Climate Underground Draft Transcript - May 2022 - Robert M. Thorson

WELCOME OPENING.

Pause ......

Introduction - This Might be for You

Pause

Welcome to Climate Underground

I'm your host, Robert Thorson

Thanks for joining us.

Pause.....

Are ***you*** feeling confused and alarmed about climate change? Or do you just want to learn about it from a different perspective?   If your answer to either question is yes, then this podcast may be for you. It offers an *earth*-centered understanding of what climates are, where they come from, and why they must always be always changing. This deeper understanding comes from knowing how planet Earth works as a natural system, what it's history has been, and what likely lies ahead.

My ***geo-***centered approach to climate change --rather than the ***human-***centered or ***eco-***centered ones dominating the global media-- may offer you an anchor of stability when sorting through the misinformation, procrastination, bias, injustice, and politics streaming our way on every single day. Going underground has helped me. And I hope it can help you too.

My sole purpose is geoscience education based on the facts as I understand them. Each of the 24 main episodes is a blend of personal stories, anecdotes, and lessons targeting a single earthly topic. Though created as supplementary materials for introductory geoscience courses at the University of Connecticut, the podcast is being made more widely available so our students can share and discuss them beyond class. Though the audio-scripts are referenced to the scientific literature, the texts have not yet been fully peer-reviewed and vetted for errors.

I look forward to heading underground with you. Thanks for being interested.

Pause...

Part 1 - Going Underground

1 - CLASSROOM SURPRISE - 2506

TAKEAWAY

Understanding how the Earth works and what it's history has been can help calm our fears and concerns about the climate future.

KEY POINTS

The current climate crisis is very real, urgent, and human caused. The solutions are clear, and hope remains.

Though weather is an atmospheric phenomenon powered by the sun, the climates creating that weather come mainly from below via geophysical and geochemical processes operating in the deep earth interior.

The composition of the atmosphere depends on geochemical cycling of volatiles between solid, liquid, and gaseous reservoirs.

Familiar objects, like ice, fossils, coal, sand, coral, rock, and stones hold clues to ancient climates that provide the only archive of climate history older than written records, and the best way of calibrating climate models.

The summit of Mauna Loa, the largest Hawaiian volcano, is Earth's most important place for climate science. Everything about that scene ultimately came from below: the ocean, the atmosphere, and the mountain growing above a mantle hotspot.

SCRIPT AND TEXT

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Episode 1 - Classroom Surprise

Pause ......

Welcome to Climate Underground

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Thanks for joining us.

Pause.....

Nearing the door, I could hear my students chattering happily. Being fresh out of high school, they were eagerly waiting the first college seminar course of their lives. Within seconds they would meet a well-seasoned professor with the temerity to claim: ***that*** climate change can be a good thing, ***that*** petroleum is just as natural as water, and ***that*** radioactivity keeps our planet alive.

A few of those students signed up out of curiosity because the course title *Climate Underground* seemed to contradict what they'd been taught in school -- that climate is an ***above-ground*** thing powered by the sun. That's certainly true for weather. But not for climates. They're created mostly by processes acting within the earth interior -- by ***exhanges*** of carbon between Earth's crust and its atmosphere, by ***geothermal*** processes associated with volcanism and tectonism, by ***gravitational*** processes pulling everything toward its dense iron core, and by ***centrifugal*** processes associated with out planet's orbit, spin, wobble, and tilt.

Imagine a basketball made of hot dense rock. Now, using both hands with a firm grasp, dunk it into water, lift it back up, set it on a hard surface, and give it a spin. The thin film of water clinging to the ball is comparable in thickness to all of Earth's atmosphere and ocean, both of which were ***steamed*** out of the underground when earth was born, and are continuously being influenced by it.

Anyone can look up and see the weather change. But it takes a statistician to define climate, and an earth scientist to explain where it comes from and why it might change. For starters, consider the word ***fossil,*** as in fossil fuel. It's derived from the Latin *fossilis,* which means "to dig up." That's indeed what fossil fuels are all about; the ***digging*** up of ancient carbon from underground reservoirs before burning it on the surface and exhausting that carbon to the sky where some of it will persist at geological time scales. The increasingly popular word *drawdown* points in the opposite direction: the drawing down of that gaseous carbon back into the solid reservoirs from which it came.

Earth's underground also holds the only archive of climate history older than the present geological moment of human history. It's under*foot* in the case of rock, soil and ice sheets, and under*water* in the case of sediment cores from boreholes.

When I reached the door to my classroom, I entered carrying a black, boxy briefcase of the sort that hardly anyone carries anymore. From it I pulled the first of many geological specimens I would pass around, one for each day of class: a lump of coal, a stalactite from a cavern, a bubbly piece of volcanic pumice, a slab of petrified wood, a glacially scratched stone, a jar of dune sand, and so forth. Each object holds a clue to climate change from the past. Though my students knew what coal was, most had never actually held a piece in their hands. From the other specimens they learned that: the limestone of caves holds far more carbon than all living things; volcanic gas turned Arctic regions into saunas; and that the original "going green" by land plants pushed the planet deep into an ice age.

The *climate crisis* we're living through now is very real, very concerning, and far more urgent than modern culture is willing to acknowledge. Despite all the talk that activist Greta Thunberg calls "Blah, Blah, Blah," the shifts we're making to reduce carbonization of our atmosphere are too slow. This crisis is a turning point in Earth history, one that can ***only be understood*** by knowing how the earth works without human interference, and what its history has been. Quoting the same idea from the prestigious journal *Nature* "Climate change will only be taken more seriously when a higher percentage of the population has a base understanding of the geosciences." Quoting the same idea from journalist Peter Brannen, "Though climate science was long an esoteric field, a familiarity with the basics should constitute a core part of any responsible civic education for citizens of planet Earth."[1]

That's what this podcast series is all about. It's about helping you understand Earth's fundamental role in climate change, an importance usually ***glossed*** by the media, and ***drowned*** out by the roar of political, economic, artistic, cultural, and spiritual actors drawing most of the attention.

Though I target college-age people who want to be part of the climate solution, I hope to catch the ears of anyone of any age who wants to know more about how earthly processes and climate change go together.

The rocky summit of Mauna Loa, on the big island of Hawaii provides a perfect example of the link between climate and the underground. Aside from being the biggest volcano in the most volcanic U.S. state, it's also the most important point on Earth's surface with respect to climate science. That's where the pioneering atmospheric scientist Charles David Keeling went in 1958 to collect an uncontaminated sample of well-mixed air that was far removed from the complexities of continents and lower altitudes. His first sample --part of a long-term program to monitor the concentration of carbon dioxide in earth's atmosphere-- was an outgrowth of the first International Geophysical Year.

After a few years of sampling, the annual and long-term trends were clear. Each summer, the CO_2 concentration fell slightly as the plants of the northern hemisphere breathed it in through their leaves to make plant tissue. Each winter the CO_2 rose back up again as the trees dropped their leaves and the pace of photosynthesis slowed. The long-term trend was equally clear, a steady rise in CO_2 from about 0.0315 percent or 315 parts per million in 1958 to the current concentration of 419 parts per million in 2022. This upward trend continued even during the global economic contraction of the Covid pandemic.

The Keeling curve is now a world benchmark for climate science, the standard to which all more complex measurements are compared. This ***measured*** data, collected in ***real-time***, is essential for verifying and calibrating the older, more complex carbon records of ice cores, which extend Keeling's method backward in time to nearly a million years.

Given its exclusive focus on atmospheric chemistry, it's easy to overlook the fact that everything about Keeling's experience came from the underground, including the atmosphere he sampled, the ocean condensed from it, and the rocky summit his observatory was built on. This narrative begins more than three thousand miles below the Earth's surface to where molten iron in the earth's liquid core is crystallizing into a solid iron alloy resembling stainless steel. Extra heat swirled upward to create a hot spot at the base of Earth's mantle, a plastic, greenish-black silicate rock. That hot spot created a volcanic plume that burned upward through the mantle and thin oceanic crust of the Pacific Plate to leak lava onto the sea floor. That outpouring created a submarine mound that grew

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[1] *Nature Reviews, Earth & Environment, Editorial, Sep 2021, p. 587* Brannen, 130

upward to create a small island that grew further upward into a broad shield volcano reaching an altitude of nearly 14 thousand feet. (4170 meters). Mauna Loa's high summit gave Keeling the sampling site he needed. Everything about his experience came from below.

After putting my rock specimens back in my briefcase, I asked my students to define climate. Everyone had the same basic idea, but most were clueless about the details. Climate, I explained, isn't a physical thing like a mountain range or an atmosphere. It's an informed *guess* about what the weather will be at any given place and time, an *expectation* based on *qualitative* past experience, and (or) *quantitative* statistical methods.

Weather answers the question *What's happening?* within the time frame of a ten day forecast. ***Climate*** answers the question *What weather should we expect?* for the time frame of about a human generation. What are the odds we'll have drenching rain, fluttering snowflakes, a perfect beach day, dangerous fog, windy gusts, the sizzling crackle of lightning, whirling tornadoes, tropical heat, or biting Arctic cold? The default answer is climate.

Urgency

The urgency and importance of the climate crisis cannot be understated.

It's real. The science has been settled for a half-century.[2] The most recent release of the world's most authoritative source, the Intergovernmental Panel on Climate Change (IPCC), reports that earth's average temperature has risen about 1 °C in the past century and will continue to warm in the near future. Based on the 2015 Paris Accord, global governments are hoping to hold that rise to no more than 1.5°C total, but the present expectation is that the rise will be 2 °C or higher if current pledges are not kept. [3]

It's us. Humans are responsible. Acting first out of ignorance, then indifference, then denial, and finally selfish procrastination, the IPPC emboldened its language in 2021 to read: "Human influence on the climate system is now an established fact."

It's bad. Every media outlet screams the news of melting glaciers, raging fires, rising sea levels, migrating refugees, warming permafrost, and so forth. Less well known is that the carbon concentration of today's atmosphere is higher than at any time since the Miocene Epoch about ten million years ago when mean temperatures were at least several degrees warmer than at present. This was long ***before*** great sheets began to scrape back-and-forth over much of the Northern Hemisphere. Then, The Arctic was lushly forested, and sea level stood nearly 80 feet higher than today at times.[4] This is where we're headed. The question is when will we get there.

It's hard. Global culture is addicted to fossil fuels, a hard habit to kick. The political system of the United States is particular is particularly vulnerable. Though our total emissions have begun to drop,

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[2] That was in 2021. Eight years earlier, in 2013, report AR5 firmly established that "human influence on the climate system is clear." Seven years earlier in 2007, AR4 concluded "warming of the climate system is unequivocal."

[3] Meinshausen et al, 2022

[4] [NOAA, 2021]

we remain most significant carbon polluter in the history of the world. From a whole-Earth perspective, the number to watch --and the only one that really matters-- is the carbon dioxide concentration on the Keeling curve. That's the end-result of total Earth System behavior, a system that includes the failures of humans to respond quickly enough.

The solution is clear. We need to immediately and dramatically shift our energy strategy *away* from fossil fuels, keep a positive attitude during our ***rehab***, and draw ***down*** some of that carbon already up there back to the underground. The drawdown may be through: the thicker ***soils*** of regenerative agriculture; the nourishment of the ***oceans*** to enhance algal growth; the return of CO_2 back into the ***voids*** where petroleum was taken from; or the sequestering of carbon into the solid ***limestone*** through technology. We've got the technology. The start-ups are well-funded. It's just a matter of political will.

Hope remains. This is where you come in. Though gray-haired baby boomers like myself have been working on this problem for their entire careers, global humanity has been unable to flatten the Keeling curve. But recent political progress is trending in a positive direction. And the rising generation, GenZ plus or minus, has the energy to keep moving the needle forward. To support them, I joined a student strike for climate action at the University of Connecticut in 2019. They gave me hope.

Hope

My trial course on *Climate Underground* coincided with the COP26 international climate congress in Glasgow, Scotland. Midway through the semester, student hopes were dashed by the lack of measurable progress, and the precipitous drop in media coverage after the gathering fell off the radar. Feelings of resignation, helplessness, dread, and anxiety about the climate crisis kept bubbling up in daily discussions. What I did not see coming was the collective surge of optimism and confidence near the very end of the course. Consider these excerpts from their final writeups:

> When I first entered your classroom in September I was under the impression that in the next fifty years... our planet would have turned into a big ball of fire.
>
> I do not have climate dread anymore, the Earth will spin on.
>
> Prior to this course, I was sure that the earth would essentially be destroyed.
>
> I was terrified that, by the end of my life I would witness a significant decline in standard of living for everyone around the globe,
>
> I would not say I had *climate anxiety* before I began this course...but now I think I can comfortably claim I have *climate confidence*; confidence in my information, and my perceptions of Earth's future.

Struck by their sincerity and lucidity, and perhaps as a distraction from grading, I made a decision to share their experience more broadly. So, in December, 2021, with a twice-delayed sabbatical leave on the horizon, I began to outline a short, easy-to-read primer that could also be listened to as a series of podcasts and shared over social media. My overall goal is to help anyone willing to listen become better grounded in climate science by showing what climate change looks like from below.

My action, I hoped, would help make up for the deficiency in Earth Science education created by tje K-12 educational system across most of the United States.

I'm not the first geologist to take climate education ***underground***. Geochemist Shahar Anat writes: "The heart of habitability" of our planet "lies in the planetary interior."[5] Geologisti Robert Hazen writes: "If we are to act thoughtfully and in time for our own sake, we must become ***intimate*** with Earth and her story." I don't know about you, but intimacy for me requires knowing what's going on beneath the surface appearances of our love interests, whether they be people or planets.

The good news is that...No matter what we do, Earth will remain a beautiful and tenacious planet, with or without the human species. So, if you hear someone describe Earth as fragile, please call them out for spreading misinformation and for amplifying climate anxiety.

Consider these random facts as a self-quiz of your knowledge about the Earth : The entire duration of our species of 300,000 years is a micro-second on the calendar of Earth history. Viewed from Earth's sweet spot at the center of its iron core, the drifting of continents in deep time and the movement of clouds in real time have much in common. Life emerged from non-life. Earth's ecosystems are comparable in scale to patches of mildew on the wall of a large room. Life on Earth persists because radioactive decay from the planetary interior fuels the tectonics that keeps Earth from freezing over.

From my whole-earth, whole-time viewpoint, the current climate crisis is merely the final frame of a long documentary that began with fire 4.6 billion years ago, and remains within the grip of a 30-million-year-long ice-house state more potent than any Earth has experienced in the last 300 million years. Only after the last of our polar ice sheets have disappeared will Earth return to its dominant and more stable greenhouse state of a significantly warmer world.

I'm not sure why the experimental course on *Climate Underground* worked so well. Perhaps they trusted me, knowing that I had volunteered to teach their seminar. Or perhaps they related to my political activism three generations ago during the civil rights movement of the 1960s. Or to my joining the throng on the first Earth Day in April 1970,. Or to my expertise in teaching the University of Connecticut's first course on Global Climate Change in 2001 before they were born.

Having earned their trust, I hope you will trust me enough to sample some of the other episodes of this podcast. Each episode is designed to stand alone, and I intentionally built in some review, choices that required minor redundancies.

The next four episodes are grouped in *Part 1 - Going Underground*. They help you re-frame your thinking about climate change within an earth science perspective.

The heart of this podcast, *Part 2 - Creating Climates*, contains thirteen topical episodes about how climates are defined, created, and changed. These include the role of underground forces in creating places, elevations, and depths, an introduction to the Earth system and its origin, and the specific mechanisms and timings of climate change.

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[5] (2019, *Science* 364, p. 434).

Part 3 - Past and Future, is mainly historical, a review of climate history and predictions for the future. The last of its six episodes is about communicating what we've learned with others. Its focus is on choosing of the right words to prevent misinformation and distortion as we move bravely ahead together. Earth. Planet. World. Globe. Nature.

Good luck!

2 - GETTING GROUNDED - 3385

TAKEAWAY

Being a responsible planetary citizen requires that you discern and distinguish climate fact from climate fiction, and avoid being steered by misinformation.

KEY POINTS

The world's most authoritative source on climate science is *AR 6- The Physical Science Basis*, a report published by the Intergovernmental Panel on Climate Change (IPCC) in August 2021.

The enormous literature on climate change contains a mixture of authority, fact, misinformation, science, emotion, boredom, propaganda, hyperbole and criticism from every conceivable point of view. Being able to discern and understand what's coming at you is your responsibility.

Our seeming inability to grapple with climate change is grounded in human psychology. The science has long been settled. The political constipation seems never-ending.

Though climate alarmism-doomism sells well in popular media and scores billions of social media clicks, it's fundamentally counterproductive, a malaise on society.

Earth is a very ancient, powerful, and sturdy planet that has worked and will work just fine without humans. We have only scraped its surface. We remain vulnerable to its forces.

Humanity's three biggest mistakes involve climate change: building cities just above the shore; believing that our atmosphere could hold endless amounts of carbon dioxide without serious consequences, and treating problems as isolated components, rather than holistically.

Cultivating a senses of timefulness, the psychological counterpart to mindfulness, puts the present moment in its proper perspective.

SCRIPT AND TEXT

Pause ......

Welcome to Climate Underground

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Thanks for joining us.

Pause.....

Episode 2 - Getting Grounded

Climbing the Windmill

The screen door banged shut, catching my attention. My mother walked away from the farm house carrying a basket of laundry to hang on the line. This would give me, a four-year-old kid, just enough time to secretly climb the spinning, clanking windmill of our family farm in Manfred, North Dakota, a tiny village midway between Seattle and New York City. Had my mother caught me climbing, I would have been harshly disciplined. And she would have been deeply embarrassed by what might appear to be bad parenting, but wasn't because I was a difficult kid to raise, being eager to take risks, and therefore lucky to be alive. So I never told my mom, or anyone else, at least not until now.

Our windmill was standard equipment on midwestern prairie homesteads before the era of electrification. It was a spinning wheel of angled metal vanes mounted on a steel frame that narrowed upward like a miniature Eiffel tower. Its wheel caught the wind like a propellor, which ran a pump, which lifted water from an unseen aquifer to plumb the house and to quench the thirst of farm animals, in this case a herd of dairy cattle, two dogs, one horse, and a half-dozen feral cats that kept the mouse population down in the barn and granaries.

Curiosity, not daring, pushed me upward. I wanted to know why the wheel spun so rapidly on top of the tower when the breeze at ground level was barely enough to billow the sheets my mother was hanging on the line?

So, I started to climb the windmill, one rung at a time, looking seeing more of the world with every step. Reaching fifty feet, I could finally look down on the barn roof and see beyond the shelterbelt of trees to the immense landscape beyond. That's when the tower began to sway.

Clinging tightly while peering into the distance, I understood for the first time the higher power of the atmosphere. This being the mid-1950s, none of my family had any idea that the global climate of that childhood experience could be changed by human beings.

Background Reading

At the start of this podcast project I grounded myself in climate science by reading and re-reading dozens of new books, hundreds of articles, and visited at least a thousand websites.

Towering above them all are the hundreds of pages of the world's most authoritative report, *AR6 The Physical Science Basis*, published by the Intergovernmental Panel on Climate Change (IPCC) in August 2021. With hundreds of authors, it's the sixth and most recent update of a series, each more refined and each more alarming than the previous.

The books I read by climate scientists include: a recent edition of a textbook I've been teaching from since 2001, William Ruddiman's *Earth's Climate: Past and Future;*   the highly political and adversarial *The New Climate War* by Michael E. Mann;   the movingly personal *Under the Sky We Make* by Kimberly Nichols;   and the futuristic *The Long Thaw* by David Archer.

The books I read by social scientists include: the resonant collection of essays and poems *All We Can Save* by Elizabeth [I-yon-ah) [Ayana] Johnson and Katharine Wilkinson; the hopeful *The Future We Choose* by Christiana [Fig-guer-ees] Figueres and Tom Rivett-Carnac; and perhaps most important, George Marshall's penetrating analysis *Don't Even Think About It: Why Our Brains are Wired to Ignore Climate Change.*

Marshall's title --Don't even think about it-- is spot-on. As with our own certain deaths, we preferred not to think about climate change for the two generations prior to 2010 because it touched every aspect of our modern lives: politics, economics, technology, science, travel, governance, religion, culture, and family. And though we're making good progress now, one stubborn fact remains. The CO_2 content of well-mixed samples of our atmosphere keeps rising. Our failure to draw **down** the carbon we've been venting **up f**lies in the face of three decades of hard diplomatic work by global climate summits between the 1992 U.N. Framework Convention on Climate Change and the 2021 climate summit COP26 in Glasgow, Scotland.

Though the physiochemical science of climate change has long been settled, the political science is as unsettled as ever, thanks to the deeply imbedded paleolithic behaviors of human beings. We respond most to visual cues, yet greenhouse gasses are invisible The ancient struggle between altruism and selfishness is a tragedy of the commons writ large. The embedded instinct to think locally, rather than globally, is hard-wired within us. The default to think **fast** emotionally before thinking **slow** cognitively makes us misbehave. We are programmed to think in the short term, are misled by implicit bias, and seek confirmation for what we already believe. Our tribalism lies at the heart of nationalism, religion, imperialism, elitism, colonialism, and racism, and presents a chronic obstacle to working together.

Journalists, politicians, and street activists depend on engaging our emotions. They know that we are story animals who prefer the passion of the moment over dull data futures. Though responsible journalism about climate change is alive and well, so too is it's evil twin , a genre of inflammatory, apocalyptic, and self-flagellating lamentation. Consider these titles: Peter Sale's *Our Dying Planet,* Nathaniel Rich's *Losing Earth,* Isaac Asimov and Frederick Pohl's *Our Angry Planet*, and Jeff Nesbit's *This is the Way the World Ends.* This last title echoes the biblical "Book of Revelations" in which the coming apocalypse leads to spiritual rapture, cleansing, and reformation. The appeal of a great trial followed by a fresh start sells very well indeed.

Pie-in-the-sky futures are far less common, and can provide helpful relief. Michael Shellenberger's *Apocalypse* ***Never,*** downplays the geological history of mass extinctions and their climatic causes. Joshua Goldstein and Staffan Qvist's *A Bright Future* presents nuclear power as a savior we can count on, though it' a difficult sell in the U.S. where the costs are exorbitant owing mainly to public mistrust." [6]

Of all the books I've read, the most balanced and hopeful are *Drawdown* and *Regeneration,* both team efforts edited by Paul Hawken. With optimism, they suggest that the climate crisis is happening not ***to*** us as retribution for our selfishness and negligence, but ***for*** us as a motivation to finally get act together. Hopefully, the climate crisis can help us find the path away from the exploitive consumerist culture that brought us to the present moment. A similar thesis, though with less grave consequences, was elegantly expressed nearly two centuries ago by Henry D. Thoreau's *Walden* in

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[6] "The New Climate War: The Fight to Take Back Our Planet Michael E. Mann PublicAffairs, 2021. 272 pp

1854, a half-century ago by Wendell Berry's *The Gift of Good Land* and a few years ago by Robin Wall Kimmerer's *Braiding Sweetgrass*. "It's not the land that's broken," she writes, "it is our relationship to land that's broken."

Uninhabitable Earth

Leading my long list of doomist and alarmist works is: *Uninhabitable Earth* by David Wallace-Wells. Climate scientist Michael Mann calls it "Climate doom porn." Some of its beautifully-written horror scenes jolted me with adrenaline, as with a suspense thriller. [7]

Consider the *tuatara*, a reptile from New Zealand that survived three of Earth's five mass extinctions during the last 250 million years without changing its basic lifestyle. It's longevity exceeds that of our species by a thousandfold. Would they consider the earth uninhabitable? Would lichens? Would the bacterial that delight in boiling, acidic, briny water? Ecologist Rob Dunn assures us in his *A Natural History of the Future* that living things are infinitely able to adapt to whatever comes their way.

"The new world we are stepping into," continues Wallace-Wells, "will be so alien from our own, it might as well be another planet entirely." This is patently false. Even the most extreme scenarios for global warming of 5 degrees Celsius lie well within the range of conditions experienced by our group of hominids on the expanding savannahs of Africa. In fact, heat was beneficial to human origins because it allowed sweating naked apes to stay cool while running down overheated furry prey animals.

Uninhabitable Earth concludes that: "Climate change suggests another kind of sphere, manufactured not out of technological mastery but first through ignorance, then indolence, then indifference --a civilization enclosing itself in a gaseous suicide, a running car in a sealed garage."

He's dead wrong about indifference. Young people everywhere are rising to meet the challenge. He's dead wrong about a new atmosphere. Doubling the CO_2 content of the atmosphere to about 500 parts per million raises its carbon content by only half of one percent. Though important, this tiny increment of mass hardly qualifies as a separate sphere.

Fear-mongering is **not** the way forward. Acute fear is good, being a naturally evolved mechanism for self-preservation in short-term situations like a rising flood or encounter with a carnivore. Chronic fear is bad, because it's disabling to the point of being deadly. The good news here is that fear of the unknown can be easily remedied by learning something about that unknown. Hopefully, the shortcomings of your K-12 Earth Science education can be easily remedied by learning how the Earth works in this podcast series. Just keep listening.

In March 2017, the American Psychological Association published the extensive report *Mental Health and our Changing Climate*. It identified ***ecoanxiety*** as a fast-growing clinical psychiatric problem. My goal for helping to quell that anxiety is to help young people understand more, so they fear less. Earth is an unknowable hyper-object. It's a natural system that **can** be understood with a little effort and help.

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[7] Mann 205

Two additional climate-related psychiatric terms have recently caught my attention. ***Pre-traumatic*** *Stress Disorder* is the notion that fear of an unknown future can be as traumatic as re-living a past experience. The geo-therapy here is to know where we're likely headed by examining the ancient climates we've reconstructed from fossil evidence. [Sole-a-stal'-gia] ***Solastalgia*** is a psychological state "characterized by a sense of desolation and loss... experienced by people forced to migrate from their home environment." The geo-therapy here involves reframing our expectations. Continuous change and migrations a normal part of Earth history. Stability is an illusion. What matters is the rate of change at any spatial scale. Timing is everything.

