on top of the crust. The oceans and the atmosphere you already know. Meanwhile, the biosphere takes up space in and on the lithosphere, in the oceans, and, to a limited extent, in the atmosphere. And every single one of these compartments of Earth contains carbon. Ignoring the core, this carbon sums to 1.7 billion gigatons.

It's easy to assume the biosphere holds most of Earth's carbon, but on a planetary scale the biosphere doesn't even approach being a smear of butter on a beachball of bread. The mantle, taking up most of Earth's volume, holds not quite 82% of the 1.7 billion gigatons of carbon, containing it within such forms as carbonate minerals, diamonds, and metal carbides, and as CO_2 dissolved in what melts occur within this generally non-molten reservoir. The lithosphere holds the next slightly more than 18%, leaving the atmosphere, biosphere, and oceans to fight over the remaining 0.003%. And fight over it they dynamically do, respiration doing battle with photosynthesis, calcium carbonate dissolution undoing the work of calcium carbonate production, and erosion making inroads against sedimentation. As noted previously, ocean waters generally win this game, holding 0.0026% of Earth's carbon, leaving young, reactive sediments with 0.0002%, the biosphere with 0.0001%, and the atmosphere with 0.00003% (which is that 1% of the total carbon present within Earth's surficial reservoirs).

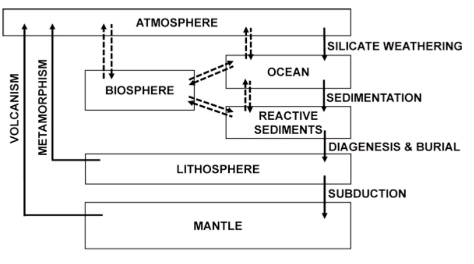

Figure 1: A not-to-scale schematic of the two carbon cycles representing the geologic carbon cycle with solid arrows with labels and the biogeochemical carbon cycle with unlabeled, dashed arrows.

But that's just the current snapshot, for these reservoirs aren't static. Carbon shuttles continuously between them, as sketched out roughly in Figure 1, split into two distinct but interconnected cycles. The geologic carbon cycle slowly moves carbon from the mantle and lithosphere into the atmosphere, then into the oceans and reactive sediments, before sending it back down into the lithosphere and mantle. Meanwhile, the biogeochemical carbon cycle busies itself churning its small allotment through and between the oceans, atmosphere, biosphere, and lithosphere in a bunch of hyperactive loops set within the slow, deep diving, geologic carbon cycle.

Over timescales of millions of years, the geologic carbon cycle prevents too much carbon from building up in Earth's surface reservoirs (including the atmosphere) or from disappearing down into the deep Earth and thus controls the longer-term evolution of the concentration of CO_2 in the atmosphere. Meanwhile, the biogeochemical carbon cycle determines the CO_2 and CH_4 content of the atmosphere on timescales of seasons to perhaps one hundred thousand years. The patterns that result look something like what is sketched in Figure 2.

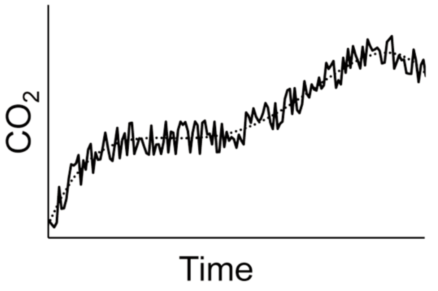

Figure 2: Idealized sketch of the rapid changes in atmospheric concentrations of CO_2 driven by the biogeochemical carbon cycle (solid line) occurring along the longer-term trend determined by the geologic carbon cycle (dashed line).

But what remains missing from this picture is how the cycles don't run themselves into the ground. Because there's no rule that says a cycle has to be balanced, only that if it isn't, on some relevant timescale, the element in question will accumulate entirely in the greediest reservoir.

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The Niftiest Feature of the Climate System

This brings us to the third and niftiest great feature of the climate system, which is its feedback loops. When a variable within the system—temperature, for instance, or the strength of the westerly winds—changes, dozens of processes adjust in response and the changes wrought by these adjustments can, a number of steps down the line, affect the variable whose change kicked the changes off. *Positive feedbacks* push in the same direction as the change, while *negative feedbacks* push back against the change.

The summing of all its cross-talking feedbacks loops running simultaneously on a number of temporal and spatial scales is a large part of what makes the climate system so thrillingly, confoundingly *nonlinear*. Depending on the state of the system, a certain initial small change could go a little way, a massive way, or sometimes even backward. Under other conditions, the same change could have an entirely different outcome. It all depends on the net effect of all the interacting feedback loops in the climate system.

To give you one example of one positive feedback currently in action, global warming has been melting Arctic sea ice, leading to a larger area of the Arctic Ocean to be ice-free for a greater duration of the year. This isn't just a bummer for the polar bears, it also means the Arctic Ocean is absorbing more solar energy, dark, liquid ocean being less reflective than the glittering, white ice that is no longer covering it. This direct heating has been adding to the warming of the Arctic's surface waters already being done by global warming, further accelerating the melting of the sea ice, further increasing the direct heating of the Arctic Ocean, further accelerating its loss of sea ice, and so on to such an extent that soon climate scientists will no longer be able to be amazed that there is any Arctic sea ice left by the end of summer each year.