To help handle everyday stress, therapists, spiritual teachers, and mental health professionals urge us to cultivate as sense of ***mindfulness*** -- a mental state that focuses on the ***here-and-now*** of the present moment relative to transient thoughts, feelings, and sensations. To help handle climate stress I also suggest cultivating a sense of ***timefulness*** -- a mental state that focuses on the ***present moment*** as the final detail of a story far longer and grander than all of human history and prehistory.

Timefulness is not instinctive. But it can be learned. You just need to train your brain to let your cognition overrule your emotion when warranted...to think in longer time scales.

Geologist Marcia Bjornerud presents an analogy: Without timefulness, we are "Like inexperienced but overconfident drivers [accelerating] ~~we accelerate~~ into landscapes and ecosystems with no senses of their long-established traffic patterns, and then react with surprise and indignation when we face the penalties for ignoring natural laws." [8] The climate crisis is one of those penalties for ignoring the carbon budget. To meet the target climate goals for 2030, we brake firmly.

Most college age students know they've been screwed by previous generations. Yet they're unwilling to keep kicking this can down the road into the next generation. In 2021, a broad European team led by Wim Thiery estimated that "children born in 2020 will experience a two- to sevenfold increase in extreme events, particularly heat waves, compared with people born in 1960, under current climate policy pledges." [9] For the sake of intergenerational equity, previous generations must help the present generation make the change we were unable to.

My final piece of advice for fighting climate anxiety is to step outside into some garden, park, woodland, or stream valley to appreciate just how beautiful and habitable our planet is and will remain relative to its nearest-neighbors of Mars and Venus. Ours has always been a gorgeous globe, a sunlit blue marble, a living oasis in the black emptiness of space.

And thought I appreciate the escapist fantasies of science fiction, I cannot understand our culture's obsession with space travel and colonization. Every object in the solar system we've visited and left our trash on is uninhabitable without external life supports. The moon we left human poop on is otherwise made of powered gray dust and volcanic rock. Mars is a cold, dead, red, nearly airless planet with no sign of life, though the preconditions of life are there. Venus retained the super-greenhouse atmosphere that Earth got rid of in its infancy: a thick, dense, suffocating veil of CO_2

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[8] Bjornland

[9] Thiery, 2021, Intergenerational inequities...

with an average surface temperature many times that of boiling water. Fly-bys of other planets, moons, and asteroids are no more encouraging. Many look like rocky balls of dust.

Earth is a very sturdy and stable place. Humans don't have the power to wreck the planet. It's survived wholescale melting, a complete freeze-over, cosmic radiation storms, countless asteroid bombardments, and now eight billion human beings consuming more and more of everything. The only significantly fragile things on planet Earth are its ecosystems, which last about a million years on average, and its social systems, the oldest of which are less than half that old.[10] The good news is that when ecosystems and social systems are disrupted during times of crisis, they quickly regenerate into different, more diverse, and more resilient configurations. For every living species in our current catalog of biodiversity, thousands have come and gone. But life on earth has always survived . Modern biodiversity has more to do with long term survivorship after mass extinctions than recent diversifications.[11]

Each discipline has its own frame of reference on climate change. Humanists look in the collective mirror. Ecologists look around at other living things. The geologist in me imagines a trip down to the sweet spot at the center of our planet where I can look upward to see the random chaos on its surface where rock, water, air, and life interact beautifully. The teacher in me imagines being with you now, sharing ideas to enhance your love of the whole planet, rather than merely one of its components. The poet in me refers you to James Merrill, who described the marriage of Father Time and Mother Earth as being "on the rocks."

Two Big Mistakes.

From this podcast's geological frame of reference, civilization has made three big mistakes regarding climate change. All three can be fixed and reversed, provided we work together globally.

First was the assumption that the edge of the sea was a stable and permanent boundary. All of Earth history shows this to be in error. The frontispiece of the first true geology text, Charles Lyell's *Principles of Geology* published in 1830, shows the barnacle-encrusted marble columns of the Temple of Serapis at [Poe-zuo'-li] Pozzuoli Italy. As with a dipstick, they reveal the emergence, submergence and re-emergence of the sea at the scale of about 20 feet, which is the amount we're heading toward in the immediate future.

Ignoring these ups and downs, nations have continued to build and defend urban infrastructure in places that will almost certainly be underwater within a century or two. The question is not if this will happen, but when. Strategic and managed retreat is the only viable solution. Walking away from a rise in sea level is similar to walking away from a rising tide, though at a much slower speed, and with much greater cost.[12]

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[10] Ecological stasis on geological time scales
PETER D. ROOPNARINE AND ROXANNE M. W. BANKER
SCIENCE • 16 Apr 2021 • Vol 372, Issue 6539 • pp. 237-238 • DOI: 10.1126/science.abh2853

[11] Bush, Science paper, 2021

[12] Hasnoot, 2021, Pathways to Coastal...

Humanity's **second** biggest mistake has been to ignore the astonishingly accurate predictions from past decades. The 1979 Charney report by the U.S. National Academy of Sciences warned that a doubling of CO2 by the mid twentieth century would warm the planet within a range of 1.5 to 4.5 degrees Celsius. These results still hold. The 1988 congressional testimony by climate scientist James Hansen announced that that the ***signal*** of climate change had finally emerged above the ***noise*** of measurement error. "It's time to stop waffling so much," he said, noting that greenhouse warming is a here-and-now problem." [13]

The urgent reality of climate change in 1988 created an existential crisis for sectors of our economy dependent on fossil fuels. In response, this group set up the Global Climate Coalition, a sometimes covert campaign of climate obfuscation and denial with the goal of preventing the U.S. of adopting the Kyoto Protocol, designed to limit carbon pollution internationally. Much of U.S. society happily followed in denial because it was convenient to do so. But within the last decade, the improved data from climate science, and the increased frequency and magnitude of extreme weather events have made denial impossible. So the lobbyists and marketers switched tactics to what Michael Mann calls "strategic inaction," with the goal being "to deflect blame, divide the public, and delay action so that business can continue as usual."[14]

Though the fossil fuel industry has finally come around to **talk the talk** about climate change, as a whole, they don't yet **walk the walk**, based on a careful review in 2021 by a team of economists: "The oil and gas (O&G) industry," they conclude, is "not on track." Only two of dozens of companies have realistic plans to meet the 2 degree upper limit of the 2015 Paris accord.[15]

When Hansen testified in 1988, the CO_2 content at Mauna Loa was about 350 parts per million. Today, it's about 420 and climbing. That the only number that really matters, the global end result of all our talking and posturing, what activist Greta Thunberg calls "blah, blah, blah."

There is hope. Lots of it. Consider this. An international airline flight emits enough carbon per passenger to melt a block of glacier ice big enough to fill many truckloads. So, if we want to melt less ice, those of us who are wealthy enough can we can decide to fly less. Eighty percent of the global population has never been in an airplane. When it comes to aviation tourism, the inconvenient truth is that, collectively, we prefer inaction to action.

Humanities **third** big mistake has been to treat problems like climate change within the fiefdoms of specialized disciplines. Alas, climate change is a "threat multiplier," meaning that a specific threat in one discipline multiplies with that of another, rather summing with it. For example, the ***meteorology*** of a rise in temperature over Greenland multiplies with the ***glaciology*** of how ice-sheets behave, which multiplies with the ***geography*** of coastal cities, which multiplies with ***sociology*** of environmental justice, (wealthier people tend to live on higher ground in more rural settings than poor people), which multiples with the ***epidemiology*** of health outcomes and the ***criminology*** of civil unrest, and so forth.

The climate crisis is fixable. We just have to decide to do so.

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[13] Douglas, 2021, Our Biggest Experiment...
[14] Mann, 2021, The New Climate Wars
[15] Deitz, et al, 2021, How amibitious are oil and gas companies' climate goals?

3 - CLIMATE KAIROS - 2867

TAKEAWAY

Though very real and very challenging, the current climate crisis can reframed as an opportunity to finally get things right for the remainder of the Anthropocene Epoch.

KEY POINTS

The vocabulary of the current climate crisis shapes our thinking about what's going on and what we can do. Know the difference between climate change, crisis, science, disruption, weirding, consternation, and global warming and heating.

The word *kairos*, from ancient Greek for "the right time" views the angst of the climate crisis as an opportunity to finally get things right, to steer ourselves away from a human-centered and exploitive worldview

The climate crisis is what scientists call a wicked problem, one so complex and interconnected that it's not amenable to a clear or rigorous solution, an requires input from divergent disciplines.

Miscommunication occurs when the words Earth, planet, world, and globe, and nature are used without defining what we mean.

In the middle of the 19th century, climate change was an exciting research program within the emerging discipline of geology, and central to its identity. In this 21st century, climate change is still literally a hot topic, but as an enormous problem to be overcome.

SCRIPT AND TEXT

Pause ......

Welcome to Climate Underground

I'm your host, Robert Thorson

Thanks for joining us.

Pause.....

Episode 3 - Climate Kairos

Pause

The Year 1968.

Nineteen sixty eight was a convulsive year in American history. Martin Luther King was assassinated by a white racist, igniting more than a hundred U.S. cities flame with anger. Bobby Kennedy was murdered, sending young Americans into despair. The Democratic Convention in Chicago featured bloody protests over the covert escalation of the American War in Vietnam -- 26,000 police, troopers, and national guardsmen were dispatched to keep order. The United States armed forces was making plans to draft all able-bodied men into the army by lottery.

The year 1968 was my junior year in high school. During an in-class reading for English class, the word *semantics* leapt out of my textbook and changed my life. Before that moment, I thought that words meant nearly the same thing to nearly everyone. They don't. So, when school ended, I walked over to the local library and spent much of the night trying to learn why the words we use to communicate are so important.

Fast forward to the present. What, pray tell, is climate change? What does it mean? Is it synonymous with global warming? Are we in a climate crisis, a climate emergency, or a climate opportunity? What's climate weirding? What's climate kairos?

Terminology

Let's start with the word ***crisis***. We're definitely in one, based on both definitions from Merriam Webster's Dictionary. The essential meaning of c*risis* is a "difficult or dangerous situation that needs serious attention." The Cuban Missile Crisis of 1963 provides a good example. That's when I remember the United States and the Soviet Union standing on the brink of thermonuclear war.... of mutually assured destruction, or M-A-D, or MAD.

The original and full definition of the word *crisis* is more nuanced, a "***turning point*** for better or worse" as with a mid-life crisis, or a "***decisive moment***" such as a proposal of marriage or choosing which college to attend.

On the short term, the climate crisis aligns nicely with the essential definition. This perspective is nicely laid out in a recent book titled *The Future we Choose.* The choice is between "The World We ***Are*** Creating" or "The World We ***Must*** Create."[16] The former assumes a *laisse faire* carbon future leading to a warming of 3° C or more by the end of this century. The latter assumes a sweeping transformation of global energy culture to hold warming to an optimistic 1.5°C by century's end.

They say that a stitch in time saves nine. We didn't make a stitch to lower our carbon emissions in 1965 when U.S. President Lyndon Johnson highlighted the issue. Now, we're faced with making nine stitches at much greater cost. The same holds true for the future. A dollar invested on climate-related infrastructure today will save many more down the road.

Besides being a threat multiplier, the climate crisis is also a hot mess -- what scientists call a wicked problem --a witches brew of ingredients and non-linear interactions with no prior precedent in Earth history. The recipe includes an addiction to cheap energy, recency bias, confirmation bias, a political system designed to discount the future, special interest groups deceiving us, an exploitative

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[16] Citation

consumer mindset, superpowers rattling their sabers, wealthy countries taking advantage of poor, and last, but not least, ignorance about how the earth works.

Every crisis has something that pushes it to the brink. For the climate crisis, it's been the daily body-blows of storms, droughts, wildfires, icebergs, and hordes of climate refugees taking place all over the world since about 2018. Meanwhile, in the background, the IPCC is busy doing its patient work. In August 2021, they reported that Earth's average surface temperature has risen slightly over 1°C above the global historic baseline average for 1850–1900, "the earliest period of reliable observations with sufficient geographic coverage." It's now rising steadily toward 1.5 °C, the hoped-for upper limit targeted by the 2015 Paris Accord. Their backup plan is a 2° C rise.

One recent analysis concludes that we should give up on 1.5 degrees as a lost cause. [17] A separate report concludes that "even if fossil fuel emissions were immediately halted, current trends in global food systems would prevent the achievement of the 1.5°C target and, by the end of the century, threaten the achievement of the 2°C target. [18] The geo-colleagues I've talked to, who understand the Earth system better than most, anecdotally expect us to burn past the 2 degree upper limit on the way to an inevitable 3° C or higher.

On the longer term thinking of the Anthropocene Epoch, the bad news of the last few years may turn out to be an opportunity. Perhaps we've entered climate ***kairos***, a Greek word meaning the "right time." Merriam Webster calls it a time when "conditions are right for the accomplishment of a crucial action : the opportune and decisive moment." Thanks to climate *kairos*, global culture finally has a chance to change for the better, a transformation we've been unable to make with will power alone.

A change away from the sapiens-centered and exploitive mindset of *more, more, and more* to an Earth-centered and sustainable mindset with greater humility and respect for other creatures. The world's successful resolution of the ozone crisis of the 1980s shows what global culture can accomplish when the time is right, and when we put our hearts and minds to it. Perhaps this new view will lengthen the Anthropocene Epoch beyond its present seven decades.

Working backwards through time, climate kairos emerged from climate crisis, which emerged from climate change, which emerged from global ***warming***, a term highlighted in the scientific community in 1975 by on one my heroes, the late Columbia University geochemist Wally Broecker.

His phrase global *warming* works for the earth's surface. Indeed, the planet's volatile layers of atmosphere and ocean are slowly warming. But if you treat the globe as a volume, its been steadily cooling for 4 billion years. Another problem with the phrase *global warming* is that it connotes a uniform change, even though its warming five times faster in some regions than others, and is locally cooling in a few places. Warming is highly localized when you take altitude into effect.

Why not global ***heating***? This was the suggestion of James Lovelock, who co-founded the Gaia theory. This would have been a better choice than global warming because it replaces the positive connotation of warmth with the neutral connotation of heat. In physics, heating is the addition of

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[17] Meinshausen et al, 2022, Realization of Paris, Nature 604, 304-309.

[18] Clark et al, 2020, Global Food System...

energy measured in calories, joules, or BTUs, and is more fundamental than temperature. Finally, the term warming doesn't work when something is already hot.

Some have suggested the term climate ***disruption***, because it conveys the immediacy and negativity. Though this is a pretty good description from humanity's point of view, a disruption for one species is usually an opportunity for another. For example, the Chernobyl nuclear meltdown was a disruption for humanity, but a godsend for the wildlife now reclaiming the one thousand square mile (2600 km2) exclusion zone declared off-limits to people. Though geological mass disruptions preceded Earth's major mass extinctions, each was a desperate ending for some groups and a hopeful beginning for others. Earth's cumulative biodiversity was enhanced above the previous background as a consequence. I am, however, very concerned about the loss of biodiversity on the short term.

There are days when I think that the term *climate* ***eruption*** would have been best because the urgency of the word *eruption* grabs our collective attention. By definition, climates can't erupt because they're backwards-looking statistical things. But, ***visually***, the carbon emissions from the smokestacks of our power plants, refineries, and factories superficially resemble those of tall, skinny volcanoes. By ***rate*** --meaning the flux of carbon per unit time-- anthropogenic emissions from smokestack definitely constitute an explosive eruption. The amount of human carbon emitted since the 1750s greatly exceeds the amount released from thousands of volcanic eruptions over the same time interval. If, thirty years ago, someone of prominence said that our emissions were a carbon eruption, perhaps we would have responded more effectively.

The phrase *climate* ***weirding*** is undefined and statistically meaningless. It's also a poor choice of because it's judgmental. What users really mean is that specific weather events are anomalous relative to the preceding condition. But let's keep in mind that the climates of today would look weird to the happy dinosaurs of the seething, scalding, and sulfurous Jurassic.

Triage of Terms

This triage of semantic terms --climate ***crisis***, climate ***kairos***, global ***warming***, global ***heating***, climate ***disruption***, climate ***eruption*** , climate ***weirding***-- leaves only one popular term standing; *climate* ***change***. One clear advantage of this term over others is that it's a neutral, factual statement that doesn't preference a rise in temperature over a fall. Nor does it preference one climate parameter over others, such as temperature over precipitation or wind direction. The establishment of the scientific journal *Climate Change* half a century ago in 1977 adds historic credibility to the term.

Though climate change dominates modern climate-speak, it is not without many semantic problems. The misalignment of definitions and nuances leads to what I call climate ***consternation***, in which well-intentioned people talk past one another without realizing it. To climate scientists, climate change is a physical and statistical thing. For the majority of others, it's a cultural meme for political action, an ecological crusade, an agency mandate, and so forth. For those of us with vested interests, which is all of us, the term climate change is ripe for deliberate obfuscation, misinformation and propaganda.

Climate change remained an academic subdiscipline with its own scholarly journal from the late 1970s through the early 2000s when, in 2003, it was adopted by conservative strategists wishing the problem would go away. They urged its usage because it sounded less ominous, less contentious, less specific, and more local than global warming. Elizabeth Rush, author of the award-winning book on sea-level rise *Rising*, deems climate change "too political, too cold, [and] too loaded to map onto everyday life." [19] Pundits and talking heads love the phrase because their silver-tongued blither is less constrained by factual details.

Climate change is the punch line of a much longer story -- a cascade of events with six main steps: (1) Humans desire access cheap energy, (2) which leads to the burning of fossil fuels; (3) which leads to exhaust gases that change the chemistry of the atmosphere; (4) which amplifies greenhouse heating; (5) which raises the temperature of the troposphere; (6) which forces regional climates to change, each in their own way. As with a captain steering a large and powerful ship, the effortless mechanical step of turning the wheel rotates a gear, which opens a hydraulic valve, which raises the pressure in one direction, which pushes the rudder, which turns the colossus. That's an analogy for what we're doing with the Earth system.

For me, one of the most frustrating things about climate change is that it's seldom pluralized, even though the word climate comes from the Latin *clima,* meaning zone or region. Each of Earth's multiple climates is changing *individually* in response to warming of the troposphere, and "socially" as it interacts with neighboring climates. The singular usage of *climate change* conveys the illusion that *a* climate is changing, rather than *many* climates are changing, each in their own way. Historian Sarah Dry agrees that the singular usage is little more than a "useful fiction, born of often necessarily crude averages... an imaginary tool for grasping the earth in one gesture."

Climate change doesn't work for *novel* climates, meaning those new to our classifications, nor for *extinct* climates, meaning those that we used to know well, but are now gone. When someone is born, their life doesn't change. It begins. When someone dies, their life doesn't change. It's over. The singular usage climate change can't account for such beginnings and endings.

New climates are already appearing in the equatorial tropics where it's getting too hot. These can't be forced into the familiar Koppen classification, the global standard used by the IPCC. Extant climates are becoming extinct, especially in in boreal climes. If our worst-case climate change scenarios for the year 2100 come true, the familiar Koppen classification will be like that old car that's no longer worth fixing. Already, the IPCC has done away with Koppen climates for aggregated statistics, instead treating the terrestrial surface as 46 hexagonal regional climates.

The singular use of climate change has trouble with cascading effects. Consider the unprecedented wildfires in Valparaiso Chile that began the day after Christmas 2019. In the 19th century, Valparaiso was a British naval port where Charles Darwin spent a winter recovering from illness and exploring the geology of its hills. In the 20th century it was the industrial city where the poet Pablo Neruda wrote most of his work. In 1998, it's where I worked for a year as a Fulbright Scholar. The proximal cause of the city's fires was the worst drought on record. The distal causes are harder to pin down because they're mixed up with the multi-year El Nino-La Nina Southern Oscillation, which is driven by the Walker Circulation over the western Pacific Ocean. Quite simply, the cause of the climate change in Valparaiso was due to a climate change elsewhere due to a climate change elsewhere. Does this count as one, two, or three climate changes?

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[19] Rising

The singular usage of the term climate change has scientific value only for spans of geological time long enough to blur out regional details. Earth has two somewhat stable and self-reinforcing climate states with tipping points between them. In its default *greenhouse* state, earth is much warmer and wetter than today, there are no polar ice sheets, and the temperature gradients from equator to poles are smaller. In its less common *icehouse* states, Earth is colder and drier, has polar ice caps, and the north-south circulation is much more vigorous. At this multi-million year time scale, Earth will remain in an ice-house climate until the last permanent ice on Antarctica melts into an ocean tens of meters higher than at present.

A penultimate challenge for the term climate change is that the media often treats it as if it was a cause of other things like ocean acidification and hypoxia, extinction, and sea level rise. Not necessarily. Climate change is one of many distinct *outcomes* of a single thing, an excessively carbonized atmosphere.

Finally, the generally negative association of the term climate change in modern culture is giving a wonderful geologic subject a bad name by association, as with the way Lyme Disease has given the lovely towns of Lyme, East Lyme, and Old Lyme Connecticut a bad name. Modern culture has made climate change a consequence to be feared, a crisis to be managed, and a lousy legacy to hand down to following generations. In the process, the name of one of geology's most exciting research agendas has joined the ranks of words like disease, war, genocide, pollution, extinction and poverty. Sad but true.

What Is Climate Science?

The final phrase is *climate* ***science*** is done whenever a curious person or team applies the methods of science to the subject of climate. Though there are many scientific methods, the main one is a **stepwise** cognitive algorithm that makes new information out of old information. The basic steps are: observation, hypothesis, testing, results, interpretation, and repetition of the same, over and over.

Though the first quickening of climate science were felt in the early 19th century, emerged in the mid-20th-century as the blend of three fundamental approaches: the *synoptic* global view of ***climatology*** emphasizing patterns and associations; the *historic* view of ***paleoclimatology*** from history, archaeology, and geology, emphasizing sequences of events through time; and the *mechanistic* view of ***physiochemistry*** taking place at any time and place, emphasizing analytical rigor.

As currently practiced, climate science came of age in the late 1980s with the availability of four distinct data sets: the *planetary* system of orbital and solar changes; the *earthly* physical climate system of meteorology, geology, and oceanography; the *global* biogeochemistry of the troposphere and ocean via chemical cycles; and, finally, the *worldly* behavior of human beings as a planetary force via their exhaust emissions and land surface changes, all via the power of fossil fuels.

In the Anthropocene, climate science is simply the biggest and most worrisome chunk of Earth System Science. A wonderful example is offered by Gudmundsson and others in a 2021 report that links the flow of rivers --a time series from over 7000 global observatories for the interval 1971-

2010-- to anthropogenic climate change. [20] Some river flows are higher, and some are lower, but all are consistent with changes in radiative forcing caused by human carbon emissions.

Another example is the problem of drought. Quoting a massive review paper by Toby Ault and others, "Droughts of the future are likely to be more frequent, severe, and longer lasting than they have been in recent decades.." [21] A team led by A. Park Williams put this to the test in the southwestern U.S. They examined a 1200-year-long time series of tree rings to reconstruct summer soil moisture for that interval. Using a meta-analysis of 31 computer models, they concluded that nearly half of the scorching, killing, modern megadrought is due to anthropogenic forcing. The inescapable conclusion is that we knowingly did this to ourselves. [22]

Climate science involves every conceivable approach, and all scales of time and space from the birth of Earth 4.6 billion years ago to the fluttering of leaves in the present moment.

So, why do leaves flutter? A physicist might say it's the fluid turbulence of kite-like leaves attached to flexible stems. A botanist might describe the selection tradeoff between the large surfaces area needed for gas exchanges and a vascular stem linked to the tree. A meteorologist might focus on the origin and velocity of the wind reaching the leaf. A geoscientist might explore any or all of these answers back to the beginnings of time -- the source of the gas that blows in the wind that flutters the leaves because of their evolved shapes. That gas is mostly molecular nitrogen (N_2), a volatile that steamed out of Earth when it melted,...which was heavy enough to be retained by gravity, ...and which was inert enough to avoid reacting with other molecules.

So, why do leaves flutter? Because of the entire chronological cascade of earthly events and processes since the birth of earth. Becauses global conditions are merely the grand sums of local conditions, right on down to the scale of a leaf.

Do climates flutter? Yes they do, but in a completely different way.

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[20] Gudmundsson et al, 2021, Globally observed...

[21] Ault, 2020, On the essentials of drought....

[22] Park Williams, 2020, Large contribution....

4 - CLIMATE AND PERSONALITY - 2605

TAKEAWAY

The analogy between a human personality and an earthly climate is compelling. Both are fairly stable expectations based on past behaviors that emerge from previous events.

KEY POINTS

Climate is what we expect. Weather is what we get.

Weather is tangible and physical, experienced in the here and now. Climate, is intangible and probabilistic, something that can only be seen in the rear-view mirror.

The analogy between personality and climate is compelling at many levels. Personality is an external state of mind created by the internal brain. Climate is an external state of prevailing meteorology created by the deep earth interior.

Earth's climates are continuously changing at all scales of space and time. Stability is an illusion.

Identifying, naming, and classifying climates is a form of categorial thinking. Though helpful, such categories give rise to implicit biases that we must be vigilant to guard against.

The familiar geographically-based Koppen classification of climates is gradually being replaced by more objective categories that are less constrained by surface vegetation.
Climate's do merely change. As with new species, novel climates emerge and others go extinct.

SCRIPT AND TEXT

Pause ......

Episode 4 - Climate and Personality

Pause ......

Welcome to Climate Underground

I'm your host, Robert Thorson

Thanks for joining us.

Pause.....

Walking to Work

Since 1984, I've been walking to work on a fairly regular schedule. For the last five years, my path follows a woodland trail through a pine-oak-hickory forest, skirts small pond, crosses two small streams, and ends with an upward-sweeping lawn fronting the historic section of campus, which is on the National Register of Historic Places. Four decades of four-season pedestrian commutes over varied terrain has given me a personal opportunity to monitor every conceivable type of weather such as dense fog, hail the size of golf balls, white-out blizzards, sweltering heat, soil-cracking deep-freezes, and drenching downpours. All but four of those years post-date the 1988 announcement by James Hansen that global warming had arrived.

For this interval of nearly 40 years, My ***personal*** qualitative sense of climate change matches the ***actual*** quantitative data of climate change, which matches the ***predictions*** of climate models. My winters are warmer and cloudier, my late summers are hotter and drier, thunder now occurs in every season, and storms are more intense. It's as if the personality of my landscape has changed.

"Climate is what we expect," wrote author Mark Twain. "Weather is what we get." His simple differentiation of the two is pithy perfect.

The National Oceanic and Atmospheric Administration (NOAA) is our official federal agency for tracking weather and climate. Their definition of weather is consistent with Twain's: the "short term state of the atmosphere" involving "both time and location." The key word is ***state,*** which integrates and describes multiple variables such as temperature, precipitation, cloudiness, and wind strength. Their definition of climate is also consistent with Twain's: the "description of the long-term pattern of weather conditions at a location," long enough to define an official "climate normal," usually "30 years or more." Time scales longer than a generation are also used to capture things like the expected frequency of great hurricanes in a century or the frequency of El Nino or La Nina conditions and the AMO, the Atlantic Meridional Circulation. The key word here is ***normal.***

Climate change is thus nicely captured by the phrase "new normal," even though this doesn't mean that the new climate is anything like the past. It means only that there's been a change from a previous meteorological state to a new one.

Top down

Precipitation comes at us from the top down. Rain **falls,** so we call it rainfall. Snow **falls**, so we call it snowfall. **Down**pours are the *direct* work of gravity, the vector force pulling each raindrop down toward earths metallic core.

Weather comes at us from the side. Wind **blows** from a compass direction, as does the steady march of weather fronts. This horizontal flow is the ***indirect*** work of gravity pulling down more strongly on colder, denser air than on warmer, lighter air. When air is pulled down against a rigid surface like the earth's crust, it's forced to move sideways as what we call wind.

In contrast, **climates** come at us from the **bottom up**. Most obviously, volcanoes blow **up** to send tiny particles called aerosols into the air, which cool the climate for a few years. The **upward** leakage of volcanic gas is constantly changing the planet's heat balance at longer time scales. Climates, being regional, are defined by the locations of continents and seas, which are random consequences of **upward**-flowing geothermal heat. The global climate state is governed by the **upward** transfer of rock carbon from the crust to the gaseous carbon in the atmosphere. Climate history is revealed by clues left **underground.**

In his somewhat outdated book *How the Mind Works,* Stephen Pinker summarizes all of psychology in a simple sentence: "The mind is what the brain does." Ephemeral **thoughts** come from mental **states**, which come from the **brain**. Paralleling his sentence, a geoscientist could say: "The climate is what the Earth does." Ephemeral **weather** comes from climate **states** which come from the planetary **interior**. Even the spherical shape of Earth is a consequence of the soft squishiness of the hot rocks below and the concentration of mass at the core.

Weather is ***tangible***. It's physical. Its local. You can feel the rain pelting your cheek, the weight of snow when shoveling, and the press of wind when leaning into it. Weather is the physical sum of whatever the atmosphere ***is*** dishing out in the present moment, ***has*** dished out in the recent past, and ***will*** dish out in the next few hours. Weather is chock full of powerful physical forces acting in real time that can enhance or destroy our lives.

Climate, in contrast, is ***intangible***. You can't feel it. It's an expectation --subconscious or conscious-- of how the atmosphere will behave over some time interval, usually a human generation or more. There are no physical forces involved. Climates are defined as statistical aggregates before being reported to us with average values, maps, and texts.

Climates change, by definition, when our expectations of the weather change. For most of human history, these expectations were based on anecdotal physical experiences like my walk to work, or on collective memories passed forward through oral tradition and almanacs. Now, they've based on physical measurements kept by government agencies and analyzed in technical journals. This transition, from **personal**-*qualitative* to **agency**-*quantitative* helps explain why it's taken so long for the general public to accept that the climates have indeed changed. Part of this is due to increasing public mistrust of government and scientific expertise in the last half-century.

A smoother transition to the acceptance of climate change would have happened if the American public school curriculum had spent more time on fundamental earthly processes than on more charismatic topics like ecology and culture. As philosopher Will Durant once quipped: "Civilization exists by geological consent, subject to change without notice." That **consent** involves more than dramatic hazards such as great earthquakes, volcanoes, and landslides. It also involves the slower, sometimes invisible transformations of Earth's surface and its atmosphere. Adding to Durant's clever adage: "Civilization exists by **climatic** consent, which exists by **geological** consent, subject to change without notice."

Each place on earth has its own climate right on down to the scale of tree or a fence. This local diversity arises from the complexities of sun versus shade, rock versus soil, windward versus leeward, and wet versus dry at a range of scales. My grandfather in North Dakota changed his microclimates in the 1930s when he planted a shelterbelt of trees to block the wind to prevent a local dust bowl. He was powerless to change the regional climate. He also had little indirect effect on it because he did not deforest a landscape, he plowed with horse-power rather than tractors, fertilized mainly with manure, and predated most pesticides.

Climate as Personality

Moments of human emotion arise from ***moods,*** which are short-term psychological states at the time scale of seconds to days. All of us have predictable mood swings when we get hungry or tired, or at different times of the month or year. Some contend that current and recent events ***put*** them in good or bad moods, for example the return of a loved one at an airport terminal, or the receipt of a shaming post on Instagram.

At the next level **down**, one's transient moods arise from one's fairly stable ***personality,*** which is quite predictable at the time scale of years to decades. Personality emerges from some combination of one's internal genetically mediated temperament and one's internal habituated responses to experiences, good or bad, loved or unloved.

At the final level **down**, one's personality arises from one's material ***brain*** -- that lump of flesh inside your skull, that pudding of gray matter, that network of neurons. In short, the interior physical system of your *brain* gives rise to the exterior intangible manifestation of your *personality*, the context from which your psychological *moods* and *moments* arise.

Earth's ***climates*** are broadly analogous to human ***personalities***. Both are expectations of behavior, in the one case leading to physical weather, and in the other case leading to psychological moods. Both expectations are very real, but intangible, meaning they can't be touched. Both emerge from physical systems of interacting solids, liquids, and gases, in one case the brain fueled by pumping blood, and in the other case the earth interior fueled by geothermal heat.

Within **our** lifetimes, our personalities have changed as we passed life stages such as infancy, childhood, adolescence, young adulthood, and full maturity, and as we experienced major turning points, for example financial independence, parenthood, incarceration, and unemployment. The archive of this change consists of memorabilia, scrapbooks, trophies, and so forth. Sometimes, we scarcely recognize our former selves.

Within **Earth's** lifetime, its experienced an untold number of climates succeeding one another in different places. We know this because each paleo-climate left a packet of rock with clues to paleo-weather that we've learned to interpret, for example the mud-cracks of a dried up lakeshore.

Classification

To understand climate ***change*** we must first understand categorical thinking. Let's start with the human condition.

Between the *one-ness* of our human species, and the *billon-ness* of all individuals -- you, me, and everyone else-- are countless categories that we've impose on ourselves. On survey forms, for example, I check the boxes male, husband, father, scientist, professor, race, and so forth, usually leaving others blank. Though sociologists can easily classify and study these discrete attributes, they can never capture the real me. The same is true with climates, or any other complex entity, like music, or food, or nations. Each is unique. Alas, the categories we put them in start to control out thinking because they are self-reinforcing, for example tropical vs. temperate climates, white vs. black people, fruit vs. vegetable food, New Hampshire vs. Vermont states, and male vs. female genders.

For example, Utah, Colorado, New Mexico, and Arizona are separate states of the United States. Fundamentally, each is very distinct legal-political unit governed by a constitutions. But where all four sates meet at a place called the Four Corners, they are physically identical. There, you will find a circle about six feet in diameter resembling the face of a compass divided into four quadrants. When my family visited there, one of my kids sprawled themselves out so they could put one limb in each state. Climatically, he was one place. Politically, he was in four.

The climates of the world exhibit continuous variation in space and time. But the sake of analysis, we force them into arbitrary mapped units during arbitrary blocks of time. Though the climates at the centers of adjacent map units may be quite different from one another, they are identical at their arbitrary boundaries. In fact, three separate mapped climates can exist within inches of one other. Imagine a baseball field where first, second, and third base are mapped as having different climates. In this situation, climate change might mean nothing more than a slight shifting of one boundary.

The word climate comes from Latin root *clima* for zone, or region, or place. Our categorial understanding of climate thus began with the *geograph*y of distant lands, whose cultures, climates, floras and faunas all changed in ways that could be described, classified, and mapped. Scientific exploration of these regional differences emerged in the late 18th and early 19th centuries through the work of Prussian explorer Alexander von Humboldt and his successors, one of whom was [Vladimir Kuppen] ~~Wladimir Koppen~~. Between 1900 and 1940, Koppen published a widely used classification of climates that still bears his name today. His categories were based on quantitative measurements of rainfall, temperature, and seasonality that matched familiar vegetation zones that he assumed were stable. The names he chose for his 20 categories of climate units are all familiar to us today: tropical, polar, temperate, monsoonal, Mediterranean, maritime, and continental.

Tropical climates with sufficient moisture for plant growth are called ***megathermal,*** meaning lots of heat. Within this hot category are three basic types based on the pattern of precipitation: rainforest, monsoon, and savannah. His dry climates are in the subtropics, where air descends as a prevailing pattern, either arid or semi-arid. The temperate or ***mesothermal*** climates occupy the mid-latitudes where it is neither too hot nor too cold. In this vast middle ground, winters may be wet or dry, deserts may be hot or cold, and and the arrangements of continents, elevation, and the pattern of ocean currents makes classification difficult. The result are nine named categories that bear only partial relationships to latitude. Further north are the continental ***microthermal*** climates of the arctic and subarctic, each divided into four different types. Finally, there are the polar climates of the high latitudes, defined either as tundra or ice sheet.

Most Koppen climates are named for the habitat they created, rather than the climate itself, for example rainforest, savannah, steppe, and tundra. This raises the question: If we cleared the vegetation, would the climate remain? One Koppen climate is named not for vegetation but for an earthly material, glacial ice. This raises the question: Would the climate migrate with the ice? One climate is named for an elevation, highland, raising the question: "What if the land subsided?

This classification --the intellectual bedrock of old-school climatology-- was invented before the modern era of satellite imaging, numerical computers and modern mathematical statistics. When artificial intelligence and machine learning algorithms are applied to climate classification, the results come out quite differently. Statistical techniques like Linear Discriminant Analysis (LDA). Principal Component Analysis (PCA), random walks, and cluster analyses each yield different categories, each of which could control out thinking about climate change. The challenges of classification is why climate models often ignore them completely. The IPCC AR6 replaces them using 46 geographic polygons instead.

The idea that climates are fundamentally regional is supported by proxy measurements of paleotemperature and paleo-moisture for the last ten millennia of the Holocene Epoch. Statistically significant regional changes average out to little net change at the global scale. In contrast, all of today's climates are changing in response to carbon emissions, each at a different rate, and in a different way.

The well-documented 1ºC rise in Earth's surface temperature over pre-industrial conditions is, by definition, not a change in climate but an average for all climates. Much higher rates of warming near the poles of at least 4ºC are being averaged into much lower rates at the equator of about 0.5ºC. The result is what's called a more ***equable*** climate state because the annual and seasonal differences between the equatorial and polar regions are more equal. This change diminishes the energy gradient in a north-south direction, decreasing the overall strength of atmospheric and oceanic circulations. Flip-flops between less-equable and more-equable climates have occurred many times in the geological past, so we're pretty sure what's heading our way.

The hardest part about predicting climate change is the "social" part of how individual climates interact with each other. For example, warming of the Arctic is reducing the temperature contrast between polar and mid-latitudes. This is changing a stratospheric wind called the polar vortex, which is allowing the north-hemispheric jet stream to meander more widely. These wider meanders help explain the more extreme toggles between subarctic and subtropical air masses in the central and southern U.S. When all is said and done, the complex interaction between Earth's multiple climates is being driven by a single phenomenon: enhanced carbonization of the lower atmosphere.

What we can be sure of is this: Just as each of Earth's cities has a dynamic community of people, Earth as a whole has a dynamic community of climates, each with its own personality. Each will respond as an individual, and as part of the community.

5 - GEOPHILIA - 3799

TAKEAWAY

Developing a love for Earth as a whole, requires that we acknowledge and try to overcome the implicit biases of the humanities, social sciences, and ecology that feature only pieces of the whole.

KEY POINTS

Biophilia is the instinctive and ineffable love of living things that aren't trying to harm us. It's a form of patterned learning selected for during evolution that preferences our interest in living behaviors over nonliving behaviors.

Anthrophilia is an even more fundamental, instinctive, and effable love of human beings that are not trying to threaten us. Being a social species, we are bonded to each other as mates, families, kin, clan, and tribe.

Anthrophilia and biophilia are powerful implicit biases that limit our understanding of how the Earth system works our role in that system as one species among many in one subsystem among many.

Placing the whole Earth system at the center of your attention is more challenging but leads to greater understanding.

One good mantra for helping remind us put things in proper perspective is: "No rocks. No ecosystems. No cultures."

SCRIPT AND TEXT

Pause ......

Welcome to Climate Underground

I'm your host, Robert Thorson

Thanks for joining us.

Pause.....

Episode 5 - Geophilia

Pause

Just outside my home is a forest conservation area with a vernal pond that holds water during the winter and spring, but is always dry in the summer. Each winter it freezes to a sheet of ice on which I slide around on for fun. Each spring it holds a chorus of peeping frogs loud enough to be heard at great distance. Overlooking its north side is a massive outcrop of coarse gray granite about a dozen feet high that provides the best view of the pond. Not once have I seen anyone else stand there. Apparently it's not attractive enough.

When I bring visitors to this outcrop and ask them to describe what they see, they always respond with something about the water, woods, or wildlife. Not once has anyone responded with the most obvious thing, the rock outcrop, and arguably the most beautiful thing, a gorgeous mass of quartz, feldspar and black mica. I suspect that if that same rock were cut and polished and laid flat as a kitchen countertop, it would be noticed and appreciated daily. As a geologist, I often wonder why most people in forested regions seldom see, appreciate, and describe rock, or know next to nothing about it. My answer is that our pre-K-12 school curriculum has failed them to appreciate earth's most fundamental substance.

Anthrophilia

In her poem "Knife," the late poet laureate Mary Oliver abhors the "outrageous divisions of time" that make earth history so unfathomable for those who measure time in human lifespans. The knife of her poem, the one that slices through her heart with the "thinnest of blades," was a typical New England fieldstone wall, the region's signature landform. Though I enjoy her poetry, the **humanist** of this one takes me aback. What she sees is a "sheer, dense wall / of blind stone / without a pinch of hope / or a single unfulfilled desire." This view of rock manifests the *anthro**philia*** --or human love-- so typical of western European culture.

Indigenous wisdom suggests an alternative -- that the stones in the wall are alive in its own way. Indeed, the protons and electrons within their minerals are vibrating and orbiting in exactly the same way as in the human brain. So, why is one entity considered alive and the other not alive? Would the stone declare us dead for being so chemically disorganized relative to its well-ordered crystalline lattice?

We must never forget that **life** came from **non-life**, not as an improvement on the former condition, but as an emergent phenomenon that came into being like a whirlpool. The oldest form of microbial life we know of was born from volcanic brines, whether ***in*** some geothermal mud pot under the orange haze of a methane sky, or ***on*** some oceanic vent in abyssal blackness. The oldest organisms with nucleated cells, the eukaryotes, are also associated with volcanic brines, in this case on the mid Atlantic Ridge between Norway and Greenland. The Earth need not be, as Mary Oliver suggests, ***outrageous*** because its old. Perhaps we humans are ***outrageous*** for being so young, having emerged as a species only in the last one-seven-thousandth of one percent (0.007 percent) of Earth history. We're the odd earthly entities, not the stones.

For the ***anthro**phile*, Earth exists for human benefit. This an ancient old-world tradition, older than the oldest literature of Gilgamesh in Mesopotamia. The Greek philosopher Protagorous once said: "Man is the measure of all things." Aristotle noted that "Nature has made all things specifically for the same of man," meaning humanity.[23]

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[23] Rich, Second Nature, p. 5.

For the ***bio**phile*, in contrast, ***Life*** is the measure of all things. Earth exists for biological benefit, with human beings being part of that biology. Ecology, rather than sociology, is the relevant academic discipline. For the ***geo**phile*. in contrast, ***Earth*** is the measure of all things. It exists for its own sake, with life being added at one stage, human life at a later stage, and with humans to be taken out of the picture at some later stage. Geology, or geoscience, or Earth Science or Earth System Science is the relevant academic discipline.

These layers of love are not mutually exclusive. Every **geo**phile like me is also a **bio**phile owing to the raw instinct evolved during natural selection, and an **anthro**phile, having been raised by human parents in a common culture. The issue is inclusion. Just as the human brain is layered like an onion, so too does the **anth**rophila of my neocortex cover the **bio**philia, of my midbrain, which covers the **geo**phlia. of my brain stem. My appreciation for the earth begins with is its deepest and oldest part, the core.

Before I studied ecology and geology in college, I was completely stuck in Aristotle's *anthrophile* world. I remember one perfect day when I was working as a farmhand on our North Dakota homestead. After a hearty breakfast, I pumped a load of diesel fuel into our John Deere 4210 tractor. Heading to the equipment yard, I hooked up a 20-foot-wide cultivator and headed out to the back forty. Pushing a lever, I set the gleaming, dirt-polished blades in the ground, engaged the clutch, and began dragging my rig through the soil. Protected from the prairie sun by a broad-brimmed hat, and hydrated by swigs from a gallon jug, I dragged that cultivator back and forth all day long, row after row, from one side of the field to the other. Eight hours later, I turned around to see 40 acres of gray-black dirt where before there had only been weeds and gray crust. I remember being amazed at how much work I had done.

Only later did I learn that virtually all of that work I did was actually done not by me, but by fossil fuel. All I did was guide the machine that did the actual work. Amazingly, one barrel of oil provides the energy equivalent of thousands of hours of human labor. The concentrated energy within that barrel ultimately came from the sun. The raw material for that oil was algal muck that accumulated in some ancient anoxic sea. Earth turned it into petroleum that was discovered by geologists, transported by pipe-liners, refined by chemists, distributed by truckers, and pumped by farmers like me. Fundamentally, my power was sun-power captured bio-power and preserved by geo-power.

Only later did I learn that the big sky country I worked in was a trivial part of the whole earth system. Sitting on a tractor all day in a horizontal world gave me lots of time to watch the sky. The tallest anvil-shaped cumulonimbus clouds I saw flattened out at the top of the troposphere at an altitude of about 7 miles. Below me, the earth extended more than 500 times deeper than those highest clouds. In scale, " writes Christopher Dewdney in his book about the atmosphere, *Eighteen Miles,* "we are like microorganisms living in an evanescent fluid film, a dampness that would burn off like morning dew if the sun" were only about fifteen percent hotter."

Only later did I learn that human beings --possessing the ingenuity of engineering and the power of fossil fuels-- have become the dominant geological agency operating on the planetary surface. This Anthropocene makeover is being driven by profligate and unsustainable consumption of earthly treasure from below. For example, assuming a life expectancy of 78.6 years,[24] a baby born in the United States in 2019 will consume 3.19 million pounds of minerals, metals, and fuels in their lives. This includes a whopping 1.36 million pound of stone, sand, and gravel, 53 thousand pounds of cement, and 20 thousand pounds of iron ore, the chief ingredients of our urban and transportation infrastructure. Though we hope that future fossil fuel consumption will decline in the years ahead, at current rates that same baby will consume 7.70 million cubic feet of natural gas, 331 thousand pounds of coal, and 75 thousand gallons of petroleum. Additionally, each will use at least 10 thousand pounds of metal for other technologies, salt for our roads, clays for manufactured materials, and phosphates for agricultural fertilizers. This is close to what I will have consumed in my lifetime. Multiply this by 10 billion souls and you can see where we're heading.

Only later did I learn that my lifespan is trivial on the scale of deep time. I was born in the middle of the 20th century at the beginning of the great acceleration in human consumption, the onset of the Anthropocene epoch. Using this 70-year duration as a ***yardstick*** laid on the ground, my entire personal family history --the six human generations I've known from my great grandmother to my granddaughter-- could be covered in two yardsticks, roughly two long steps. Ten steps back brings me to the Medieval warm interval of about 1300 CE, when many of Europe's castles and cathedrals were being built. One hundred steps back takes me to 7,000 years ago, when the first granaries were being built for the emerging cities of civilization. A thousand yardsticks takes me to the time when our species began migrating out of Africa about 70,000 years ago to inaugurate a wave of extinctions around the globe. Ten thousand yardsticks brings me to the onset of vigorous global glacial cycles. One hundred thousand yardsticks brings me to the branching point between our genus of *Homo* and that of *Pan*, the chimpanzees. One million yardsticks brings me beyond the extinction of the non-bird dinosaurs. Ten million yardsticks brings me past the beginning of animal life. And one hundred million brings me just beyond the origin of Earth. My lifespan constitutes less than one part in a hundred million parts of Earth history.

Only later did I learn that I'm an individual only in the sense of my psychological ego. Biologically, we are all nested sets of plurals. Inside us are living colonies of microbes that outnumber our own cells, and without which we would be dead. Each of our nucleated [eukaryotic] cells is a cooperative arrangement of microbes that learned to work together billions of years ago. Each of our bodies is a cooperative system of subsystems called organs, with our brains being only nominally in charge. Our evolutionary success derives from the fact that we are social organisms, selected more often for being team players than a the best individual.

Biophilia

Biophilia is the ineffable love of living things that aren't trying to kill us: the things we eat, the things we keep as pets, the flowers we appreciate, the trees we climb, and wildlife we enjoy. Biophilia is the emotional manifestation of placing life at the center of all things. This form of organic love is instinctive, a schema of patterned learning selected for during human evolution that preferences living over nonliving behaviors. Escaping a hungry tiger and escaping a falling rock do not lead to the same level of engagement. Eating grilled meat and eating mineral clay do not yield the same level of satisfaction. In my bones I can feel my biophilia on every day of the year. It's natural. It's wonderful.

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[24] These facts were compiled by the U.S. Geological Survey, the U.S. Energy Information Administration, and the Minerals Education Coalition,

Consider a polar bear on an ice floe. Our attention is instinctively drawn to the bear, rather than to the **ice** that supports it, or to the **climate** that gave us the ice, or to the **tectonics** that gave us the climate. Most of us feel a closer affinity for mammals than birds, for vertebrates rather than invertebrates, animals over plants, and plants over rocks. In this chain of interest, we progressively lose interest as we step downward in evolution from charismatic mammals like Simba the lion, to flowering plants like roses, to fungi such as mushrooms, to protists such as amoeba, and to microbes we cannot see.

During the 1960s and 1970s I watched ecology grow from a fairly obscure academic field concerned with energy flows to the hyper-elevated status of a new secular religion. Ecosystems were seen as super-organisms with almost god-like oversight. This ***Clementsian*** view dominated mainstream thinking as the environmental movement gained steam, and remains true today for non-scientists. In this stage, learning how the living **component** of earth worked was deemed more important that learning how the larger **system** that holds those ecosystems worked.

In thickness and spatial scale, the sum total of all living things is trivial compared to other components of the earth system, analogous to the film of mildew on the wall of a large room. By mass, it's likely that more of Earth's biota occurs invisibly within rock fractures and sludgy anaerobic sediment than in all of the visible plants and animals put together. Stated another way, most of the so-called biosphere may lie within the lithosphere. No earthly or cosmic event has ever come close to sterilizing the Earth of its microbes, notwithstanding exaggerated claims to the contrary.[25]

When smitten by biophilia, we blind ourselves to the brutal reality of the food chain. The industrial scale of our slaughterhouses shows just how instinctive human carnivory really is. The polar bear, the leading icon for climate change, is seldom shown with a bloody muzzle eating a bloody seal that ate the bloody big fish that ate the small fish that gulped the zooplankton that gulped the phytoplankton in a trophic cascade at least six steps long. When writing this podcast script in January 2022, marine biologists were documenting how a pod of orcas (killer whales) was slowly killing a large blue whale over a 24-hour period. One orca was observed eating the whale's tongue while it was still alive.

As biological organisms, humans have an innate propensity to frighten, harm or kill each other for territory and reproductive success. Like all species, "writes Stephen Pinker, "*Homo sapiens* is a nasty business." Of course, they also have an innate propensity to care for and love one another, provided they are seen to belong in our group.

The most amazing thing about Earth's biota to me is its diversity. Approximately 10 million species are known to exist, with three times as many on land than in the sea. Relentless natural selection has filled millions of granular niches that that are quite ephemeral at geological time scales. This explains why the duration of a mammal species is only a million years long. Paleontologists estimate that Earth's current count of 10 million species is only about one one-hundredth of one percent (0.01 %) of all species that ever existed. Consider this. All of Earth's trilobites --a once-common marine arthropod-- are now extinct, even though paleontologists estimate there were once 20,000 different kinds during their protracted reign of 200 million years.