This positive feedback loop also operates at a global scale, since the increased direct heating of the Arctic Ocean enabled by the melting of the sea ice being done by global warming is also increasing the pace of global warming. Likewise, if climate were to start cooling, the regrowth of Arctic sea ice would accelerate the cooling of climate and yet more regrowth of Arctic sea ice, thus acting as a positive feedback in the cooling direction as well. But no matter which direction climate is going in, eventually this positive feedback won't feedback anymore because either there will be no sea ice left to melt or there will be no additional Arctic Ocean surface left to be covered with sea ice. Any further warming (in the first case) or cooling (in the second) won't cause any further change in the reflectivity of the Arctic Ocean and the global warming or global cooling will continue merrily along without further amplification from changes in the extent of Arctic sea ice.

But not all positive feedback loops are self-terminating before they drive too much change in temperature. Thus, while positive feedback loops picking up could help the climate system dig itself out of a dangerously deep pit, negative feedbacks are where it's at in terms of preventing climate from straying to deadly extremes.

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Silicate Weathering

One negative feedback loop in particular maintains the good balance between Earth's reflectivity and the atmosphere's emissivity over geologic time by fine-tuning the greenhouse effect by adjusting the concentration of CO_2 in the atmosphere in response to changes in global temperature. Put briefly, the dissolution of the silicate minerals that make up silicate rocks converts CO_2 into those $CO_3^{=}$ and HCO_3^{-} ions that serve as the main form of carbon stored in the ocean, and this chemical weathering of silicate minerals happens faster when it's warm than when it's cold. Thus, silicate weathering rates increase when climate warms, reducing the amount of CO_2 in the atmosphere, cooling climate, and decrease when climate cools, allowing atmospheric concentrations of CO_2 to build back up, warming climate. Voilà, on paper at least, the perfect thermostat to keep Earth's climate mild no matter what shenanigans albedo and the solar constant are getting up to.

But in real life, rather than revolving around a single setpoint temperature, climate wanders from one setpoint to another. Most notably, Earth's climate moves very slowly from "greenhouse" to "icehouse" conditions and back again, for reasons partly related to plate tectonics (long story, short: icehouse climates tend to have continents at high enough latitudes for highly reflective polar ice caps to form and they also tend to have exposed expanses of particularly easily weatherable silicate rocks, especially in warmer, wetter tropical regions). In the last 55 million years alone, climate has dropped from the dinosaurian-warmth of 25°C (77°F), with swampy continents, shallow seas, and polar rainforests, to its current glacial epoch (wave hello to the miles-high piles of ice on Greenland and Antarctica). Worse still for the silicate-weathering hypothesis, atmospheric CO_2 concentrations did not increase to counteract this cooling. Instead, they decreased over the last 55 million years, aiding and abetting the cooling trend.

But before we throw the silicate-weathering hypothesis out with the glacial meltwater, we ought to acknowledge that silicate weathering does not operate in a vacuum, unaffected by any variable other than average annual global temperature. Regional temperatures and rainfall patterns, the character of the rocks available for weathering, continental topography and location, plant cover, and a whole host of other factors have their influence. These factors are also not constant, but may rise, fall, appear, and disappear related to the creation, collisions, subduction, buckling, and destruction of Earth's tectonic plates that moves the continents around. Or their development may be unidirectional, such as with land plants, which went from not existing to covering the land with a great diversity of form, function, and ability to alter conditions in the soil, all the while having an increasingly greater set of effects on local and global weathering rates. End result: the relationship between global weathering rates and global average surface temperatures changes through geologic time and that means so does climate's stable setpoint temperature. Meaning that while a decrease in global average temperatures will inevitably slow weathering rates, it will do so sometimes more so than at other times. Right now, the constellation of factors affecting weathering rates has it that high silicate weathering rates can be maintained despite the chill to the air, and that is how climate was able to cool from the dinosaurs' greenhouse to our current icehouse over that stretch of 55 million years.

The most important thing is that the cooling stopped, having reached the relatively cold setpoint of the silicate weathering system's current configuration, rather than dragging climate down into the next global Snowball glaciation. For the last several million years, instead of continuously cooling, climate has been oscillating back and forth between cold and colder glacial conditions over cycles of roughly 20,000, 40,000, and 100,000 years, lately reaching roughly the same maximum and minimum temperature every 100,000 years. Right now, it's 6°C (11°F) warmer and twenty thousand years later than the Last Glacial Maximum. Before we disrupted things by pumping additional greenhouse gas into the atmosphere, annual average global surface temperatures would have eventually cooled down towards the next glacial maximum, which would not have gotten colder than the previous several of them, before warming again for the next still technically glaciated "interglacial."

As to the far future, anthropogenic global warming or not, eventually the continents will move away from the poles, removing the possibility for polar ice caps, and Earth's climate will entirely naturally shift back toward greenhouse conditions that would be uncomfortably warm for even we fairly hairless mammals. And silicate weathering rates, despite adjusting to a new setpoint set by changes to the global weathering environment, will increase to prevent the warming from running catastrophically out of control.

In the meantime, *we* are causing the next severe test of the climate system with all this greenhouse gas we're sending into the atmosphere with geologically unprecedented speed. If the Earth's luck holds, we won't overshoot the climate system's ability to prevent a runaway greenhouse warming but, barring miraculously rapid advance in longevity research, you and I won't live to cash in on our bets on that. Wouldn't it be sad, though, if the bad luck that forever destroys the habitability of Earth turns out to be brainy brains that weren't quite brainy enough, a thought that has certainly launched a few thousand science fiction stories down through the decades.

Christina De La Rocha, a recovering biogeochemist, currently lives in a settlement in northern Germany. She has published both nonfiction and science fiction, tries to be entertaining on Twitter (@xtinadlr), occasionally updates her website (https://germanium-geranium.com), and is now serving as a nonfiction editor at Solarpunk Magazine.