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[25] . [hazen 230]

In the last 542 million years of macroscopic life, a geological Eon called the Phanerozoic, peak biodiversity was reached just before the current Anthropocene onslaught. This was achieved in spite of five major mass extinctions driven by non-biological causes. The last major one, the end-Cretaceous extinction, offers a clear case in point. **On land**, the dinosaurs gave way to an enormous mammalian radiation that was further enhanced by widely dispersed continents. **In the open sea**, the extinction of ammonites allowed bony fish to explode in abundance. **In shallow water**, the extinction of tabulate corals and brachiopods made room for the modern (Scleractinia) corals, mollusks and crabs. Nearly everything we struggle to conserve today is new to Planet Earth within the last 66 million years, and benefited from the extinction of others.

At a finer scale, the fossil record for 21 million years of this 66 million-year block was carefully studied for patterns of stability and change. Remarkably, ecosystems --as functional units-- turned out to be somewhat independent of --and much more stable than-- the species composing them. Groupings based on taxonomic biodiversity lasted only a million years, whereas groupings based on interactive function lasted three times longer. In other words, species tend to enter and leave systems, rather than create them.[26]

The origination and extinction of a species is as routine as the birth and death of an individual organism. Life is not in charge. Earth is, the planet energized from below and tweaked by life at the surface.

Geophlia

Though I feel biophilia deep in my bones, the geophilia I feel within me is deeper and more inclusive. A love of *all* earthly things not just living ones. I call this feeling *geophilia*, a word I didn't invent, but which I'm helping to spread as a cultural meme. The iron in my flowing blood and the iron in Earth's swirling core come from the same igneous source. The salt in my blood and the salt in the sea come from the same place, the weathering of rock.

Another way of cultivating geophilia is to see Earth as a habitat, a "sweet" home for life in the solar system. Journalist Peter Brannen reminds us that life "constitutes a remarkably thin glaze of interesting chemistry on an otherwise unremarkable, cooling ball of stone, hovering like a sand grain in an endless ocean of empty space." As I write, the wet chemistry of life is indeed slowly consuming the surface of our ball of stone. The details involve the roots of vascular plants and their symbionts of microbes and fungi. These symbionts evolved the ability to dissolve the minerals in order to obtain the metals to trade to the plants in exchange for the carbon the plants trade back. The end result is soil, the centroid of the critical zone extending from the top of the forest canopy to the base of circulating groundwater.

Consider the element phosphorous. It's a lynchpin of life on earth, ***the*** critical limiting nutrient in many situations. The main source of phosphorous is apatite, a common accessory ***mineral*** in granitic rocks. As with iron in the center of a hemoglobin molecule, phosphorous occupies the center of a molecule called adenosine triphosphate, or ATP. This ancient molecule is required of every living thing, is a precursor to RNA and DNA, and is a kind of energy currency that moves within and between life forms. Phosphorous is the only element in ATP that can't circulate freely as a gas, which means it must cycle in an out of solid minerals. In short, life depends on eating rocks.

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[26] Roopnarine and banker, 2021, Ecological Stasis on geological...

During the past two decades, I've given more than a thousand invited slideshows on the historic fieldstone walls of New England. The interest never seems to fade. Midway through the process, I added a slide showing a lichen-covered wall edging a grassy field with a small pond, beyond which is a forested horizon against the sky. The slide's title, *A Brief History of Time,* credits the famous physicist Stephen Hawking. Five objects shown in the slide offer a five-word summary of Earth history in nutshell. In sequence they are 1-Rock, 2-Air, 3-Water, 4-Life, and 5-Intelligence. The rock of asteroids and planetesimals, when melted, differentiated in stages into atmosphere, crust, ocean, living things, and human intelligence.

During the same last two decades, I've developed an equally concise mantra for my students to chant in classrooms: “No rocks, no ecosystems, no cultures." Less parsimoniously, ***geo*** gives rise to and nourishes the ***bio*** that gives rise to and feeds the ***anthro*** of our human world. One of the most tantalizing connections here is the possibility that mineral crystals, especially those of clays, served as templates for ordering the molecules of life from a less-well-ordered ore-biotic soup. [27]

For me, the ***inclusive*** secular mono-thesim of the whole planet is preferable to the ***exclusive*** secular polytheism of reverencing one component above one another. Life is one of the critical components of this system. But it's not the main thing.

Consider this example. Biodiversity is a major buzzword in common culture. To understand where it comes from, paleontologists synthesized data from 11,000 marine fossil species from more than 3000 global stratigraphic sections to create a new biodiversity curve for the Paleozoic. It turns out that the partial pressure of carbon dioxide in the atmosphere and oceans --which is governed by underground processes-- is the ***only*** factor that matches the biodiversity curve, suggesting a cause-effect. In short, the carbon balance that controls biodiversity is, in turn controlled by the balance of vulcanism versus rock weathering. This may be the ultimate long-term global driver of biodiversity.[28]

In the early 19th century, geology was the queen of the sciences? Back then it was so potent it rise to the American Association for the Advancement of Science, the most powerful science organization in the United States. What happened to this historic emphasis? Could our proverbial "wrecking" the planet have anything to do with no knowing much about it?

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[27] Hazen, 2019, Symphony in C (Pohn Science The Grand Story of Carbon.

[28] Fan, XXX, Science, 2019?, A high-resolution summary...

Part 2 - Creating Climates

6 - LAND AND SEA - 3428

TAKEAWAY

Though powered by the sun, Earth's climates are random surface expressions of deep-seated, geothermally-driven tectonic forces.

KEY POINTS

The size and distribution of Earth's continents relative to its global ocean is a random surface expression of geothermally powered tectonism within earth's mantle.

Earth's climates, being created by random continental arrangements, must also be random.

The ideal place from which to understand Earth's surface landscapes, climates, biomes, and cultures, is the sweet spot at the center of its iron core.

The present Mediterranean climate is one of many created in that basin by tectonics. Scarcely 5 million years ago, the sea had evaporated, leaving a broiling hot desert basin more than ten times deeper than modern Death Valley, California.

Other tectonic climate stories include the globe-cooling drift of Antarctica toward the pole, the game-changing creation of the Gulf Stream at Panama, and the super-monsoons of Pangea.

The locations and arrangements of continents control the global amount of solar energy absorbed, the potency of Earth's greenhouse effect, and the flow of ocean currents.

SCRIPT AND TEXT

Pause....

Episode 6 - Land and Sea

Pause ......

Welcome to Climate Underground

I'm your host, Robert Thorson

Thanks for joining us.

Pause.....

Late 60s

At 2:56 Greenwich Mean Time on July 21, 1969, two astronauts, Neil Armstrong and Buzz Aldrin, were the first humans to walk on the moon. I watched them live on TV, a tiny, black-and-white, American-manufactured Zenith at a friend's house in central North Dakota. After their lunar walk, I took an Earth walk out into the starry night with a pair of binoculars to scan the moon's surface, hoping to see them bouncing around like kangaroos, knowing this was impossible. The forty pounds of rocks they hauled back to Earth would jump-start a new subdiscipline called planetary geology.

Less than one year earlier, on September 15, 1968, three seismologists from Columbia University's Lamont Earth Observatory, Bryan Isacks, Jack Oliver, and Lynn Sykes published a comprehensive review paper *Seismology and the New Global Tectonics,* that brought four separate strands of geo-thinking into an emerging theory known as Plate Tectonics. The pattern of global seismicity unified what had been previously been four disparate concepts: the compressional origin of mountains, the extensional origin of sea-floor spreading, the volcanic Ring of Fire around the Pacific, and the linear faults cross-cutting ocean ridges called transforms.

The combination of these two paradigm-shifting events in the jolt of one year changed the way humans saw themselves Looking down on Earth from the moon, the astronauts saw Earth holistically, a blue marble, a collection of lands and seas over which the clouds appeared, disappeared, and drifted. Looking up from below with their seismic rays, the pioneers of plate tectonics saw a dynamic spherical volume running the show of Earth's eggshell-thin tectonic plates.

Plate tectonics shattered our sense of *terra firma*. Every single place on Earth's surface, even the largest continent, was moving relative to some other place, with no fixed frame of reference on the surface, each like a large ship in an open sea. To obtain the fixed datum they needed, seismologists went down to the center of the earth. From there, Earth's main geodynamic motions were upward and away from Earth's core, sideways at the surface, and then back down in a continuous cycle called mantle convection.

Earth's dozen large tectonic plates are thin, slightly curved shells of rigid lithosphere moving above the squishy bulk of the mantle.   The base of every plate is similar, being a slab of the uppermost mantle cold enough to behave rigidly. Called mantle lithosphere, its dominant rock is black-green peridotite. Above this continuous basal layer are two kinds of crust. Continental crust averages 35-40 km in thickness and floats higher than oceanic crust because it's thicker and less dense. Oceanic crust averages 7 km in thickness, a quarter that of continental crust, and floats low because it's thinner and more dense. Importantly, oceans are oversized puddles occupying topographic basins between the high-floating continents. The depth of the sea is controlled by the density of oceanic crust, which is controlled by its temperature, which is controlled mainly by its distance away from volcanic spreading centers. The deepest ocean crust below trenches is the coldest.

It turns out that the average thickness of active continental crust being created by mountain building has varied during geological history, as Ming Tang and his research group have recently shown. [29] During the main episode of craton formation in the Archean, the average thickness of continental

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[29] Tang, et al, 2021, Orogenic quiescence in Earth's Middle Age.

mountain belts was 50-60 kilometers. Before about 3.5 billion years, and during Earth's Proterozoic "boring billion," or Middle Age, the active crust was thinner, averaging only 40-45 km thick, mainly because there was less mountain building, and therefore less nutrient cycling, which led to "a persistent famine in the oceans, stalling life's evolution in Earth's middle age. Once again, tectonics rule and life follows.

Looking up from the seismologist's datum at the Earth's center, the iron core is stable in shape and position. In contrast, the locations, shapes, and distributions of our continents and oceans are utterly random.

Recall that our modern oceans are covered by enormous patches of ***plastic*** flotsam separated from others by open water. Though each piece of plastic is broadly similar in composition, each has a different source and history. Within patches, each piece clings, jostles, and slides against its neighbors as they are being lifted and lowered and sheared by currents of water.

Much the same is true for earth's continents. They are oversized patches of discrete fragments of silicate rock called ***terranes****,* each with a unique source and history. These patches of terranes, having been welded together into continents, float above the softer, squishier part of the upper mantle a zone called the ***aesthenosphere*****.** Endlessly, they rise and fall and are sheared by currents beneath them.

Climate and Tectonics

It's been known since antiquity that the shapes of the coasts of west Africa and east South America mirror each other. When cut into puzzle pieces, they fit together. And it's been known since the 1970s that continents occasionally gather together into supercontinents before dispersing again. Since then, we've learned why. Deep mantle convection on a spherical earth from a common center requires that continents are pushed outward, requiring that they eventually meet on the other side of the world. When gathered, they insulate the outflow of geothermal heat, allowing the crust to warm, expand, rise, break, and rift outward from a slightly higher center. After dispersal, they come back together, renewing the cycle once again.

The physics of materials and processes require certain shapes. Surface tension require that soap bubbles and cloud droplets be spherical. Thermal contraction requires that cooling sheets of lava form polygons. For clots of plastic flotsam or clots of silicate terranes, there's no requirement for any particular shape, and no requirement that they arrange themselves in a certain way, as with the atoms in a mineral or beads on a string. Instead, continents are random amalgamations that are always in a state of joining, unjoining, and sliding past one another. Highlands are the sites of joining and piling up. Rifts and continental shelves are sites of unjoining and sagging down.

The inevitable conclusion from these tectonic considerations is that that Earth's climates must also be fundamentally random because the distribution of lands, seas, and elevations control the distribution of climates. This may be the single most important conclusion for *Climate Underground,* so it bears repeating. Earth's regional climates are random surface expressions of what's going on below the surface.

Unlike living organisms, continents cannot ***evolve***. Nor can climates. They can only ***emerge*** from previous random conditions as a consequence of tectonic motions within the earth's interior. This means that, absent human morality, there are no good or bad climates *per se*. And because tectonic motions never stop, climate change must be a continuous process with no particular outcome or goal. It's directionless.

Consider these four examples.

The modern Mediterranean Sea is the namesake for the Mediterranean Climate of the familiar Koppen classification, one characterized by hot dry summers and cool wet winters. The great size of this inland sea moderates the climate because the "wine-dark sea" absorbs heat more readily than the surrounding land and stores it more efficiently. Th resulting land-sea thermal contrast is responsible for twice-daily sea breezes and monsoons.

Between 6 and 5 million years ago during the late Miocene Epoch, the Mediterranean had ***three*** very different climates, all in the span of ***one*** million years. This was very late in geological time scale, well after the time our ancestors of upright apes --*Ardipethecus*, *Australopithecu*s, and the like-- had already diverged from the genus *Pan*, which contains chimpanzees and bonobos.

All three of these Mediterranean climates were random consequences of tectonics. Pulled northward by the flowing mantle, a continental terrane later called Africa collided with one later called Spain to close the Strait of Gibraltar, shutting off all inflow from the Atlantic. Within several thousand years, the early Mediterranean sea had completely evaporated, leaving an empty, dry, dusty, salty, broiling-hot basin 2 to 3 miles deep (3-5 km). Next, a later turn toward wetter conditions about 5.5 million years ago caused the basin to partially refill with brackish water, forming semi-arid inland seas similar to the modern Caspian and Aral Seas. This epoch ended about 5.3 million years ago when the tectonic pressure that pinched the Strait of Gibraltar relaxed, allowing the Atlantic to pour back into the empty basin via the most spectacular waterfall known to Earth. That's three radically different climate in a million years or less.

An unrelated and equally random climate story involves Australia and Antarctica. Before about 41 million years these unglaciated continents were linked as a single landmass. When Antarctica broke off and began to drift southward, it opened up a marine passage between them. Known as the Drake Passage, this set up a southern, circumpolar, oceanic current that remains today. As the ice-free Antarctic continent drifted further toward the pole, it eventually cooled enough to allow an ice cap to develop beginning 34 million years ago. This initial cap rose to higher and higher to create the Antarctic Ice Sheet we know today. This cooled the globe enough to allow ice sheets to develop in the northern hemisphere. This Cenozoic icehouse climate state was the first one since the Late Paleozoic days of Pangea about 260 million years earlier.

A third random climate story happened between North and South America. Before their linkage at Panama, warm marine currents used to flow between these lands in a passage between the tropical Atlantic and tropical Pacific. Beginning about 3 million years ago, this marine passage was blocked by the Isthmus of Panama rising up where the Caribbean Plate buckled against the Pacific Plate. West-flowing warm water was shunted northward to create the Gulf Stream, which greatly warmed western Europe relative to eastern Canada at the same latitude. With seemingly unlimited quantities of warm moist air flowing northward, continental-scale ice sheets were able to grow on the subarctic Canadian Shield on the colder, western side of the current, ushering in the Pleistocene Epoch, commonly known as the glacial epoch.

A fourth and final, random climate story involves Pangea, Earth's best known supercontinent. Between its gathering in the late Paleozoic about 335 million years ago and its breakup in the early Mesozoic about 200 million years ago, all of Earth's continents were lumped together in a huge mass extending from pole to pole. The opposite three quarters of Earth's surface was a single enormous ocean called Panthalassa.

One outcome of a supersized continent is a supercharged monsoon. The Spanish explorer Francisco Vazquez de Coronado saw its result in 1540 CE. Though he failed to find the fabled Seven Cities of Cibola, he did find an unusually colorful landscape of desert badlands he called El Desierto Pintado. This Painted Desert, now a U.S. National Park in Arizona, has a pallet of colors dominated by dusky reds, yellow browns, pale gray-greens, and faint lavenders.

The horizontal *layers* of sand and mud of the Painted Desert required drenching rains to create the sediment, transport it in river channels, and deposit it on floodplains and ponds. The polychrome *colors* required baking droughts to lower the water table enough to allow the iron and manganese in the sediment to oxidize completely. Having a potent wet season and dry season in the same place each year required what is called a *mega-monsoonal* circulation. The combination of Pangea (*all earth*) and Panthalassa (*all ocean*) gave us exactly that.

When Pangea broke apart and marine passageways formed between them, the mega-monsoon was replaced by a maritime climates. Once again, circumpolar and equatorial currents became possible, courtesy of plate tectonics.

Thought Experiments

These four examples of random reality --Mediterrania, Antarctica, Panama, Pangea-- should be sufficient to convince you that tectonics runs the climate show at time scales of a million years or more. Now I'll address the same subject with a thought experiment based on physical facts

Let's start with the thermal differences between sea and land. Open oceans reflect back only ***6*** percent of the radiation falling on them, absorbing the remainder and warming the water surface. In contrast, ice sheets reflect back ***75-85*** percent, absorbing so little that the area is effectively cooled. The average value of this reflectivity for land surfaces, called ***albedo,*** is about ***30*** percent, roughly five times more reflective than the sea. Land albedos range upward from about ***10*** percent for dark green forest canopy to about ***30*** percent for savannahs and rocky or scrub deserts, to nearly ***45*** percent for sand dunes.

Water also has a much higher ***thermal capacity*** than land, meaning how much heat it can hold per unit volume for any change in temperature. Water is thus a heat sink, relative to the land and air. This is what's happening today with global warming. The oceans are absorbing about 90 percent of the extra heat we've created, the land much less. Water also has a higher thermal conductivity than sediment or soil, meaning it can transmit heat from one surface to another much more quickly and efficiently. Conversely, it's a terrible insulator.

Now please bear with me for one more mini-lesson -- a quick primer on global meteorology. The amount of solar radiation shining on a globe peaks at the equator and falls to zero at the poles. Accordingly, Earth has a surplus of heat from the equator to 38 degrees latitude north or south, and a deficit of heat at higher latitudes. On non-spinning Earth, and for both hemispheres, the air would rise at the equator and descend at the pole to create a single cell of circulation. Now let the earth spin in your thought experiment. The resulting Coriolis force sets up three cells of rising and falling air in each hemisphere. These, in turn, set up three global wind belts in each hemisphere. In the northern hemisphere, the ***tropical easterlies*** occur where descending air in the subtropics flows back toward the equator. The ***polar easterlies*** occur where the coldest and densest air drains toward lower latitudes. The ***prevailing westerlies*** between them occur where descending air of the subtropics is forced northward toward higher latitudes. Three comparable belts occur in the southern hemisphere. As these six wind belts blow over the oceans, they create enough drag on the water surface to create shallow ocean currents flowing in the same direction as the source winds.

Setting aside global circulation for now, let's make three simplifying assumptions. First, that the relative ***amount*** of land *versus* sea and their ***distribution*** relative to one another are the only two variables controlling climate. Second, that all land and all sea have the ***same albedo*** contrast, perhaps something like an unchanging steppe. Third, there is no greenhouse effect.

Given these three assumptions --the land layout, its albedo, and no-greenhouse-- we can easily infer how earth's thermal state and its regional climates will change. The warmest scenario is to have maximum ocean and minimum land. This could happen either by having less continental crust to work with, or by having the sea submerge much of that crust beneath shallow water. This latter scenario is close to what happened during the early Paleozoic, when the bulk of Earth's continents were flooded with warm shallow seas. The coldest scenario is to have the maximum amount of land by having it lifted up higher relative to a more sunken sea. This scenario is close to our present circumstance during the late Cenozoic Era.

Now let's assume that sea level is stable and that the ratio of land to sea is constant. If our land is located near the poles where there's a deficit of heat, earth's average temperature will be warmer because more heat-absorbing ocean would be exposed at low latitudes where solar radiation is highest. In contrast, if lands were located near the equator, more of the sun's heat would be reflected back into space and earth's average temperature will drop.

Now, a third scenario. If lands were clustered together as with Pangea, we will have a much more continental climate than if all our land were scattered about. A global Indonesian archipelago would be far more maritime than a single oversized Asia. In the latter case, strong monsoons are inevitable.

A fourth scenario involves the alignment of continents in opposite directions relative the global wind belts. If lands are aligned in an east-west direction parallel to the major wind belts, there is little effect on oceanic currents, which will stream around them. But if lands are aligned in a north-south direction, the general case today, the oceanic currents will be seriously deflected, transporting water warmed or cooled at one latitude to another. For example, at high south polar latitudes today, no land mass blocks the steady Antarctic circumpolar drift. But further north, the three continents of South America, Africa, and Australia all extend far enough south to catch parts of this ocean current like an oar dipped upstream in a river. These three air currents, the Peru, Benguela, and West Australia currents hug the western shores of their respective continents. They warm as they flow northward, meaning the air above them becomes drier and drier. It's no accident that all three continents are super dry to the west and become wetter to the east. The Atacama Desert in Chile, the [Nam-ib-ian] ~~Namibian~~ Desert in Africa, and the Great Sandy Desert in Australia are three examples. The tectonism rules.

Between these simple scenarios are countless possibilities because the three main variables --the amount of land versus sea, the gathering of lands versus their dispersals and the alignment of land patches by latitude vs. by longitude. -- all work independently of one other. The inevitable conclusion is that, by randomly shuffling pieces of the continental jigsaw puzzle, a random tectonic history leads to a random climate history that will never quite repeat itself.

Believe it or not, that's the simple version of the story. Now let's add back the complexities we previously set aside. What happens on an Earth with seasons? Or on an Earth where the land albedo is constantly changing? On an Earth where the greenhouse effect varies? Yikes!

Now, let's add back three complexities, one at a time. ***First,*** let's allow snow and ice to persist on land at high latitudes. This gives us two outcomes: a third albedo condition that's also the most highly reflective; and a place to store water on the continents above the edge of the ocean basins. In such a world, the drift of continent to a threshold high latitude sets up an irreversible positive feedback loop that amplifies the climate change toward cold. The addition of permanent ice and snow lowers Earth's average albedo, which cools the thermal state of the planet, which allows glaciers to expand further, which lowers the albedo even more, which cools the climate even more, and so forth.

Amplifying this ***aerial*** feedback caused by albedo is a ***volumetric*** feedback caused by ice storage. The more ice there is on land, the less water there is in the sea. This lowers sea level, which exposes more land relative to sea, which raises earth's average albedo, which cools the climate even more, which causes glaciers to grow even more, etc. Ice sheets are fated to grow as big as the amount of land at high latitude allows. Getting rid of ice sheets is a lot harder than getting them to grow.

The good news is that peak glaciation creates a tipping point in the reverse direction. If ice sheets shrink just a little, the effects of reduced albedo and a rise in sea level cause warming, which shrinks ice sheets even further, which causes them to shrink further until they reach a minimum size allowed by the availability of land. The scenario above can take place without any greenhouse gas exchanges. On our realistic earth, however, these changes are amplified by the release of dissolved carbon from the deep ocean and from other sources. Once you start deglaciation, it's hard to stop it.

We now know that the distribution of land near the poles controls Earth's long- term climatic history at the million- to hundred-million year scale. For most of earth history, large ice sheets were completely absent and temperatures were at least 5 °C warmer than today. Thy call this a *greenhouse* or *hothouse* condition. Less commonly, there were seven intervals ranging from about 10- to 100-million years long when there was sufficient land near the poles to inaugurate the opposite state, an *icehouse* condition.

Now let's add back a ***second*** complexity. The rate at which the heat engine of the mantle is running. Like the sun, it normally idles at a fairly constant rate. But every once in a while there's a faster burn, meaning more geothermal heat rises upward. This increases the rate of volcanism and plate motion, both of which have important geochemical consequences.

When the tectonic burn is fast, the floors of the oceans bulge upward in the vicinity of their mid-oceanic rift zones. This shrinks the volume of the global ocean basin without removing any of the water, forcing sea level to rise dramatically. This extra heat also creates more vulcanism, which emits more greenhouse gasses into the atmosphere, notably carbon dioxide, methane, and nitrous oxide. The combination of *greater heat absorption* by higher seas and an *enhanced greenhouse effect* by more volcanism raises the average temperature of the planet. Both these factors combined during the Cretaceous Period about 100 million years ago, when sea were hundreds of feet higher than present, ice sheets and permafrost were absent, atmospheric carbon dioxide reached five times the present level, average temperatures were 5-10 degrees C higher than today, and dinosaurs hatched eggs in the high Arctic.

Now let's add back a ***third*** complexity. Changes in global oceanic circulation. The present thermohaline global circulation, called the global conveyor belt, looks like a twisted wide ribbon in shape. Starting with the Gulf Stream the flow moves ***northward*** at the surface off the east coast of the United States all the way to near Iceland. Along the way it evaporates, which concentrates salt, and cools down to the freezing point where the formation of ice increases the salinity further. At some critical tipping point, this enormous surface mass of cold salty water sinks to abyssal depths, reverses direction, and flows ***southward*** in the deep abyssal plains all the way to the tip of South America. There the current turns ***eastward*** to flow into the equatorial Pacific where, being warmed by equatorial heat and diluted by rainfall, it rises back up to the surface. At this point it's a warm surface current that flows ***westward*** between Australia and Southeast Asia. This warms even more in the Indian and south Atlantic Ocean before turning ***northward*** to join the Gulf Stream, closing the loop. At high southern latitudes, there are no continents blocking deep or shallow currents, so instead they circle round and around Antarctica.

The convoluted shape of the main thermohaline current is created by the random positions of the continents. The strength of the main current is governed by the strong thermal contrast between high and low latitudes, which is twice as strong in our Cenozoic Era than it was in the previous, more equable Mesozoic era. The present climates on Earth are controlled by these oceanic currents, which are set up by the blocking continents, which are positioned by random plate motion.

Of course, the links between land and sea involve ***so*** much more than tectonic configurations. One of the great mysteries of paleoclimate has been the abrupt, decade-scale shifts in temperature over Greenland during the last glacial stage and its transition to the Holocene. We've known for years that these temperatures are linked to millennial scale switches in the ocean circulation of the North Atlantic, which are, in turn, associated with iceberg armadas from the Laurentide Ice Sheet to the west.. What we had not known until very recently is that these north Atlantic armadas --called Heinrich Events-- were set up by changes in the prevailing westerlies, which were caused by thermal changes and ice rafting in the North***eastern*** Pacific in the Gulf of Alaska, which were caused by nonglacial changes in the North***western*** Pacific Monsoon. Everything on land and sea, is connected to everything else in a cascade of change. [30]

The ***fourth*** and final complexity is the human singularity of the Anthropocene Epoch. This is the only one that isn't about tectonism. We lack the power to close off the Mediterranean Sea, block an ocean current, lift the sea floor, or move a continent. But we do have the power --vented from

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[30] Jaeger, and Schevenell, 2020, Steering Iceberg... Walczak et al, 2020, Phasing of millenial-scale....

billions of geographically dispersed fires, smokestacks and exhaust pipes-- comparable to that of a volcanic superplume erupting carbon to the sky.

7 - HIGH AND LOW - 2402

TAKEAWAY

Land elevation controls climate just as surely as does land location. The elevation of Earth's surface topography is fundamentally controlled by crustal buoyancy above the denser, softer, upper mantle.

KEY POINTS

At the scale of mountain ranges, basins, and ice caps, the surface elevation of Earth's crust above and below the sea is fundamentally controlled by buoyancy above the denser, softer upper mantle beneath.

In turn, the solid surface topography created by crustal buoyancy controls the movements of fluids above it by blocking, enhancing, lifting, and guiding flows. Tectonic topography thus controls meteorological climates above sea level, and oceanic circulations below it.

Earth's troposphere, the lowest layer of the atmosphere where weather happens, cools upward at a thermal gradient called the lapse rate, making it colder at high elevations and hotter at lower elevation.

Climates follow this thermal gradient from low hot places like Death Valley, California to high cold places like Mount Everest, Nepal. Desert, scrub, forest, tundra, mountain glaciers, and nunataks occur in predictable sequence.

The onset of extensive mid-latitude continental ice sheets during the Pleistocene occurred not when the land was lifted above the climatic snowline, but when the snowline fell below the elevation of the land surface. Ice sheets grew because more snow fell than melted over vast areas.

The great weight of former ice sheets changed the crustal buoyancy through an effect known as glacial isostasy. Lingering effects of this change remain with us today, lifting areas like Hudson Bay and Maine.

SCRIPT AND TEXT

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Episode 7 - High and Low

Pause ......

Welcome to Climate Underground

I'm your host, Robert Thorson

Thanks for joining us.

Pause.....

Topography

Do you remember learning to swim? Like everyone, you begun on the water surface, probably with someone holding you up from below. Only after becoming a confident swimmer did I have the courage to dive beneath the surface. I vividly remember my first dive to the bottom of the deep end of a swimming pool to a depth of about 15 feet. There, I felt something new for the first time. An inward tightening squeeze coming at me from all directions. My ears popped. Swimming back to the surface, that tightening relaxed back to normal. My ears popped again.

That tightening and ear-popping was caused by fluid pressure, a fundamental concept in physics. The deeper a fluid is above something, the more weight there is pressing inward from all directions. The same principle applies to air, as well al water.

When we climb a mountain, our main frame of reference is altitude which gets higher and higher. But if your frame of reference were pressure, it gets lower and lower. As you ascend, there are fewer and fewer molecules in the same volume of air, so they bang against each other less often. This lowers the temperature, making the air feel cooler. For every kilometer of elevation gained, the temperature drops about 6 ºC. This upward rate of cooling is known as the dry adiabatic lapse rate.

A separate effect involves the fact that Earth is heated from below. Photons of solar radiation are absorbed at the surface and converted to heat, most of which is radiated back out to space. But air immediately above the land is warmed by conduction, which means it will rise and cool.

It's no coincidence that Death Valley, California is both the ***lowest*** and ***hottest*** place in the United States. Based on ground measurements, it's 282 feet below sea level and has reached the scorching temperature of 56.7 ºC or 134 ºF.[31] Being so low, the atmosphere fills it more deeply than elsewhere. This raises the pressure, which raises the temperature, which makes it feel hotter. So why is Death Valley the lowest? Because it's a newish tectonic rift basin located where there hasn't been enough time to fill the growing void with sediment. In short, the tectonics made the topography that made the climate.

It's also no accident that nearby Mount Whitney, California, is both the highest summit in the contiguous U.S, and one of the coldest places in the state. Being so high, the atmosphere covers it less deeply, lowering the pressure and thus the temperature. So why Mount Whitney so high? Because it's underlain by thick, low-density granite, causing it to float high above the plastic aesthenosphere, and because that portion of the crust is locally tipped up to create a ridge. In short, the tectonics made the topography that made the climate.

There is no grander example of the link between elevation and climate than the Tibetan Plateau. It's dry because its cold, and its cold because it's high, and it's high because it was lifted that high by the collision between India and Asia, which thickened the crust, causing it to float higher. It's also dry

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[31] Science, May 21, p. 771

because the plateau lies leeward of the spine of the Himalayas, which wring out most of the moisture from monsoon precipitation. In short, the tectonics made the topography that made the climate.

In standing water, rather than a standing atmosphere, fluid pressure and temperature work in the opposite direction because liquids don't compress like a gas. In a freshwater pond the coldest water is the densest water and therefore sinks the deepest. In the ocean, salinity and water temperature work together to control the density of water. Densest is salty cold water. Least dense is fresh warm water. When these two meet, the denser water mass always flows beneath the other in an attempt to equalize the pressure.

Just as topography controls the climate of the atmosphere, so too does topography control the *climate* of the ocean. In the simplest case, oceans are shallowest above the ocean ridges where the crust and lithosphere are the *warmest* and least dense, having just been born. They are deepest at oceanic trenches where the crust and lithosphere are *coldest* and most dense, which is why they're sinking back down into the mantle. Between these two extremes, there is a direct relationship between the age of the ocean floor and its depth because: older ocean crust is cooler ocean crust, which is denser ocean crust which is lower ocean crust. This relationship would hold true without or without any water in the ocean basins.

Now let's add water. As with filling the atmosphere with fluid gas, we can fill the ocean with fluid water. Because deep oceanic currents must follow the bottom topography, they are therefore following the dictate of tectonics.

Crossing the Snowline

Volcanism can also change surface climates by building up elevation. There is no more clear-cut example of this than on isolated volcanic islands like Mauna Loa in Hawaii, which has been growing upward in the shape of a broad shield. When the island was small and its summit just above the ocean surface, the climate was like that of any other low Pacific island. As it grew upward and larger, however, the volcanic topography partitioned one climate into two climates: a wetter, windward side facing the cool trade winds and a drier, leeward side facing downwind.

As Mauna Loa grew further upward, its summit reached a threshold altitude in the regional atmosphere where the temperature could reach the freezing point of water, 32ºF (0ºC). Snow became possible for the first time. If the mountain were to keep growing upward, eventually its summit would reach an elevation high enough to support glaciers year round, as with the ice-capped volcanoes of the Andes During the last glacial maximum the freezing elevation or climatic snowline fell by as much as 800-900 meters, creating a permanent summit snow cap that later melted when the postglacial earth warmed, and the climatic snowline rose back up.

Far more complex than the case of Mauna Loa is the progressive tectonic lifting of entire mountain belts above the climatic snowline to create mountain ice sheets like Southern Alaska and Patagonia, which have been experiencing continuous glaciation for millions of years. Initially, they were too low for any glaciation. As uplift continued, and as global Pleistocene temperatures dropped, the high summits became glaciated during glacial epochs but remained ice free during interglacials. As uplift continued, the summits were raised to an elevation that brought permanent valley glaciers into existence even during interglaciations. As uplift continued, valley glaciers merged into mountain ice caps which, during glaciations, became mountain ice sheets.

This progressive rise of land happens at collisional boundaries, where mountain ranges are buckled upward through compression. It can also happen by non-compressional uplift in a process called *delamination*. This occurs when the lowermost crust and (or) the lithospheric mantle become denser than the warmer aesthenosphere beneath it, breaks off, and sinks from negative buoyancy. After the delamination, the less dense aesthenosphere flows in to fill the gap with an expanded volume, lifting the upper crust with it. The Sierra Nevada and the Colorado Plateau are examples of this style of broad uplift.

The Greenland ice sheet started with the process of coastal mountain glaciation, as with southern Alaska. As the edge glaciers expanded, they eventually coalesced in the middle of the continent to create a single ice sheet. From that point on, the Greenland Ice Sheet grew, in a manner of speaking, by lifting itself up by its own bootstraps. Being ice covered, the continental interior reflected away more solar radiation, making it cooler. this meant more snow, which meant a higher ice sheet, which meant a higher summit elevation, which meant colder snow, which meant stiffer ice, which meant higher ice, and so forth.

At the same time, something else really fascinating happened in Greenland. The central ice sheet thickened enough to flex the crust downward. As ice sheet growth kept pace with land sinking, it's thickness became greater than its elevation, meaning it could receive even more water from the sea. Ironically, the tectonic activity that raised the coastal mountains that brought the ice sheet into being were then lowered by the great weight they inaugurated.

Eizeit

Evidence for much more extensive mountain glaciation in the Alps has been known to European scientists since the late 18th century, and were nicely summarized by Horace-Benedict de Saussure in his *Voyages dans les Alpes*. Similar field evidence for extensive lowland glaciation radiating southward from Scandinavia was also compelling by this time, but there seemed to be no source. In this historic epoch, the Greenland Ice Sheet was known only along its edges and the Antarctic Ice Sheet was truly *terra incognito*. Then in 1857, U.S. naval surgeon and Arctic explorer Elisa Kent Kane published a book titled *Arctic Explorations,* his account of his second expedition in search of the missing Sir John Franklin. After being locked in the ice northwest of Greenland for nearly a year, and seeking a way out, Kane traveled inland to encounter the main mass of the ice sheet "moving onwards like a great glacial river seeking outlets at every fjord and valley... Here was a plastic, moving, semi-solid mass, obliterating life, swallowing rocks and islands, and Ploughing its way with irresistible march through the crust of an investing sea." This was an ice sheet flowing outward from its own center, rather than from a highland source.

Seven years later, in 1864, Scotsman James Croll published *On the Physical Cause of the Change of Climate During Glacial Epochs*, confirming in theory what Kane had seen with his own eyes. Like actor Matt Damon in the classic movie *Good Will Hunting,* Croll was a janitor working at Andersonian University in Glasgow with full access to the library. Teaching himself physics and astronomy, and corresponding with the internationally famed geologist, Charles Lyell, Croll came up with a truly novel theory of climate change, an astronomical theory.

By this stage of development of the glacial theory, there was overwhelming evidence that Earth had experienced multiple ice ages. During each, great ice sheets inundated the lowlands of North America and Europe. This was especially amazing for North America, where unambiguous evidence for continental-scale glaciation extended 3,000 miles along a great arc curving from Nova Scotia through the lower Midwest to the Rocky Mountains. Where could such a large mass possibly come from?

It was clear from the European Alps, Scandinavia, and the American Cordillera that highlands were glaciated lands. Thus, the simplest explanation for continental glaciation was to raise the land surface high enough to reach the climatic snowline, after which the albedo feedback mechanisms would take over. Making an ice sheet disappear would then be as easy as lowering the land back to its former condition. This up-and-down mechanism for ice sheet growth and disappearance was supported by the geological establishment led by Sir Charles Lyell, who promulgated it in eleven of the twelve editions of his famous *Principles of Geology,* published from 1830 to 1875. Croll, the self-taught janitor, would prove him wrong.

Croll postulated that ice ages were triggered not by changing the land elevation, but by reducing the amount of glacial snowmelt during summer, by having less sunlight due to Earth's well known orbital variations: the eccentricity of its orbit around the sun; and the tilt and wobble of its spin axis. Slight differences during summer would then trigger the positive feedbacks involving albedo and other factors to push Earth into, and out of, glacial epochs. Croll's theory, when combined with Kane's descriptions, unified theories of both alpine and continental glaciations by giving them a common global cause.

Though this orbital theory of ice ages is not tectonic, it's reference frame is the gravitational center of the earth, where there is no net change in tilt or wobble.

Isostasy

It's no accident that Canada's most interior body of salt water, Hudson's Bay lies immediately beneath the center of what ***had been*** Earth's largest, thickest mass of ice, the Laurentide Ice Sheet. Though the ice has been completely gone from this vicinity for at least 8,000 years, the enormous dimple in the earth's crust created by the former, full-size,d load has not yet completely healed. The enormous dimple was created when the aesthenosphere below the ice-loaded crust was squeezed outward in all directions, a dimple now being erased by the mantle flowing slowly back in. This concept of vertical changes and flexure of the Earth's crust due to ice loads is called glacio-isostasy.

On the western shore of Hudson Bay at Churchill, Ontario, sea level is falling at a rate of about 13 mm per year, the thickness of nearly nine pennies, even though global sea level is rising an average of about 4 millimeters, or less than 3 pennies per year. There, the local isostatic uplift of 17 mm per year outpaces the 4 mm-per-year rise of global sea level to leave a net balance of 13 mm of uplift per year.

The down-and-up vertical changes caused by isostatic loading and unloading are much more important for local sea level rise than most people realize, because the scales of distance and time are hard to fathom.

The iconic image of coastal Maine is a place with a rocky shore with lobster boats anchored in a tidal inlet. The most common view is from the water looking outward perhaps to a dory pulling against the tide or to a lighthouse on a point. The vertical bandwidth of this view is typically about 10 meters, and it's mostly rock. The far less familiar view is from above, perhaps from an airplane or a high drone. This horizontal bandwidth of the shore is usually less than a mile for a state that's about 310 miles north to south. In that band is a thin fringe of rock is exposed only where the mud has been washed away by the surf and swash of storm waves. Inland from that narrow strip, southern Maine was mainly a thicket of spruce-fir forest growing on muddy soils before coastal development.

The muddiness of southern Maine inland from the bedrock strip doesn't come from weathered soil or marsh growth. Nor is it mud smeared onto the land at the base of former glaciers called glacial till. Instead, it's what geologists call the Presumpscot Formation: a silty drape of clam-bearing, often sulfur-smelling marine mud of variable thickness that buried all but the highest points of the coast about 13,000 years ago. This marine mud extends far inland, well north of Bangor, nearly to Mount Kahtahdin. Why?

During the transition out of the last ice age, the vast lowland of Maine's Penobscot Valley was a marine inlet fringed to the north by a fast-moving ice stream like those of Greenland today, one discharging immense icebergs into open water. Meltwater streams carried a relentless gush of pulverized mud into that lowland, which was simultaneously being swirled and dispersed by marine currents and tidies. Eventually, the mud settled downward to drape the bottom of that great bay with gray silt.

Recall that coastal Maine was formerly covered by ice at least a kilometer thick. As with a ship being unloaded with cargo, the land being deglaciated began to rise at the rate of an inch or more per year. This was faster than global sea level was rising at the same time. So, as with the case of Churchill, Ontario today, the higher rate of land uplift relative to sea level rise caused the shoreline to recede southward, exposing the muddy bottoms of what had been coves and bays covered by glacial silt. These bottoms were then lifted above the sea by isostatic uplift and covered with vegetation to become the inland landscape we know today. Only later did the sea begin to rise and move inland, rinsing mud away in the surf zone as it rose. The rock shoreline of today is a transient strip between mud above and mud below.

This same isostatic mechanism is helping to minimize the urgent threat of sea level rise from Antarctic melt As the edge of the ice sheet thins, the land beneath it rises, helping to keep it grounded on land instead of floating in the sea. This grounding stabilizes the ice front, slowing the rate of ice loss. To this vertical uplift we can add the lateral effect of local gravity. As the ice sheet thins, there's less mass on land to draw the surface of the ocean upward toward it, allowing local sea level to fall, rather than rise. [32]

As Maine rises from rebound, the highest peaks in the state are also being raised upward toward the climatic snowline. Were it not for Anthropogenic global warming, New England highest peaks of the White Mountains and Katahdin Range would be on track to be glaciated again with small cirque and valley glaciers, as was the case for so much of the recent geological past.

Land rises and falls from below. The climate responds accordingly.

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[32] Steig, 2019, How fast will the Antarctic...

8 - DEEP TIME - 3005

TAKEAWAY

Earth materials contain an archive of continuous climate change dating back 4.4 billion years.

KEY POINTS

Good meteorological measurements of Earth's climates at the global scale extend no further back than about 1850, the beginning of the historical control period for the IPCC.

Characterizing earth's paleoclimates requires using proxy records in which a stratigraphic signal can be translated into one or more climate parameters, for example a paleotemperature from an oxygen isotope.

For the last million years, the highest resolution and most versatile proxy record available comes from deep ice cores taken at the summits of polar ice sheets. From them we can reconstruct continuous paleotemperatures, ice volumes, and the concentration of atmospheric gases.

For the last billion years, the rock record show that Earth overall climate has toggled back and forth between greenhouse states when polar ice sheets were absent, and icehouse states when they were present.

Using the Grand Canyon as an iconic example, Earth's record of sediments and sedimentary rocks is also a story of continuous climate change. The oldest thing on earth is sand grain.

We are erroneously habituated to think of ice as something fundamentally different from rock. Ice is a perfectly respectable mineral, making glacier ice a perfectly respectable rock, making a continent-sized ice sheet a perfectly respectable layer of the Earth's crust.

SCRIPT AND TEXT

Pause ......

Episode 8 - Deep Time

Pause

Welcome to Climate Underground

I'm your host, Robert Thorson

Thanks for joining us.

Pause.....

As with Archaeology

Humans are storytelling creatures. We especially like creation stories that explain who we are and where we came from. Before science, most stories were symbolic myths or fictions. Since the emergence of science, however, most creation stories are non-fiction narratives grounded in hard evidence.

The hard evidence for credentialed historians is the catalog of written documents --census counts, commodity prices, tax lists, land deeds, territory maps, legal documents, and so forth. Moving back in time, such archival records eventually trickle down to zero in the ruins of ancient civilizations. The oldest writings --Egyptian hieroglyphics, the Dead Sea Scrolls, Norse runes, Mayan codexes, and Mesopotamian cuneiform-- bridge the document-based ***histories*** of historians and the artifact-based ***prehistories*** of archaeologists. Beyond that oldest documents are the Neolithic architectural monuments of early civilizations, Paleolithic projectile points, the oldest bones of our species *Homo sapiens* dating to ~0.3 million years, the oldest hand axes dating to ~3.3 million years ago, and the oldest bones this side of the split with chimpanzees more than 5 million years ago. The increasing depth of time is offset by the progressive loss and fragmentation of the record.

Just as surely as archaeology provides the back stories of human technology and civilization, so too does the stratified archive of geology provide the back story for Earth history and climate change. From this archive we learn that the stepwise creation story of human culture was a stepwise consequence of climate changes ultimately driven by geothermal heat flow from the deep underground.

The most definitive current text for the climate crisis is the IPCC's report A*R6 the Physical Science Basis*. It's grounded in terabytes of quantitative data gathered by thousands of scientists using well-calibrated, accurate, measuring devices deployed around the globe by satellites, monitoring stations, and on-site visits. We have gas sniffing drones, oceanographic buoys, and borehole data loggers working 24/7 around the world. Proving, rather than asserting, that the earth is actually warming was no small task, given the size, scope, and complexity of what's being measured.

Given this deluge of data, it's easy to forget that a continuous and well calibrated data set for the concentration of atmosphere's CO_2 extends no further back than 1958, the first year of the Keeling Curve. Establishing that curve was an attempt to gain some control over what, one year earlier, pioneering climate scientists Roger Revelle and Hans Suess described as "perhaps the greatest geophysical experiment in history."[33]

The globally distributed, continuous, and quantitative meteorological records of temperature and precipitation that are required to accurately define and differentiate climates extend no further back than about 1850, the beginning of the historical control period for IPCC analysis. Earlier climate records of manually read thermometers, rain gages, and barometers were discontinuous, poorly

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[33] Douglas, 2021, Our Biggest Experiment...

calibrated, and geographically restricted. For earlier centuries, we depend on phenomena like the price of wheat or wine, or dates when harbors and rivers became unfrozen. All such records eventually peter out into nothing.

To extend climate history back beyond the human time frame, our oldest measured climate records are overlapped with stratigraphic records to create what are called proxy records. In this technique, quantitative measurements of annualized growth systems --lake lake varves, clamshell rings, ice-sheet summits, and tree rings,- are used as surrogates for the climate measurements we're really after, for example average temperature or precipitation.

For example, the annual widths of tree rings are strongly correlated to ground moisture during the growing season, which turns out to be much more strongly driven by heat-induced evaporation than by precipitation. This year, we learned that the current mega-drought in the U.S. southwest is the strongest since the record began in 800 C.E., and that nearly half of this drought is due to human effects.[34] This tree-ring proxy record extends the much shorter record of equivalent meteorological measurements by a factor of five. The result is a paleo-moisture gage.

Another proxy --less useful but more direct-- involves the strength of ancient winds. The statistical pattern of grain size textures in dune sand are directly related to physical factors such as the threshold wind velocity required to mobilize the grain, and the minimum wind speed required to transport it. The result is a paleo-wind gage.

A third proxy --the most useful of all for the last million years-- involves the succession of annual layers of new ice on the summits of ice caps. Within its solid H_2O, the ratios of hydrogen isotopes and oxygen isotopes are directly related to the temperature at which that snow crystallized, giving us two records to cross-reference against one another. The result is a paleo-thermometer

Ice Cores

To reach the South Pole for the first time in 1911, a team led by Norwegian explorer Roald Amundsen trekked 1400 miles southward into trackless whiteness. The ground on which they walked, slept, and huddled their dogs was new-fallen snow, the crystalline mineral phase of water. Beneath that ground was an archive of time that they were not yet aware of.

Indeed, everywhere beneath our feet --whether on snow, or sand, salt, mud, soil, or rock-- is evidence of the past. Exploring those stories and sharing them with the world is the central task of geologists. Without their story, we would have no clue whether Earth's present climate is warmer or colder, or wetter or drier, or windier or calmer than any climates preceding the emergence of human records.. Without geological evidence, we would have no choice but to accept or reject on faith what the designers of the Creation Museum in Petersburg, Kentucky tells its visitors, that Earth is just a few thousand years old, and that dinosaurs walked the earth with humans. Without geology, we earthlings would be unmoored in time.

Cognitive science has revealed to us that short term memory and long term memory are stored in separate parts of the human brain. Without our long-term memories, we earthlings would be like medical patients with amnesia, possessing short-term memories of only recent moments. We could

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[34] From Science

not know who we are or where we came from. Luckily, Earth cannot have amnesia, thanks to the durability of long-term memories stored in ice, mud, sand, lime, bones, and rock. This archive allows us to know who we are as a species, and where we came from.

For a world pre-occupied by climate change, the important part of time is the future. With geology, predictions about what might happen can be constrained by what could happen, knowing what we know about what has happened, based on hard evidence.

Consider this quote from historian Gordon Wood's *The Purpose of the Past.*

"Having an historical sense" is "to be able to see the ***participants of the past*** in [a]... ***comprehensive way***, to see them in the ***context*** of their own time, to describe their blindness and folly with sympathy, to recognize the extent to which they were caught up in ***changing circumstances*** over which they had little control, and to realize the degree to which they created ***results they never intended***—to know all this about the past and to be able to relate it ***without anachronistic distortion*** to our present.

Riffing off his paragraph:

To understand climate change, is to see all the players of the earth system --air, water, life, rock, metal-- in a ***comprehensive way*** without privileging one component over the other, to see each in the ***contexts*** of their times, whether eons, era, periods, and epochs, to see how every fossil group, including humans, was caught up in ***changing circumstances*** over which they had little control, due to ***results they never intended.*** And most importantly, to see earth history without the ***anachronistic distortion*** of human egos and the implicit bias of biophilia.

My favorite example of anachronistic distortion involves the common semiotic exaggerations of Earth going up in flames as a consequence of carbon emissions. This is chemically impossible because there isn't enough oxygen. More importantly, the *geo*-historical ***sense*** elevates the stubborn fact that the present Quaternary Period remains one of the coldest long-term intervals of Earth history.

In 1964 the pioneering Danish scientist W. Dansgaard published a game-changing paper *Stable Isotopes in Precipitation*. This allowed the instrumental record of weather to be spliced to the stratigraphic record of ice cores. After two generations of work, the result is a reliable climate history of the global atmosphere based of bubble samples from the Antarctic and Greenland Ice Sheets and Tropical ice caps, dating back to about 800,000 years. At ice sheet summits, there is a net deposition of snow every single year. Each creates a stratigraphic layer that will be buried by the next year's snow in what is effectively an inverted sedimentary basin. At their summits, the ice sheet flow is remarkably simple, being straight downward until it finally flows outward near the base.

Since the early 1950s, we have drilled ice to a depth of over two miles, hauled cylinders of it home to laboratories, and explored every aspect of those cores with special attention to the thickness of annual layers, ash from distant volcanic eruptions, dust from the land, salt from the sea, soot and acids from chemical pollution, the fallout of atomic bombs, and most importantly, bubbles of ancient atmosphere trapped during the conversion of fluffy snow to solid ice.

In the lab, this imprisoned ancient air can be released and the concentration of gasses within it can be carefully measured. The half century of overlap between 1958 and 2008 between air sniffed by the Keeling Curve and air sniffed from ice bubbles of the Vostok ice core validates the accuracy of both techniques. This allows us to extend the archive of atmospheric composition back nearly a million years.

There are four main conclusions from the important Antarctic Vostok core relevant to the present climate crisis.

First, and most alarmingly, the concentration of CO_2 in the modern atmosphere of about 420 parts per million and the concentration of methane of nearly 2000 parts per billion. Neither has ever been higher. In former times, the concentration of carbon dioxide varied between 300 during interglaciations and 180 ppm during glaciations, and the methane varied between 750 and 350 parts per billion. This comparison reveals that modern concentrations are literally off the charts with respect to the last million years.

Secondly, Vostock shows a sawtooth pattern at a frequency of about 100,000 years with periods of graduate cooling about 90,000 years long followed by abrupt rises in temperature for a few thousand years before the record shifts back toward colder conditions. Three variables --reconstructed temperatures, carbon dioxide, and methane-- march in lockstep with one another. In every case, the rise in temperature slightly precedes the rise in greenhouse gasses being liberated from the deep ocean reservoir.

Thirdly, Earth was heading toward its next predictable glacial buildup until --uniquely-- that trend was reversed for all three indicators now off the charts. What this means is that human greenhouse warming more than reversed a natural cooling, and is now pushing Earth's out of the long-term icehouse state that it's been in for at least 30 million years.

Fourth, and finally, the precision and scope of ice core analyses are truly astonishing. In one 2022 paper published in *Science,* Yang and others tracked the integrated *primary biological productivity* of photosynthesis for the whole earth over the last eight glacial cycles of 100,000 years each. The main control on biological productivity, they found out, was not sunlight or temperature but the fertilizing effect of CO_2 content in the atmosphere. Importantly, biological productivity usually starts rising a millennia or more before thermally induced deglaciations, showing that greenhouse warming caused deglaciations, rather than vice versa. Also, they proved without doubt that the concentration of CO2 is a brake applied to photosynthetic productivity, one that keeps earth from freezing over. All this from bubbles of air trapped in ice. [35]

Fluffy snowflakes are beautifully symmetrical crystals of water ice that usually assume the shape of hexagonal disk. They are solid crystals that grew from water vapor, a gas. Though we don't normally think of ice as a mineral, it easily meets the technical definition of such, being a naturally occurring crystalline solid with a fixed chemical composition that varies within specific limits.

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[35] Yang et al, 2022, Global biosphere primary productivity.

A clear crystal of quartz, like those that grow in geodes, is also a mineral. As with ice, the composition of quartz is dominated by the element oxygen. Both are clear, and have a hexagonal symmetry that can easily grow into elongated prisms. One main difference between these two minerals is their melting temperatures. Quartz melts at 650° C, which is unusually low for a silicate. Ice melts at 0° C (32° F), which is unusually low for crustal materials. Frozen carbon dioxide, known as dry ice, is also a perfectly respectable mineral. Though it does not occur naturally on Earth because its freezing point is -78°C (-109°F), it's common on Mars, where it often snows dry ice.

Each layer of snow on the surface of an ice sheet is thus a layer of mineral crystals that either fell from the atmosphere or drifted into place. Physically, this is comparable to a layer of quartz-rich dust called loess. In strata, the main difference between water dust and quartz dust is that the snow can quickly recrystallize just a short distance underground, whereas the loess will remain stable unless heavily weathered or deeply buried.

Glacier ice easily meets the definition of a rock, being an aggregate of one or more minerals. Marble, made from the mineral calcite, is also snow white. Given sufficient heat, pressure, and time, marble will, like glacier ice, also compact, recrystallize, and flow plastically.

Age cannot be the criteria for differentiating rock from non-rock. The oldest glacier ice we know of --2.7 million years old from the Alan Hills of Antarctica[36] At a minimum, this is three times older than the oldest basalt on of Mauna Loa, Earth's largest volcano and largest mountain when measured up from the sea floor. Some Antarctic Ice is likely to be 5 million years old, and the shield shaped ice cap has been there continuously for at least 30 million years.

At the surface of the South Pole, the snow is loose, unconsolidated sediment similar to what you might find on a fine-sand beach. Beneath that surface it becomes sedimentary rock through compression and recrystallization. This is the part sampled by ice cores. When melted and re-frozen, the new ice is technically an igneous rock created by a process known as partial melting. When deeply buried, stretched, and sheared by glacier flow, that same ice becomes a metamorphic rock. These latter two types of ice-rock are generally avoided for borehole investigations because its the uninterrupted sedimentary layers they seek.

At even larger scales, the weight of an ice sheet is enough to flex the crust downward like a heavy block of ice placed on a large sheet of plywood. To make room for the downward flex in this analogy, the board pushes the air out of the way. On the actual Earth, it's the soft underbelly of the aesthenosphere that yeilds to flow outward in all directions. As the ice blocks melts and the weight shrinks, both the plywood and the crust flex back up and the materials beneath them --air and aesthenosphere-- flow back from whence they came.

An ice sheet sliding over bedrock exhibits the same basic physics as one part of the earth's rocky crust sliding over another along a low-angle geological fault. In both cases, there is grinding pulverization, scratching, and streamlining. A formerly glaciated land surface can thus be thought of as a fault plane for which the upper layer has disappeared, melting in the case of ice, or dissolving in the case of limestone.

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[36] *Voosen, 2017, 2.7-Million-year-old ice...*

Ice sheets are the most high-resolution and high-fidelity sedimentary archive we have for reconstructing past climates. Countless others with lower resolutions also exist, each with its own special offering. All provide data that constrain the help improve the climate models on which we have become increasingly dependent. One recent review having two colleagues of mine as co-authors, Ran Feng and Clay Tabor, put it succinctly in their title: "Past climates inform our future."[37]

The most iconic paleoclimatic archive is the Grand Canyon of Arizona, which is gawked at by nearly 5 million people per year. Approaching the canyon rim, no-one can be adequately prepared for the sublimuty they are about to see -- a mile-deep chasm sliced downward through the Earth's crust by the Colorado River. With everyone's attention riveted to the canyon walls, they overlook the fact that the same rock lies beneath their feet in the underground. The proverbial "book of time" for such sedimentary rocks is accessible by drill cores nearly everywhere.

Each of the canyon's sedimentary layers is analogous to a single page of a very long book. Just as each ***page*** in a novel describes different people, places, and events, each ***stratum*** exposed in the walls of the canyon has its own color, texture, strength, fossil content. Each attribute of each layer tells its own story, sometimes sharply set off from the rest, sometimes blended in, the grand total of which is the epic of Earth history.

Climate change is an enormously important part of that epic at the Grand Canyon and elsewhere. From such rocks, we learn of times known as *greenhouse* states, when tropical lushness extended to both poles, or times known as *ice-house* states, when the lands at high latitude were smothered by snow and ice. We learn of times when the land beneath what is now the southwestern United States was so arid that a sea of sand dunes the size of the Sahara produced waves of with stark beauty, a sea that fossilized into a geological formation called the Navajo Sandstone. We learn of times when drenching monsoon rains and dry-season aridity painted the landscape in rusty reds and yellows. Layer after layer, those individual stories sum upward in space and forward in time to reveal a narrative of constant climate change.

Though ice cores hold the archive of highest resolution, and though the Grand Canyon holds the archive of greatest fame, the black layer-cake terrain of Siberian traprock holds the key to the most potent underground climate event in life history.

The word trap comes from the Swedish *trappan* which means staircase. As used by early geologists, the word was attached to thick sequences of dark lava flows that --when downcut by rivers and etched by erosion-- gave the landscape a stair-step profile. Each of these thick sequences marks a place where great rift fractures opened up at the Earth's crust, through which erupted primitive magmas derived directly from the mantle. They gushed up to flood the land surface, not with water, but with vast lakes of molten lava that hardened into flat plains of a solid rock called basalt. These *flood basalts* come from what are called Large Igneous Provinces; LIPs for short.

About 252 million years ago the supercontinent of Pangea began to rift apart. Vertical fissures opened up, allowing the Siberian Traps to flood an areas the size of the conterminous United States

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[37] Tierney et al, 2020

with steaming, smoking, degassing lava. If you look closely at a sample, you'll see the vesicles or fossilized bubbles from which gasses were vented. Combining theory and lab analysis, competing research teams of geochemists agree that the carbon dioxide content of the atmosphere increased nearly sixfold from about 425 ppm to over 2500 ppm within an interval of 75 thousand years. In this heavily carbonized atmosphere, the climate heated rapidly to super-greenhouse conditions, and the ocean acidified and became anoxic. The result was earth's most deadly extinction of the fossil record, with ~90 percent of marine species and ~70 percent of terrestrial vertebrates dying out. The traprock formations are only one archive of this event. Far better ones with higher resolution were deposited in contemporary lakes and seas.

The longest, uninterrupted and continuous archive of earth history comes from the floors of the abyssal oceans where the record extends to about 200 million years old. There, the dark, cold, soft, mud of the ocean bottom transitions downward into firmer unconsolidated sediment that transitions further downward into sedimentary rock. Sampling this record for the U.S. Ocean drilling program is the task of the ship JOIDES Resolution, which can drill in water up to 27 thousand feet deep (8,234 m) to obtain cores up to several thousand feet long. These are deep enough to reveal the 50-million-year-long, punctuated cooling of our planet from its previous greenhouse state into its current ice-house state, and, higher up in the core, the coming and goings of repeated glacier advances during the last 2.6 million years of the Pleistocene Epoch.

Other paleoclimatic archives are spectacular in their own way. I've seen razor-thin laminations in the Green River Formation of Wyoming between 54 and 48 million years ago are so high-fidelity that they reveal changes in seasonality owing to Earth's orbital variations. I've seen glacial scratches and scrapes on boulders embedded in mudrock near Lake Huron that confirm Earth's first well-known episode of glaciation about 2.4 billion years ago.

The oldest underground archive of sedimentary rock on Earth is the Jack Hills Formation in Australia. This sandstone contains stream-rounded grains of zircon so resistant that they've been recycled from older rocks several times. One tiny grain the size of the period at the end of a sentence contains an even tinier defect called an inclusion. Isotopic analysis of water from within that inclusion proves that Earth was covered by liquid water as early as 4.1 billion years ago.

Another even older zircon grain, dating to 4.4 billion years old, is the oldest earthly object known, older than any rock. It's ironic to me that the oldest thing on our planet is not some immense resistant block of crust, but a tiny speck of sand. Similarily, the oldest living thing on earth is the genome of a tiny microbe, against which the giant elephants and blue whales are young upstarts.

9 - SWEET SPOT - 2947

TAKEAWAY

To deal with climate change clearly, objectively, and dispassionately requires that we abandon anthrocentric, biocentric, and spiritual frames of reference for a geocentric one.

KEY POINTS

From the planetary perspective of distant space, Earth is a single pale blue dot. From the global perspective of its surface, Earth is a complex mosaic with no unique point of reference. Only from the sweet spot of its deep interior does it make holistic sense.

The *anthrocentric* or people-centered view of the humanities sees everything from the bubble of human consciousnesses. The *biocentric* or ecocentric view of the life sciences, seeing everything from the bubble of living things. The *geocentric* or Earth-centered view of the grand, unified system doesn't unfairly preference any one of its subsystems.

The quasi-spiritual, feel-good Gaia hypothesis, which envisions a biotic Mother Earth taking care of us, muddles the anthrocentric and biocentric viewpoints and gives us an excuse for not cleaning up our own mess.

Earth does not evolve. Only one of its components evolves, its biota, of which we humans are a part. Instead of evolving, Earth is emerging continuously as a consequence of its life.

Earth is not an emergent consciousness. It's near-surface critical zone a natural subsystem system kept in a steady-state by negative feedbacks. Beneath and above this narrow zone it's a lifeless, but energized planet.

SCRIPT AND TEXT

Pause ......

Episode 9 - Sweet Spot

Pause

Welcome to Climate Underground

I'm your host, Robert Thorson

Thanks for joining us.

Pause.....

Though born a twin, I knew instinctively that I was the center of all things. Growing older, that feeling stayed with me, even as the radius of my understanding enlarged outward from home to neighborhood, nation, world, solar system, galaxy, universe, and finally to the quantum possibility of a multiverse. With each conceptual leap, I saw myself as a smaller speck of something far larger and grander. But the centrality of my experience to everything else has remained unchanged.

Everything I'm aware of at every level emanates from the brain inside my skull. My ego --the me, me, me-- part of my consciousness is deep ***instinct*** selected for during animal evolution, a ***mechanism*** of self-protection designed to ensure that ***my*** genes make it into the next generation.

Cognitively, I'm a bubble of thought surrounded by everything else. I know this feeling of centrality is an illusion. That *my* bubble is no more central than *your* bubble, and that human bubbles are no more central than those of other *creature*s.

This leads me to the question: "Does planet Earth have an equivalent centrality?" The answer is ***no*** with respect to consciousness, but ***yes*** with respect to physicality. It's Earth's sweet spot, the exact center of its gleaming iron core, ***from*** which all heat radiates outward, and ***to*** which all objects are drawn gravitationally. The bubble surrounding Earth's center is the outer surface of the sphere on which we live.

Frames of Reference

Most people don't look underground for deeply satisfying explanations of why things are the way that they are. Instead, they screech to a halt in the shallows of human culture, seeking explanations in religion, creations myths, and philosophy. This is the ***anthrocentric*** view of the humanities, which views everything from the bubble of the collective human consciousnesses.

A few people seek a deeper understanding of human cultural behaviors --the urgency of terrorism, the theater of politics and the potency of celebrity — in our biological origins. From this ***biocentric*** perspective, we are individual members of tribal clans of upright apes whose eusocial brains have a unique intelligence that gave us great power. By eusocial, I mean that we experienced natural selection simultaneously at the *individual* level ***and*** the group level. This *biocentric*, or ecocentric, view of the life sciences sees everything from the bubble of living things.

Rarer still are those who adopt a truly ***geocentric*** view of the grand, unified system of the whole Earth that doesn't preference any one of its subsystems.... humanity, life, ocean, atmosphere, land, and lithosphere. I am one of those people.

Being geocentric does not erase or banish the other two frames of reference. I remain utterly anthrocentric. Family, friends, community, and other people occupy that reference frame at progressive distance. I remain utterly biocentric, seeing myself and other humans as members of a biological species that, despite its technological wizardry, remains part and parcel of Nature. But in my core, and with practice, I've reached the higher power of being geocentric. The center of this bubble is the center of Earth's core, ***to*** which everything else is attracted, and ***from*** which comes the heat that keeps the entire system going. It is this larger unified system that creates ecosystems, human beings, and climates.

On February 14, 1990, and at astronomer Carl Sagan's suggestion, the engineers controlling the Voyager 1 spacecraft turned it around to take a final snapshot of Earth before leaving the solar system forever. From a distance of about 4 billion miles (6.4 billion kilometers), and obscured by the dust of Saturn's rings and the glare of the sun, Earth was barely visible, a tiny point of light, a dot only one tenth of a pixel in size. Sagan famously called it a "pale blue dot," using that phrase for the title of his 1994 book.

“Look again at that dot," he wrote. "That's here. That's home. That's us. On it everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives. … a mote of dust suspended in a sunbeam.”

It’s a beautiful image. Sagan's poetic impulse was about isolation and loneliness. Earth is but a speck lit by a sunbeam whose pale blue color signals a veneer of liquid water that appeared about 4.1 billion years ago. This global ocean is the oldest feature on the planet's surface, older than the oldest rock. The biblical phrase "Rock of Ages" misleads us. "Water of Ages" would be more accurate.

The word environment comes from the Latin root *environs,* meaning "that which surrounds us." For Voyageur 1 in that moment, the environment was a mostly empty space speckled with undifferentiated objects at distance. This is Earth's *universal* frame of reference. We're one of countless undifferentiated objects among everything else.

Now, let's imagine that we steer the Voyager 1 spacecraft into a U-turn and send it back toward Earth. Somewhere between Mars and the moon, that pale blue dot enlarges to become a bright blue halo of atmosphere, a lighter hue of ocean, white clouds, and a blurry mottle of pastel earth tones, mainly brown and green. Closer in, we see what the famous “Earthrise” photo revealed from the moon... recognizable places, beginning with named continents. Closer in, the horizon becomes a broad curve against the blackness of space.

As we approach Earth, the view is mainly downward. Then, at some point, the perspectives change again, and the view becomes mainly outward toward discrete places; Uzbekistan here, Japan there. Soon, we spot famous cities like London, Sidney, Singapore, Fargo, and Mecca, all known more for their human history, not their Earthly physicality. All planetary curvature disappears.

Finally we land somewhere on an continent, exit the spacecraft, and look around. We are flatlanders. Everything we see now is upward and outward through the transparent medium of the atmosphere. Our visual bubble is a half-bubble defined by the sky overhead and the four cardinal directions of the compass. There is no downward view because the organic and crystalline solids we're standing on are opaque.

Being primates, we are dominantly visual creatures. As a result, the Earth below has become the ***dark matter*** of our lives, and its geothermal heat the ***dark energy***. Unlike the whales of the deep sea, and birds of the air, we occupy only half-bubbles. Henry Thoreau understood this limitation, explaining: "My instinct tells me that my head is an organ for burrowing."

Being desirous of a full bubble, I imagine myself with X-ray vision and the ability to withstand any heat and pressure. My center becomes the center of Earth's iron core, the only other place from which we can imagine seeing Earth as a unified whole. If you can train your brain to think from that perspective, everything that takes place on Earth's surface, especially its climates, makes more sense.

Running this thought experiment of looking upward from Earth's core brings me to thinking about other thought experiments involving frames of reference. One famous one involves Albert Einstein's *Special Theory of Relativity*. He imagined a beam of light to be motionless when he travelled alongside it at the same speed.

A current example of a reference frame getting lots of recent attention is within a forest soil --the symbiosis between the network of tree roots and the network of fungal strands called mycelia. Elegant experiments prove that the sharing of commodities like sugars and metal nutrients takes place. But why? In *Finding the Mother Tree,* ecologist Suzanne Simard sees the mutual network between fungi and trees as the means by which trees take care of one another. Mycologist Merlin Sheldrake's *Entangled Life*, shifts the frame of reference to view the fungal network as distributing resources between trees to ensure ecosystem health for the benefit of the fungi. The answer you get depends on your frame of reference.

The most famous historic example of rethinking a frame of reference was the *throwing off* of Ptolemy's (105 CE) geocentric universe of Mediterranean antiquity in favor of Copernicus's (1543 CE) heliocentric universe of the European Enlightenment. Ptolemy erroneously thought earth was surrounded by a series of concentric celestial spheres beginning with the clouds, our atmosphere, our troposphere. Above it were the orbiting shells of the moon, Mercury, Venus, Mars, Jupiter, Saturn, stars of the Zodiac, and the infinite shell of the Firmament. Quite literally, everything revolved around the Earth. This viewpoint lasted for over a thousand years because it was reinforced by Christian doctrine. Scientists like Galileo were imprisoned for thinking otherwise.

The heliocentric view was overthrown by 19th century astronomy when we learned that our sun was merely one of billions of stars within the Milky Way galaxy, which is only one of billions of galaxies in the known universe. Unlike Earth, the universe has no center. Everything is expanding outward relative to everything else.

Within geology, the canonical frame of reference problem involves Alfred Wegner's theory of continental drift. This German polymath published *The Origin of Continents and Oceans* in 1915, arguing that, despite their size, the continents must move over Earth's surface by some unspecified mechanism. Sadly, he froze to death on a Greenland expedition before his theory was accepted by the American geoscience establishment. They resented the intrusion of a German meteorologist into their discipline during World War I. Their other mistake of putting theory ahead of observation, saying, effectively, that continents couldn't move because there was no known mechanism to make them move. Wegner's paradigm-shifting insights would have to wait half a century before we could see that he was right all along.

Also to blame for not accepting Wegner's ideas in the early 20th century was our *terra firma* continental frame of reference. It's hard to understand the motion of a continent when you're located on one and moving along with it, as with an airline passenger trying to sense forward motion from the aircraft's windowless bathroom. Happily, continental drift is easy to see and understand from the fixed datum of the Earth's center -- as with a scuba diver at great depth looking up to watch the hulls of boats moving on the water surface.

From Earth's sweet spot, we can imagine looking upward and outward to see how earth works. Earth's continents can be seen as surface ***patches*** of amalgamated flotsam drifting over the slow-but-steady currents of deep tectonics. Earth's oceans can be seen as ***puddles*** trapped within the shallow depressions of tectonic basins that deepen away from the ***warm**-crust* of spreading centers to the ***cool**-crust* of abyssal plains and to the ***cold**-crust* deep trenches. Were we living in ancient polytheistic Rome, out king would not be ***Jupiter*** of the mountains or ***Neptune*** of the sea, or ***Silvanus*** of the vegetated land, but ***Vulcan*** of the underworld looking up from below: Vulcan working in his forge with hammer and anvil to make the other places.

Cultivating a geocentric reference frame takes practice because it must be imagined. The sophisticated astronomy of Galilei Galileo in late 16th century and of and Isaac Newton in the late 17th century predate the late 18th century birth of geology by a century because astronomers can see and study the objects of interest with their telescopes. This was not true for the *terra incognita* of the underworld prior to the arrival of seismic tomography in the late 20th century, as with medical ultrasound. Earth's deepest reach into its interior is the Kola Super Deep Borehole, which was halted at 7.5 miles or 12 kilometers dept because the rock got too hot for the cutting tools to work.

This invisibility of Earth's interior gave rise to wacky ideas like the 19th century misinformation of John Symmes -- that Earth was hollow and had openings at the poles. This idea was widely debated, and taken seriously enough to prompt French author Jules Vernes to write his blockbuster novel, *Journey to the Centre of the Earth.* Reading this book as an adventurous boy with an insatiable curiosity helped launch my geological career.

The Earth interior has remained so inaccessible that, we've only recently learned what the bulk of our planet is actually made of. In a word, bridgmanite, a mineral, a high-pressure (perovskite) magnesium silicate that had long been known as a theoretical possibility, but which could not be verified and officially named because no specimen had yet been collected. Only recently was this mineral identified in a meteorite fragment that had been shock-melted under ultra-high pressures comparable to those of Earth's deep interior. This late discovery of Earth's most dominant material illustrates that astronomy remains more accessible than deep geophysics. In May 2022, the world saw an image of the black hole at the center of the Milky Way. Our view of the Earth's center is fuzzy by comparison.

In the opening to *Half Earth,* naturalist and scientist E.O. Wilson writes that "we need a much ***deeper*** understanding of ourselves and the rest of life than the humanities and sciences have yet offered." I agree that a deeper understanding is needed. A literally deeper understanding. One that takes in more of what geologists, geophysicists, and geochemists have been sharing. From their perspective, the social systems of humans and the ecosystems of all organisms are razor-thin patches sandwiched between the much larger volumes of lithosphere below and atmosphere above.

We must keep in mind that photosynthesis, which energizes nearly all of life, captures less than ***eleven*** percent of the sun's radiation. The other ***eighty-nine*** percent energizes our weather and colors our sunrises and sunsets. In his masterpiece *The Magic Mountain,* writer Thomas Mann suggested in that life could be “an infectious disease of matter.”[38] Though this view strikes me as too negative, a block of granite being slowly consumed by microbes, fungi and roots within the soil may think otherwise.

Setting aside material reality, the sweet spot at Earth's center is also the starting point for earth history. Almost nothing changes there because alsmot nothing *can* change except for the occasional atomic burst of radioactive decay. There is only a solid crystal or iron alloy confined by the vice grip of gravity squeezing inward from all directions.

The instinctive bias of biology requires practice to overcome. Consider the famous ***land*** ethic of Aldo Leopold from his beloved *A Sand County Almanac* published in 1949, a book I've treasured my whole adult life. My most-caring professor gifted me a copy when I left college "A thing is right" Leopold writes, "when it tends to preserve the integrity, stability, and beauty of the ***biotic*** community. It is wrong when it tends otherwise." The land about which he writes, however, is, so more than its biology. His expanded definition of land --" soils, waters, plants, and animals, or collectively: the land" treats only the surface on which we live, one created from above and below.

Leopold's emphasis on ***conservation*** --preserving the status quo-- though prudent in the short term, is inconsistent with the long haul of geological history, for which constant change, rather than stability, is the benchmark. I'm glad that the the "integrity, stability, and beauty" of the end-Cretaceous biotic community of the dinosaurs was destroyed by an asteroid 66 million years ago.[39] Was that asteroid ***wrong*** because it created a new world order that allowed mammals to take over?

Recent research on the early, post-asteroid-impact mammal fossils from Colorado reveals that mammalian diversity and body size nearly doubled in the first 100,000 years after the extinction. Subsequent pulses of biodiversity within the next million years were ***all*** associated with abrupt greenhouse warmings caused by pulses volcanic gas, each of which disturbed the previous biotic community.[40] The thing called volcanism was not wrong in venting so much gas.

Recent theoretical work on the stability of biological communities, or the lack thereof, prompted a team of ecologists to write: "A nostalgic longing for a lost Garden of Eden, which permeated the roots of the [biocentric] conservation movement, is not supported by what we know of the past and expect in the future."[41]

The tropical old growth forests of Amazonia are a case in point. A basin-wide study overlaying archaeological sites with 85 woody species domesticated by pre-Columbian indigenous reveals that much of the forest structure is the work of humankind. [42]

Our implicit bias for biology penetrates our language. In my New England town are small permeable basins designed to capture and hold surface runoff until it seeps away. The point is to steer contaminated surface water away from streams and to facilitate aquifer recharge. These are

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[38] Drewdney, 9

[39] Hull, et al, 2020, On impact and volcanism...

[40] Lyson et al, 2019, Exceptional continental record....

[41] Dornelas and madin, 2020, Novel Communities...

[42] Levis et al, 2017, Persistent effects of pre-Colonbian plant domenstation.

called "bio-retention" ponds even though they're not about biology. To market them even more effectively, they are also called rain gardens, even though gardening is hardly the point. Our bias for "bio" helps us tolerate them in landscape architecture, which is a good thing, offset somewhat by the misinformation being promulgated.

Our frames of reference influence how we perceive the climate crisis. The anthropocentric frame sees climate change mostly as disaster politics, climate refugees, and adaptation. The social science disciplines of political science, economics, and international relations are also fully engaged. The biocentric frame sees climate change mainly as habitat disruptions and the extinctions underway. The geocentric frame of reference sees mainly business as usual, but with an unusually novel and rapid disruption called humanity that is causing serious ecological harm on the short term.

Gaia

All four reference frames discussed thus far --universal, anthrocentric, biocentric, geocentric-- are based on the secular reality of an actual world. For many, however, secular reality is not enough. The reach is to a cosmic reference frame of gods and supernatural influences operating on human behalf. This is the natural impulse that gave rise to the polytheism of ancient Greece: Zeus of the atmosphere, Silenus of the forest, Gaia of the land, Poseidon of the sea, and Hades of the underworld.

Within modern geoscience, there is no better example of ***spirituality*** posing as ***secularity*** than the Gaia hypothesis, which proposes that life regulates non-life at the scale of the planet to ensure the continued existence of life. In Greek mythology, Gaia, derived from *land* or *earth,* is a goddess, the original Mother Earth. In Hesiod's classical text, [Thee-Og'-an-ee]~~*Theogony,*~~ "wide-bosomed" Gaia emerged from the Chaos to have sex with Father Sky to birth Oceanus and the Titans to manage the details.

The Gaia hypothesis was a crowd-pleaser from the get-go. Having a loving Mother Earth feels better than not having one. This is a primal instinct. Actually, it goes deeper than primal because that sense of wanting protection predates the origin of *primata*, our taxonomic class.

Modern culture insists on gendering the planet? When I asked Robin Wall Kimmerer, bestselling author of *Braiding Sweetgrass* why Earth was a mother and not a father, she responded by saying that the father's role was reserved for the sun. Does treating the nurturing Earth as mother and the sun as a more powerful distant father reinforce gender stereotypes? Ultimately, Father sun will expand to destroy Mother Earth as we know it. Is this a misogynistic thought?

Gaia has been trying to seduce me since I was midway through college. I first met her in 1972 when atmospheric chemist James Lovelock introduced her in the article "Gaia as Seen through the Atmosphere" in the scientific journal *Atmospheric Environment.* By the time I graduated, he had teamed up with the biologist Lynn Margulis to author two clarifying papers in 1974. "'Atmospheric Homeostasis by and for the Biosphere' in the journal *Tellus*, and 'Biological Modulation of the Earth's Atmosphere' in the journal *Icarus.* My main resource for understanding Gaia is Toby Tyrrell's masterful, but daunting 2013 scholarly book from Princeton University Press *On Gaia: a critical investigation of the relationship between life and earth.* Spoiler alert. Tyrell agrees that, prior to the Anthropocene, life was not in charge, and that there was no intentionality involved at that scale.

Some believers still cling to the notion that mommy Gaia will clean up our mess. Or, failing that, she will administer corrective discipline when we behave too badly. Or, that she will steer us in the right direction. Believing that we have a nurturing mother working behind the scenes, or even an ungendered system working on life's behalf has taken off some of the pressure for us to act on our own with respect to climate change. This has made us slower to respond, like the kid who wants to do the right thing, but can't.

More than a few dead, white, male philosophers have taken issue with the idea of a loving beneficent Gaia. "Kant, Nietzsche, and Thoreau," notes Robert Moor, "all describe nature not as a mother, but as a "stepmother" --a winking reference to the wicked villainess of German lore." [43] To this, Moor adds Aldous Huxley's view that nature "is always alien and inhuman, an occasionally diabolic." In Dante's *Inferno,* for example, the motivation for descending into the underworld was to escape the greater violence lurking on the surface in the form of flesh-eating carnivores, wolves and leopards.

Every soil reveals that living and non-living entities influence each other. There's also no question that organic evolution has permanently changed Earth's geochemical processes, for example: photosynthesis leading to the deadly oxidation of the atmosphere; or the spread of forests on the land pushing the planet into its most protracted glaciation.   But true co-evolution isn't happening because non-living things cannot evolve in response to biotic events. There's no selective pressure for a better ocean or a more uniformly shaped hill. When ***life*** makes an initial move, for example the origin of animal mobility at the base of the Cambrian explosion, earthly entities merely absorb the consequences, in this case a bioturbated sea floor. But when ***Earth*** makes an initial move, as with enormous magmatic outpourings during superplume eruptions, life has the power to adapt and change.

At the end of the day, the Gaia hypothesis fails three important tests. ***First***, Evolutionary innovations, by definition, have had detrimental consequences to Earth's biotic status quo. ***Second***, environments have varied widely through time rather than be kept in balance. ***Third,*** much of Earth history has been sub-optimal for life. Only in the last eighth of its span has there been enough oxygen for animals to exist.

The Earth system ***emerges,*** rather than ***evolves***. There's no selective pressure for Earth to be a better planet than its seven siblings. There's no agent or selective pressure favoring one climate over another. Biotic populations are ruthlessly culled for failure. This can't happen to climates. Instead they emerge, mainly from below, and the biotic populations respond and interact accordingly as dampeners and amplifiers.

At the planetary scale, it is the ***microbial films***, not the ***gardens of Eden*** or the forests of our imagination, that dominate geochemical processes. Inside your gut are more external microbial cells than there are cells of your own genome. Ditto for the whole Earth. When measured as biomass, it's been estimated that more life exists within cracks in rocky crust and within the pores of buried sediment than in our visible soils and seas. Living microbes are responsible for creating coal down to depths of many kilometers, separated from the rest of the biota for 100 million years.   Microbes were the only living things for nearly all of Earth history.

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[43] Moor, on trails, 33.

To deal with climate change --*clearly, objectively, and dispassionately*-- requires that we abandon a spiritual frame of reference. Ditto for the planetary reference frame, which is too cold, too distant, and too unfeeling. We must also try, at least initially, to avoid the deeply ingrained, instinctive, implicit biases of the anthrocentric reference frame which extends human morality over the rest, or the biocentric reference frame, which sees the planet mainly as habitat, rather than a larger system. The only reference frame that makes objective sense to me is the one looking outward from the center of the planet to see the whole shebang performing like different instruments in an orchestra.

Two deep thinkers, Timothy Lenton and Bruno Latour, suggest the Anthropocene is Gaia 2.0. [44] I agree. This makes far more sense to me than Lovelock and Margulis's Gaia 1.0 In the updated version, 2.0, life --meaning human life-- is in charge of intentionally regulating the planet for the benefit of all life. Though we are not succeeding, at least we are trying.

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[44] Lenton and Latour, 2018, Gaia 2.0

10 - THINKING LIKE A PLANET - 3498

TAKEAWAY

Earth is a unified natural system that's been in continuous operation for 4.6 billion years. It's most important subsystem is the ultra-thin layer called the critical zone, where rock, water, soil, biota, air, and humans are hopelessly entangled.

KEY POINTS

A single fragment of a broken seawall composed of concrete and iron, encrusted with limpet shells, and rolled in the surf tells an incredible story from an oxygen-free earth to humanity's attempt to control nature.

The atmosphere and lithosphere make sense as continuous concentric spherical shells. The rest do not because they are either trivial in scale, discontinuous, or overlap too much with others. They remain as historic baggage from the early era of scientific reductionism, and are barriers to integrative thinking.

For terrestrial landscapes, the concept of the critical zone is a great improvement over the separation of the sciences. Everything from the top of the vegetation canopy to the base of flowing groundwater constitutes a single system.

Auto mechanics, ecology, and earth system science deal with different materials and spatial scales, but are unified by the emphasis on systems thinking.

Earth system science was first envisioned by the James Hutton during the Scottish Enlightenment of the late 18th century.

SCRIPT AND TEXT

Pause ......

Episode 10 - Thinking Like a Planet

Pause

Welcome to Climate Underground

I'm your host, Robert Thorson

Thanks for joining us.

Pause.....

Crepedula

In my cabinet at work is a curious object that my wife considers a piece of junk. Yes, it's a fragment of rubble, but it's also an artifact that symbolizes for me how the earth works as a unified grand system in time and space. Several times a year I toss this object into my black briefcase and bring it to class to share with students who are always confused at first, but then gradually get my point.

I found my artifact many ago when walking a beach on the Connecticut shore, which faces a fast-rising sea and is frequently battered by powerful storms. Within a millennia, most of its seaside homes will have been long washed away.

During my walk, I was initially attracted to a bright orange blotch about five feet to one side. Veering to investigate, I picked up a fist-sized fragment of a concrete sea wall that had been obliterated, probably during the disastrous 1938 Hurricane. My fragment was spindle-shaped, with the wide middle being an irregular mass of pebbly concrete and the ends being prongs of rusted iron bar. Its outermost layer was a dense coating of battered shells of the species *Crepedula fornicata*, the common slipper shell, a snail-like limpet whose somewhat insensitive name points to its hermaphrodite growth habit.

From the worldly perspective of humans, my object was just another piece of junk that became a beach cobble. But from an earthly perspective, it's an exem*plar* of how the Earth works as a coherent system, and what it's deep history has been, one that includes us.

The story of the last century begins with the contractor who built a sea wall to protect the private property of a client against shoreline erosion. That process involved pouring a slurry of concrete around a latticework of iron re-enforcing bars within a wooden mold. After hardening, the wood was removed, the landscaping was finished, and the wall did its job for a while. Inevitably, the weather and salt spray weakened the concrete and corroded the rebar. Then, during some powerful storm, at least part of the wall fell apart. One of its many fragments was rolled back and forth in that stormy surf to become a spindle shaped cobble that came to rest offshore. There it was colonized by slipper shells, which coated the fragment, giving it a larger surface area and making it less dense. This allowed it to be more easily transported, so it washed back up onto the beach, battering a few of the shells during the process, and exposing the orange rusty blotch that attracted my attention.

The story from deep time begins with the ***iron ore*** from which the iron rebar was smelted. That was likely precipitated from seawater somewhere in the global ocean about 2.4 billion years ago when the global atmosphere was being oxygenated for the first time by photosynthetic cyanobacteria. The ***cement*** holding the concrete together was quarried from limestone before being baked in a hot kiln, pulverized, and sold. That limestone consisted mainly of shells that convert the dissolved marine salts of weathered rock into biological armor. The ***aggregate*** used to make the concreate was sand and gravel deposited about 20,000 years ago by meltwater streams of glaciers that earlier had broken fragments of rock away from outcrops and crushed them against one another. Melting of that glacial ice caused sea level to rise, progressively drowning what had previously been dry land, and allowing the climate to warm enough to generate stronger waves. Humans, thinking on the short term, armored the shore in a futile ***attempt*** to hold back the rising sea. Destruction of the sea wall gave the slipper shells something new to grow on, and something to prompt my musings. Think of all the history in that single object! This back story can't be meaningfully understood or shared without knowing how the earth works, what its history has been, and how this knowledge can be put to good use.

Spheres

During the Middle Ages, we humans were flatlanders. Maps were drawn on flat sheets of parchment and paper, even though every sailor knew that the earth's surface was a sphere. Otherwise the topsails of ships would not have come into sight before the hull appeared. And anyone who'd seen the moon wax or wane a would have watched Earth's curved shadow creep across the face of the moon.

In Ptolemy's geocentric universe, Earth occupied the center of a series of concentric spheres in which the heavens moved. His innermost sphere was the sky, the atmosphere, the place of clouds and wind.

The atmosphere is truly a sphere, entering the English lexicon in 1638. Following Ptolemy's system downward, the hydrosphere was added in 1887, the biosphere in 1899, and all others in the 20^{th} century. To date, the acronym for Earth's alphabet soup of spheres is ABCHLA, for Atmosphere, Biosphere, Cryosphere, Hydrosphere, Lithosphere, and Aesthnenosphere, Ab-chlah for short. Ironically, the ***truest*** spheres at greater depth are not named as such: mantle, outer core, inner core.

Of this short list, only the atmosphere is visible from space in an edge view, and only half of the spheres are spherical. The atmosphere, lithosphere and aesthenosphere are indeed continuous concentric shells surrounding the planet. The ***atmosphere*** is seen in cross section from bottom to top because it's generally transparent. The ***lithosphere*** is the brittle rocky crust we walk on and have sampled to a depth of about 10 km, together with the rigid cold part of the uppermost mantle down to a depth of about 80 km. The ***aesthenosphere*** below that is the softer, warmer, mechanically weaker part of the upper mantle extending to a depth of 700-1000 km. Though it's never been seen, it's nicely confirmed by countless geophysical and geochemical observations. Ironically, the most spherical layers and uniform layers of all, the liquid outer core and solid inner core-- are not considered as part of the parfait.

Sandwiched between the atmosphere and lithosphere are various objects and surface phenomenon located in different places and at different elevations, none of which are continuous like the overlying air or underlying crust. Consider the crisp whites of alpine ice and snow fields, the dark browns of soil and sediment and the variegated greens of vegetation, each in its own place. When seen from above, these color patches exist *side-by-side* as a mosaic, not a *one-above-another* parfait. These material patches overlap, interweave, conflate, and entangle one with another at a range of scales. The biggest object sandwiched between the continuous spheres is the ocean. It would qualify as a sphere if it covered everything, as it once did in the Archaean Eon, or if it was the only place where water is important, which it isn't.

The downward differentiation of earth materials into spheres of increasing density --air, organic, ice, water, rock-- made perfect sense during early Enlightenment science of the 17th century when the reductionism of taking things apart was a high priority. In the inductive science of the 21st century, however, I believe that most of the spheres are more harmful than helpful. Birds fly in the air, fish swim in the water, and clams dig in the sand. Why put them in a separate biosphere that doesn't really exist, and which is so thin it can't be seen in cross section?

Earth's imagined parfait of materials reminds me of the QWERTY keyboard, which we continue to use today. This sequence of keys in the upper left part of the keyboard was chosen during the late 19th century to facilitate transcription from Morse Code and to prevent typewriter keys from jamming up. Though these mechanical limitations have long since disappeared, the original, now atavistic, sequence persists on our electronic keyboards not because it's most efficient, but because of cultural habit. The word "biota" works well for the sum total of life, who's organisms live in three spheres at once: the the so-called lithosphere (as with cave spiders), hydrosphere (as with dolphins), and atmosphere (as with albatross). There's no need to fictionalize a unique sphere where one doesn't exist.

Several years ago, I devised an new gateway course for undergraduate earth science majors titled *Earth System Science*. On each of six field trips, we visit the Glen -- a beautiful, small, New England valley bisected by a clear brook flowing out of local aquifers, into a channel, and over rock outcrops and glacial boulders. Surrounding us was a closed-canopy forest of mixed deciduous and conifer trees and a gridwork of fieldstone walls from agricultural farmsteads of the 18th and 19th centuries. Local exposures of stone were dotted with lichen, painted with microbial mats, shaded by ferns, and submerged by flowing water.

At this scale, the concentric parfait model is not only invisible, but is an obstacle to systems thinking. The gas of the atmosphere occupies most of the volume of the forest canopy, and penetrates downward to fill every crack in exposed rock, every pore in the soil, and every bubble in the water. The water of the so-called hydrosphere is not only in the flowing stream, but also in the humid air we were breathing, the fog in the distance, the turgid cells of every leaf, the dampness of the humus, and the groundwater seeping beneath us.

There's a much better way of thinking about all this. Geologists call it the critical zone. It's the complex terrestrial surface below the base of the uninterrupted true sphere of the atmosphere and above the uninterrupted true sphere of the lithosphere which is either rock or sediment. The emphasis of the critical zone is on integration, rather than separation.

Integration of the so-called spheres also takes place in the sky. Above Mount Everest, earth’s highest peak, the *atmosphere* contains so much more than dry air. Its bulk of inert molecular nitrogen is merely the ambient medium in which other stuff is intermingled: water vapor and condensates of the so-called *hydrosphere*, ice crystals of the so-called *cryosphere*, dust and volcanic ash of the *lithosphere*, and the soot, pollen, gaseous biomarkers, and synthetic chemicals of the so-called *biosphere*.

Integration of the so-called spheres also takes place in the crust. Steaming geysers are as hydrothermal as they are geothermal. The soaring albatross that's been aloft for a month, and the whale that never leaves the water are simultaneously part of one so-called sphere immersed in another. Cirrus clouds of tiny ice crystals are simultaneously cryo-, hydro-, atmo-, and litho-. Coral reefs and coal seams are as geo as they are bio and hydro. Microbial populations buried millions of years ago are still happily feasting on deep lithospheric carbon. At a depth of 1.2 km below the Nankai Trough, and at temperatures of ~70 °C, vegetated cells indicate hyper-themophillic lmethanogenisis.[45] Pore-water in marine mud dragged down into the mantle by tectonic forces lowers the melting point of magma, creating volcanic gasses that regulates the climate. Without water, plate tectonics would likely seize up completely, earth would freeze over, and life would disappear. Mass extinctions don't arise within ecosystems; they arise when physio-chemical-biogeochemical cascades push the earth system beyond the physiological limits of large organisms. The microbes barely notice.

Now consider the many internal contradictions of the so-called cryosphere. Crystalline hydrosphere is a perfectly respectable mineral, making glacier ice a perfectly respectable rock, albeit one with a low melting temperature. This rock made of water is mostly metamorphic on the inside, having been strained by plastic flow; mostly sedimentary at the top where buried snow was subjected to processes similar to that of a sandstone; and mostly igneous near the bottom where melting and re-freezing are common. The glacier bed is a gravity-driven low-angle geological fault zone called a *decollement* where ice rock shears over silicate rock. The oldest ice in Antarctica predates the oldest basalt of Hawaii.

Below Earth's lithosphere is the aesthenosphere, which is technically too soft to qualify as a rock. Below it is the mantle transition zone, where there's probably enough water to fill earth's oceans three times over. So what sphere would that be? My answer is the parfait of ABCHLA is really ALA, with BCH being square pegs forced into round holes.

Based on purity and uniqueness, Earth's inner core is probably the most uniform sphere of all, a single crystalline mass of iron alloy. The outer core is nearly as uniform, and is the source of Earth's so-called magnetosphere, which stretches the meaning of the word sphere too far. Our magnetic field is oddly shaped, bilateral, and lopsided. And unlike the other so-called spheres, it's not a material at all, but force field, like gravity.

Systems Thinking

I did poorly in high school in the late 1960s because I was too immature to comply gracefully with how the so-called Greatest Generation insisted we behave. After being kicked out of physics class, and refusing to pay for administrative negligence, the principal huffed and puffed that I would not graduate until certain ultimatums were met. The only class left for me was auto mechanics, which turned out to be my best course in high school. With no plans to attend college, I was learning an employable skill that catered to my learning style, which was hand's-on and experiential. During class, randomly assigned teams of man-boys took cars apart and put them back together. I can still vividly recall the magic moment when our group's old Pontiac roared to life and whisked us around town for a test drive.

That summer I worked as a pipe-liner, becoming a lunch-bucket, blue-collar, clock-punching laborer. Getting my first paycheck, I bought a used Chevy Biscayne with a 283-cubic-inch V-8 engine, which burned leaded gasoline and got about 12-15 miles per gallon. It was easy to work on, with no computers and lots of room under the hood. I learned how it worked in great detail.

Two years later, when taking cology in college, I discovered another reason why my auto mechanics course was so appealing. At the conceptual level, both subjects were about systems analysis. Both

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[45] Huer, 2020, Temperature limits to deep seafloor life...

were open systems, which are ***energized*** entities with definable outer boundaries, ***two*** or more interacting components, inputs, and outputs.

As with Earth's climate system, our Pontiac was an open system. Its outer ***boundary*** of paint, glass, and metal, held the interacting ***components*** of chassis, engine, and electrical, that were ***energized*** by ***inputs*** of gasoline and air, and had ***outputs*** of exhaust and mechanical energy. Its fundamental purpose was transportation. To achieve this purpose inventors created a way of tapping and controlling power. That's what ecosystem do.

The human body is a more familiar system to most of us because it's taught in schools, and it's midway in complexity between cars and climates. The outer ***boundary*** of skin, nails, hair, holds the interacting ***components*** or subsystems of digestion, nerves, hormones, and reproduction, that are ***energized*** by ***inputs*** of food, water, and oxygen, and have clear ***outputs*** of poop, pee, and activities. Each ***organ*** in that body, each ***cell*** of those organs, and each ***organelle*** in those cells are subsystems that meet the same criteria above.

Now let's leverage these ideas to the Earth system. For our purposes, it has a clear but gradational outer ***boundary*** of the mid-stratosphere that holds interacting ***components*** of air, ocean, life, rock, and metal, that are ***energized*** by ***inputs*** of radioactive heat from below, solar heat from above, the angular momentum of spin, and some asteroids and cosmic dust, and has clear ***outputs*** such as the re-radiation of heat at thermal wavelengths, the energy consumed by tectonic activity and tidal friction, and some gas lost to space.

At the systems level, meaning the conceptual level, automobiles ecosystems, organisms, and planets are very much alike.

The phrase *climate system* is widely used, and works well as shorthand for what we really mean: the Earth System -- the integrated total of all components working together. Climate is thus an ***output*** of earth processes, a statistical expectation of meteorological conditions, based on recent Earth history. It is not a material component like one of the so-called spheres.

The notion that earth works as a coherent unified system, a concentric machine with a volume of solids, liquids, and gases, was first shared in April 1785 when Scotsman Sir James Hutton read a lecture to the Royal Society of Edinburg titled *Concerning the Systems of the Earth, its Duration, and Stability*. Known as a dull speaker, and reading from a turgid text, I suspect that much of his audience tuned out or dozed off. That lecture was published three years later in 1788 as *Theory of the Earth or an Investigation of the Laws observable in the Composition, Dissolution, and Restoration of Land upon the Globe* in the Transactions of the Royal Society. Seven years later in 1795 this theory was re-published, virtually unchanged, as a 2-volume book titled *Theory of the Earth, with Proofs and Illustrations*. Hardly anyone noticed, because the initial print run was only a few hundred copies, and mainly because the prose very challenging to get through.

Fearing that such Hutton's genius was being ignored, his colleague and friend, the mathematician John Playfair, wrote out his own summary of the theory from scratch in 1802, based mainly on conversations he'd had with Hutton. This reframing, titled *Illustrations of the Huttonian Theory of the Earth*, was the crucial text read by a London barrister named Charles Lyell in the 1820s that inspired him to switch careers and bring the fledgling science of geology to a global audience. His result *Principles of Geology*, was published in 12 editions between 1830 and 1875. This is the book that launched deep time as cultural idea, inspiring the young geologist/naturalist Charles Darwin to develop evolutionary theory. Darwin's first book *Voyage of the Beagle,* was dedicated to Lyell.

Hutton's spherical concentric Earth had three basic subsystems, each with different materials and sources of energy. The ***upper*** realm, where *sunlight* runs the show, is the ***meteoric subsystem*** of meteorology, the movements of volatile materials through phases of air, water, and ice. They circulate quickly and globally through differences in gravitational pressure set up by differences in heat. This subsystem is energized from the ***outside*** by the sun as modulated by the spin, tilt, wobble, and eccentricity of earth in its orbit.

The ***lower*** *zone*, where *geothermal heat* runs the show, is the ***tectonic subsystem*** of Earth's interior, its crust, mantle, liquid outer core, and solid inner core. It's motions, circulate globally via differences in gravitational pressure set up by differences in heat. This subsystem is energized from the ***inside*** where the heat flows outward from Earth's core.

The intermediate ***surface subsystem***, in which the flow of matter and energy from the meteoric subsystem above and the tectonic subsystem below interact in complex ways in the presence of liquid water and evolved life. The main result is the downward decomposition of rock within soils, and the transport of its residues back to the sea by streams so they can be turned back into rock and raised back up once again by internal heat. For Hutton, Earth was a gigantic recycling machine in steady state equilibrium, a system designed to mirror Isaac Newton's steady-state clockwork universe.

The surface system of Hutton's three-layer sandwich is generally just a few tens of meters thick, extending downward from the top of the land surface to the base of the groundwater aquifers transporting water that leaked down from above. Geologists call this thin layer the ***critical zone***, the place where everything comes together not in spheres, but as an integrated subsystem. It's broadly analogous to a terrestrial ecosystem except for one enormous difference. The focus is not on the air and land ***serving*** living things, but on everything working as a system that integrates all components between the unobstructed air-flow of meteorology above and the unobstructed rock-flow of crustal tectonics below. The center of this critical zone, or surface subsystem, is the soil, not as a place to grow plants, but as a membrane where the products of meteorology, biology, and lithology are equal co-stars. The center of that central soil is the contact or interface between topsoil, which is dominated by organic activity, and subsoil, which is dominated by inorganic activity.

To Hutton's three layer sandwich, we can now add a third main source of energy, the orbital phenomena of gravitational and centrifugal forces associated with the earth's spin. This energy drives both the tides and climate change at orbital frequencies of 21,000, 43,000, and 100,000 years. The duality of gravity and centrifugal forces energizes fluid processes in all of earth's great subsystems: the vortexes and swirls of: circulating ***gases*** in the atmosphere, gyres of ***liquid*** **water** in the oceans, convection of soft silicate ***rock*** in Earth's mantle, and the magnetic swirls in the liquid outer core.

With a frame of reference at the Earth's center, it's easy to broaden Hutton's surface subsystem beyond the tens of meters of the critical zone to a broadened critical zone averaging about 50 km thick, thick enough to take in everything between the lower stratosphere to the base of the crust beneath land and sea. Within this zone is ***all*** the surfrace topography from the summit of Mount

Everest to the Marianas Trench, ***all*** sedimentary rocks, ***all*** reservoirs of petroleum and coal and gas, ***all*** mountains roots in the deep crust, and **all** tectonic plate boundaries.

It is this broadened critical zone, this surface subsystem is, to use an old saying, where the rubber meets the road, the rubber of Earth's meteorology meeting the road of Earth's crust, to govern Earth's climates at long time scales.

11 - SOLID EARTH - 2770

TAKEAWAY

Earth is one of eight planets in the solar system with its own birth story. Attributes from infancy continue to influence its climates today.

KEY POINTS

The Universe had its Big Bang, sending out dust, clusters of galaxies, black holes, solar systems, flecks of dust, and gas into the emptiness of space. From nothingness came quarks, leptons, bosons and the like to create the elements and compounds we know

Earth has its Big melt. After reaching a critical temperature a homogenous cluster of gravitationally accreted space stuff melted and separated into concentric layers, the oldest of which was the atmosphere in which climates change today.

Earth's planetary neighbors of Venus and Mars were born roughly the same way, but have taken very different directions since.

Earth's core is composed of a molten iron alloy that's solid in the center. Heat-driven convection is swirled by Earth's rotation to produce the magnetic field, without which the solar wind would have long since swept our atmosphere away.

Heat leaking upward from the iron core creates thermal plumes that burn their way through Earth's soft silicate mantle to create hot spots, and broader convection cells that drive the surface tectonics that drive our changing climates.

SCRIPT AND TEXT

Pause ......

Episode 11 - Solid Earth

Pause

Welcome to Climate Underground

I'm your host, Robert Thorson

Thanks for joining us.

Pause.....

The earliest books I sought to read as a child were all adventure stories. Almost exclusively, they were vivid third person narratives written by privileged white European and American males who --I later earned, were unknowingly promulgating racist, sexist, and hyper-masculine behaviors. Examples include the Tarzan books of Edgar Rice Burroughs, the pirate adventures of Robert Lewis Stevenson, the stories of medieval knights by Walter Scott, the science adventure books of Jules Verne, and the wilderness adventure tales of Jack London.

Also hard for me unlearn for me were the biblical stories of Genesis I'd been taught since infancy, which featured the deliberate creation of Earth by a white male patriarch about six thousand years ago. And about how the first human was made from clay. And about how Noah saved life on earth by building an ark to ride out the flood.

Little did I know then that I would spend nearly a lifetime un-learning what these books and stories taught me about human differences, and about science. The cultural baggage about human differences was jettisoned years ago The biblical stories have all been replaced by narratives based on fact. Earth, we now know, was born from gathered cosmic debris and experiences continuous creation. Clay is mostly decomposed rock. And life was less ***saved*** during catastrophes than ***re-booted*** into new and improved and more diverse forms with every eon.

The universe experienced its ***Big Bang*** about 13.8 billion years ago. From nothingness came quarks, leptons, bosons and the like -- to create elements and compounds, from which came solids and liquids, and forces and places, and life and death. In short, everything we know. Every place in the universe is made of the same stuff, yet no two places are alike because each has a different story.

Planet Earth experienced its ***Big Melt*** about 4.6 billion years ago. From initial homogeneity came a parfait of layers separated by material density. Planetary embryos, planetesimals, asteroids, dust, ice, and gas had accreted together under the influence of gravity. Then, reaching some critical threshold temperature, this lumpy mass experienced wholescale melting, perhaps more than once.

This melting initiated an irreversible gravitational settling process called differentiation that continued for perhaps fifty million years. The result was a concentric Earth: a molten metal core, a taffy-like silicate mantle, a magma ocean, and a clinging veil of gaseous volatiles. Arriving later would be a solid basalt crust, a water ocean, smelted continental crust, and a solid iron inner core.

From that initial concentric simplicity, the complex history of Earth began to play itself out. All ***creatures*** great and small would emerge from a microbe called LUCA, a Last Universal Common Ancestor, a theoretical microbe not yet discovered. All ***continents*** great and small would be smelted out of the mantle and crystallized to float above it. During the next four billion years, no two snowflakes, no two waves on the sea, and no individual organisms would ever be exactly alike. Each moment on earth is a unique moment.

Regular cycles emerged at all time scales ranging from the twice-daily tide to the billion-year-long supercontinent cycle. Flip-flops between stable states were common, whether the normal versus reversed *magnetic* polarity of Earth's electrical dynamo, or the icehouse vs. greenhouse *climatic* polarity of Earth's carbon budget.

Everything in Earth history was contingent on what came before it. As with human origins, Earth's present climates make sense only when you know where they came from, how they got here, and what their predecessors were like.

In the beginning, all of the space, matter, and energy of the universe was compressed into an ultra-hot dot so small you would have needed powerful microscope to see it. Beginning about 13.8 billion years ago, that dot expanded and cooled to create the universe we know today, a configuration of empty space, dust, clusters of galaxies, black holes, solar systems, flecks of dust, and gas.

During that expansion, what had been a single force became the four fundamental forces: the strong nuclear force, the weak nuclear force, the electroweak force, and electromagnetic radiation. Subatomic particles leapt into being, including photons of light, a type of boson, and electrons, a type of lepton. These subatomic particles fused into atoms as physics gave rise to chemistry. The dark energy and dark matter comprising the bulk of the universe came into being.

Slowly rotating clusters of gas called nebulae become galaxies, flattening to make spiral arms. Our Milky Way is one of millions spiraling around a massive, but unseen black hole. Within that galaxy was a small interstellar cloud or nebula that formed bout 7 billion years ago. After some kind of neighborhood shock about 6 billion years ago, perhaps from a nearby supernovae, that nebula collapsed under the influence of gravity to form a protoplanetary disk tens of billions of miles across. That disk rotated around a concentration of mass that would later ignite to become our sun. Ninety-nine percent of that disk was hydrogen. Making up the rest were dusts rich in ice, mineral grains, and organic molecules.

Then our sun switched on with a flash. Everything within the disk either melted or vaporized. The flash faded back to a glow, allowing the rotating disk to cool. About 5.6 billion years ago, an ubiquitous mist of molten droplets called chondrules chilled into tiny beads of minerals and glass the size of poppy seeds.

Then the cosmic cleanup by gravity began. Chondrules gathered into concentric sedimentary masses, layer upon layer. These masses merged with other dusts and ices and stony fragments to create larger and larger objects of irregular shape, the stuff we see on comets and meteorites. The oldest dusts included the mineral corundum, an aluminum oxide known in the gem trade as ruby or sapphire, depending on the color. Diamond dust was there as well, along with graphite. Volatile gases, mainly methane, carbon dioxide, and water froze into ices.

"Within around fifty million years after the formation of the first condensates," writes cosmo-chemist Timothy Gregory, "the Solar System had run out of planetary building blocks. The era of planetary formation was over. From a common origin, the stories of the eight planets --four rocky worlds and four gaseous worlds --and the myriad of moons and smaller worlds diverged, and each followed their own unique path into the deep future."

The outer planets --Jupiter, Saturn, Uranus, and Neptune—became gas giants composed almost exclusively of hydrogen and helium. Within them, writes planetary geologist Robert Hazen, there are "no solid surfaces, just an ever-thickening atmosphere the deeper you go." In contrast, the four inner planets are terrestrial, composed of the "coarser, mineral-rich grains of dust that remained closer to the hot central star quickly clumped together to form the rocky inner planets." They're missing most of the primordial gas because the early, more intense, solar wind blew most of this mass out to the distant realms of our solar system before Earth's magnetic field switched on.

The cosmic cleanup was nearly perfect, except for two exceptions. The rocky leftovers formed the asteroid belt, whose combined mass is only a hundredth that of our smallest planet, Mercury, never congealed. The more ice-rich leftover planetesimals of the outer solar system became comets with highly elliptical orbits that take them great distances from the sun, before bringing them back close in. The tails of comets are the visible trails of ices being vaporized in our high atmosphere.

Planet Earth was born with the other terrestrial planets 4.568 billion years ago. Everything on earth, including its 60 thousand known meteorites, is that age or younger, except for a few tiny grains of truly cosmic star dust about 7 billion years old that comes from somewhere far, far away.

To say that we live on the third rock from the sun -- Mercury, Mars, Earth, and then Venus—exaggerates our solidity. Except for the egg-like shell rigidity of the lithosphere and its solid iron core. Most of Earth is squishy enough to blob out at the equator and to circulate in continuous motion.

For me, one of the most fascinating things about earth history is that it's oldest rocks are half a billion years *younger* than planetary formation. That time-gap is aptly called the Hadean Eon, named after Hades, the god of Hell. An Eon is the largest subdivision of geological time, not to be confused with its smaller subdivisions of Eras, Periods, Epochs, and Ages. Earth's earliest rocks are missing because its surface was either continuously or intermittently molten, preventing their crystallization. So, to understand Earth's first half-billion years, we have to look to the moon and meteorites, which, being smaller, froze into permanent rock much earlier. Four hundred known meteorites have been splashed here from the moon. And a few came from the Mars.

Meteorites are highly variable. The three main types are: stony, iron, and stony-irons. Earth's creation story is best told by a class of stony iron meteorites called ***achondrites.*** These are fragments of previously molten planetary embryos that are layered like the Earth, with a stony outer crust, a darker stony mantle, and a metal core consisting chiefly of iron.

Iron Core

At Earth's center is its inner core, a solid metal ball, an alloy of mostly iron with some nickel and other metals. We know it's solid and dense because seismic pressure waves whiz right through it, and because that phase of matter is required by the physics of heat and pressure. We don't know the chemical details of the core because sampling it lies far beyond technical know-how, the outermost core being no closer than five hundred times deeper than our deepest borehole and with a temperature of about 5000 °C, similar to that of the sun. Our best guess at what it's made of comes from the study of achondrite meteorites, which contain fragments of other planetary cores.

The main heat sources responsible for melting the early Earth are: the ***conversion*** of kinetic to thermal energy during meteorite impacts, the radioactive ***fission*** of naturally occurring radioactive isotopes on the ^{238}U to ^{206}Pb decay series, and the ***friction*** of what were then colossal tides. As the homogenous mass of the proto-Earth began to melt, different fractions either sunk down or floated upward to create concentric layers. I imagine liquid iron dribbling and seeping downward through the silicate mush of Earth's nascent mantle. I imagine volatile gasses bubbling upward and steaming outward to create Earth's atmosphere, then composed mainly of hydrogen, nitrogen, carbon, and oxygen.

The highest pressure within that original liquid core lay at the exact center. At some tipping point of cooling history, probably only about half a billion years ago, molten iron began to crystallize into a something resembling stainless steel. Since then, the solid inner core has been growing slowly outward at the expense of the still-molten outer core. That deep process ultimately manifests itself as surface volcanoes. [46]

For four straight winters I lived in Fairbanks Alaska just south of the Arctic Circle. The nightly displays of the aurora borealis, or northern lights, more than compensated for the bitter cold. Shimmering ribbons, curtains, swirls, rays, and pulsations of fluorescent lights danced from horizon to horizon against a backdrop of stars. The lights come from ionization of the upper atmosphere as Earth's magnetic field guided the solar wind toward the pole, a stream of electrically charged particles that intensifies during solar flares-- Seeing the auroral displays swirl is a visceral visual proof of the earth's constant spin and the liquid iron that our magnetic field.

Slight surpluses of heat flow at the top of the solid core set up rising convection cells of molten metal at the base of the outer core that are constantly being swirled by Earth's Coriolis force. Localized differences in heat come from differences in the rate of crystallization. Speeding up the convection are rising local concentrations of lighter elements like oxygen and silicon that rise up from the solid core.

This liquid rising and swirling of an electrical conductor creates the dynamo that produces Earth's dipole magnetic field. Like a bar magnet, it's fairly stable. Unlike a bar magnetic, it's chaotically variable in direction and strength. In fact, every moment of each day has its own magnetic weather. The resulting magnetic climates have two prevailing modes: normal versus reversed polarity, in which the magnetic field lines reverse direction.

Without Earth's strong magnetic field the solar wind would have swept our atmosphere away toward Jupiter and beyond. The field also protects us from cosmic rays, making it a prerequisite for the origin of life at the surface.

An example of how our magnetic field protects us comes from a fascinating article by Alan Cooper and his colleagues involving the study of ancient trees from New Zealand. More specifically, the

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[46] Voosen, The Planet Inside, Science 31 Mar 2022.

chemical study of fossilized rings from the swamp [Kar'ee] ~~kauri~~ tree dating to about 42,000 years old. Based on precise measurements of the carbon 14 concentration in the rings, the team concludes that Earth's magnetic field weakened and began to reverse itself for a period of about 500 years before flipping back to normal. [47] With 75-95 percent more cosmic radiation striking the earth, the ozone layer thinned, which changed the heat balance, which changed the tropospheric circulation around the globe. This so-called Lechamps event revealed a clear underground link between Earth's interior magnetic climate and its exterior meteoric climate.

Were Earth's outer core visible, it would be blindingly white hot. The top boundary of the outer core is much more complex than its inner boundary because it's the meeting on two very dissimilar materials: liquid iron and silicate rock. The contrasts between them ---chemical, density and thermal-- are extreme. One consequence of this variability is an irregular topography with liquid mountains and rock valleys hundreds of kilometers high. Another consequence are liquids of unknown composition gathered at the interface like the brines excluded from sea ice when it freezes.

The summits of these liquid mountains, are locally hot. Above them, volcanic superplumes drip upward like lava lamps of molten silicate all the way through the earth's mantle to penetrate its crust and leak out into the atmosphere. At times, they release staggering quantities of carbon dioxide in the atmosphere.

Mantle

You're probably familiar with solids that are soft when warm, like beeswax, tar, taffy or caramel. These can be bent and stretched and squashed without breaking or rupturing them, and they retain the deformed shape when the forces abate. These are ductile, or plastic solids. Earth's mantle is similar in behavior, but very different in composition. It's dominated by two groups of silicate minerals with lots of iron and magnesium: bottle-green olivine and green-black pyroxene. With a mass of 4.01×10^{24} kilograms, the mantle comprises two thirds of Earth's mass and 85 percent of its volume.

The dark, soft mantle floats like a concentric cork above the much denser liquid core. In relative position it's analogous to the white of a large egg above the yolk-core, and beneath the shell-crust. Knowing what the mantle is made of has been an enormous challenge because nobody's ever been able to go down there to sample it. Most of what we know comes from geochemical theory, geophysical data, and fragments called xenoliths that exploded upward during ancient violent volcanic eruptions so fast they brought up diamonds. Upward velocities of up to 1,300 miles per hour have been suggested. Only recently have we learned that the mantle is dominated by something called *bridgmanite*, Earth's most common mineral, which probably makes up an estimated 93 of the lower mantle.[48]

Earth's water came from the mantle during Hadean Eon differentiation. For years, it was thought that its original source of Earth's water were late-arriving comets and carbonaceous chondrites from the outer solar system. Recent work shows that that most of Earth's water likely came from the meteorites and planetesimals from the inner solar system. It's estimated that enough water remains in the mantle to fill Earth's present oceans three times over.

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[47] Cooper et al, 2021, A global environmental crisis...

[48] [Tschauner et al, 2017]

The outermost mantle is too cold to move like taffy. Instead it forms the rigid lower part of every tectonic plate, and is known as lithospheric mantle. Above that lithospheric mantle is the Earth's crust, which is dominated by the less-dense, more silica-rich minerals we're familar with. It averages about 35-40 kilometers thick below the continents and about 5 kilometers thick below oceans.

Given the vast bulk of the mantle, the relentless decay of widely scattered radioactive elements adds copious amounts of heat. Though the mantle is hot enough to melt at Earth's surface, it remains solid at depth owing to intense confining pressure. In the aesthenosphere, or upper mantle, it flows easily and slowly like stiff tar. Thermal differences set up by deeper events drive grand convective patterns where the hotter portions rise upward toward the surface, cool as they move sideways, and, when cold enough, sink back down. Such convection is the same basic mechanism that occurs in the Earth's troposphere at much faster rates, where hot air rises, moves sideways, and sinks back down to the surface.

These slow motions within the hot plastic aesthenosphere generally. but not exactly, align with the tectonic movements of the rigid slabs of lithospheric mantle. Some of the movement is caused by gravitational ***pulling*** where cold oceanic crust is sinking back down into the mantle, pulling the plate from the end. ome is caused by gravitational ***pushing***, where continuous collapse of the warm, elevated submarine ridges pushes the plate from behind. Finally, there is the horizontal ***flow*** of the plate at the top of a convective cell, where basal drag may also be occurring.

On the plates, the continents travel like enormous containers on even more enormous container ships sailing over the plastic sea of the aesthenosphere. These are the horizontal motions that re-arrange and randomize the continents relative to one another, and buckle and bend the boundaries between them to create mountain ranges and lowlands.

One climatic consequence of this is chemical, rather than physical: the burial and release of organic carbon and limestone carbon in sedimentary basins and their subsequent uplift and exposure. Another is volcanism, both at the mid-ocean spreading centers and the convergent boundaries where plates collide. At geological time scales, geothermal heat flow from the deep interior is the ultimate force behind climate change.

12 - VOLATILE EARTH - 2673

TAKEAWAY

Earth's atmosphere consists of the volatile gasses that boiled out of the infant Earth, were massive enough to be retained by gravity, and were sheltered from being blown away by our magnetic field.

KEY POINTS

The Lake Nyos disaster in Cameroon, West Africa, where thousands were suffocated by an invisible flow of carbon dioxide, dramatically reveals that this common volcanic gas us continuously seeping from volcanic terrains.

Earth's Big Thwack occurred when a Mars-sized planetary embryo struck earth with a glancing blow to create the moon, set the original spin rate, and tilt the axis of that spin. These phenomena continue to exert strong influence on earthly climates today.

Earth's original atmosphere consists of the volatiles that volcanically degassed from its bulky interior during wholescale melting. These include nitrogen, hydrogen, helium, argon, water vapor, carbon dioxide, methane, carbon monoxide, hydrogen sulfide, and others.

Earth's water ocean condensed from clouds after its magma ocean froze into the volcanic rock basalt and cooled below the boiling point of water.

Earth escaped the super-greenhouse fate of Venus when its carbon dioxide precipitated into carbonate rock, mainly limestone.

SCRIPT AND TEXT

Pause.....

Episode 12 - Volatile Earth

Pause ......

Welcome to Climate Underground

I'm your host, Robert Thorson

Thanks for joining us.

Pause

Lake Nyos

All was well at Lake Nyos in northwest Cameroon, Africa on the morning of August 21, 1986. Moments later, nearly 1700 African villagers and twice that many livestock were gasping to death as they were suffocated by an invisible killer. This sad scene was initially a mystery. After days of investigation, however, the culprit was clearly identified -- a quickly moving volcanic flow, not of lava or ash, but of carbon dioxide, an invisible volcanic gas.

Lake Nyos is a type of volcanic crater lake known as a ***maar,*** created when copious water and hot lava exploded together in in a flash of steam about 12,000 years ago. The empty crater quickly filled with a lake nearly 2 kilometers across and over 208 meters deep. Millennia later, three villages of rural agriculturalists occupied land above what scientists would later declare to be an extinct, and therefore non-threatening, volcano.

Triggered by something, perhaps a small landslide, as much as 1.2 cubic kilometers (0.29 cubic miles) of gas that had been dissolved in deep water was released in a chain reaction that created a fountain of fizz up to 100 m high, the same stuff that spurts from a bottle of seltzer or champagne. A few of the villagers from nearby ***Cha*** may have heard a background rumble, but otherwise everything seemed quiet It wasn't. An invisible cloud of heavier-than-air CO_2 thickened above the lake, overtopped a low dam, and noiselessly flowed down the valleys, hugging the ground and lifting the normal air up like a fast-moving weather front. Suddenly, there was no oxygen to breathe.

Here's what happened. A slow degassing of the remnant magma chamber at depth allowed carbon dioxide to dissolve in the cold water occupying much of the deep lake. Eventually, the water became saturated with CO_2. A small triggering event caused some of the saturated water to rise, lowering the water pressure, which created myriad small bubbles. This lowered the bulk density of the water, causing it to rise upward. This process accelerated toward the surface until the whole lake effervesced like a shaken bottle of champagne. Later, when the oxygenated air returned, iron that had been dissolved in the water rusted to the color of terra-cotta. Clay- -and colloid-sized particles of rust then sank to the lake bottom in a small-scale replay of what happened to the global ocean during the Great Oxidation Event about 2.4 billion years ago.

I tell this story to drive home two points frequently overlooked by school Earth Science curricula. First, Earth's atmosphere originally came from below as a similar exhalation of Vulcan during the Big Melt. Second, though we are mesmerized by visual spectacle and astonishing power of infrequent volcanic eruptions, their most important legacy for climate change is the way they invisibly change the atmosphere the background of our lives. The two most common volcanic gases, water vapor and carbon dioxide, are also the two most important for climate change at the century scale and beyond.

Theia (pronounced ThayAhh or TayAH

We've had the Big Bang and the Big Melt. Now it time for the Big ***Thwack.*** That's what planetary scientists call the powerful collision between the newborn Earth and a Mars-sized asteroid so big that they call it a planetary embryo instead. The ***thwacker*** was named [Thay'-Ahh] ~~*Theia*~~ after one of the GreekTitans, daughter of the union between the Gaia, goddess of Earth, and Uranus, god of the sky. The ***thwacking*** took place about 4.5 billion years, near the final stages of Earth's Big Melt. The result gave birth to our moon and gave Earth's a spin, tilt, and wobble.

Theia struck Earth with a blow that was ***direct*** enough to remelt both objects, adding a final ten percent to Earth's mass. Two super-dense concentrations of mass at the base of the mantle, each the size of a continent, may be remnants of Theia that escaped being mixed in.[49] The blow was ***glancing*** enough to create a spray of vaporized silicates that condensed into an encircling cloud of hot magma that quickly congealed and cooled to form our igneous moon. Some of Earth's early atmosphere was likely lost at this time.

The thwack occurred after Earth's mantle had differentiated and was covered by a molten magma ocean. This explains why the bulk of the lunar surface is covered by basalts with a composition similar to those rising up from Earth's mantle above hot spots. The 842 pounds of moon rocks we've studied prove this point. A post-differentiation thwack also explains why the moon has such a tiny iron core, comprising only three percent of its weight, a tenth of what would be expected from a duplicate Earth.

Theia's blow was ***potent*** enough to give the infant Earth a much more rapid spin, estimated to have originally been many times faster than today's. Earth's spin is responsible for the whirls and spins of earthly fluids, ranging in scale from oceanic gyres, air masses over land, cyclones, tornadoes, whirlpools, and dust-devils. Her thwack also pushed Earth's axis of rotation out of alignment to more than 20 degrees off kilter. Had this ***not*** happened, Earth would be without seasons, and therefore without seasonal climates, and therefore with much lower biodiversity. We're lucky to have not been the planet Uranus, which got thacked on its side, or Venus, which was thwacked to spin in the opposite direction.

Because *La Luna* revolves the earth, it's technically a moon. But in terms of mass, it's huge relative to other moons in the solar system, making it more like a sister planet. Earth and Moon revolve the sun like a dancing couple circling a ballroom. Their common center of gravity, called its barycenter, is located within Earth's mantle about 4671 kilometers out from its center.

When born, the moon orbited the earth so closely that the broiling radiant heat from the still-molten Earth may have kept the moon's near side molten while the far side crystallized. Though the moon's ***actual*** diameter of 2160 miles hasn't changed since then, it's ***apparent*** diameter when seen from Earth has become much smaller. One estimate is that the moon was once 250 times wider than at present, eight times wider than the setting sun of today. Being so close, the moon revolved the Earth about seven times faster, making each month just a few days long. And being so close, the tidal force of the moon pulling on the earth was enormous, creating tides in the original magma ocean upward perhaps a mile or more.

In color, both Earth and its moon were originally blackened spheres, the color of freshly cooled Hawaiian or Icelandic lavas. Breaking both surfaces were red-hot cracks, through which gushed magma fountains. Subsequent shades of gray on the moon reflect the powdered dust of meteorite impacts and cosmic weathering. Lacking a strong magnetic field, whatever atmosphere the moon once had was quickly blown away by the solar wind, or gathered as ice on the dark side of the moon. Being large enough for a magnetic field, Earth kept its atmosphere, without which there woud be no climates at all.

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[49] Voosen, 2021, Remains of Moon-forming...

Theia was not the last great collision. Both the moon and earth were heavily bombarded with asteroids until about 3.8 billion years ago, after which the cosmic cleanup was largely complete. Some impacts may have been large enough to remelt the Earth completely, returning its surface back to a universal magma ocean and extinguishing any life that might have been.

Volatiles - Air

Earth's atmosphere is no more, and no less, an essential part of the whole system than its core or mantle. And it came from the same underground, an originally homogenous place. By mass, the modern atmosphere is a trivial part of the planet, being only one ten-thousandth of a percent (0.0001%) of the total. By significance, however, it's an outsized player in the system because it chemically reacts with every square inch of the surface, and is powerfully energized by the sun.

The planetesimals from which Earth was made were too small and too unprotected to retain atmospheres this close to the sun. This means that Earth's atmosphere arose by volcanic outgassing. Billions of tons of nitrogen, hydrogen, helium, argon, water vapor, carbon dioxide, methane, carbon monoxide, hydrogen sulfide, and other gases would have vented outward every day during differentiation, a chemical composition that reflects the original chondrules and ices of the solar nebulae. However, Earth's carbon content is only one thirtieth that of the primitive chondrites from which it came, being less than one tenth of one percent (0.1) of Earth's bulk mass. Water is also much scarcer than expected. In both cases, the missing inventory was either lost to space after outgassing or remains undetected deep within the Earth interior

Earth's ***first*** atmosphere was its hottest and darkest. The planet was fully molten with no solid crust. Lava fountains from violent volcanic eruptions and splashes from incoming asteroids created an atmosphere so hot that drops and droplets of molten rock fell back to the surface from which they came.

Earth's ***second*** atmosphere remained hot, with pitch black skies dimly lit by streaks of incoming meteors, and flashes of lightning. This was a much denser, much more turbulent atmosphere that was devoid of oxygen and consisted mostly of carbon dioxide, water vapor, nitrogen, methane and organic molecules including cyanide. All of these except nitrogen easily enter chemical reactions. Water vapor, would later precipitate to become the global ocean. With liquid water, carbon dioxide could then precipitate to become limestone. Hydrogen compounds could gather to become organic matter. But the molecular nitrogen (N_2) couldn't do much because it's mostly chemically inert. So it remained. When the wind blows today, eighty percent of its strength is due to this unreactive gas.

Black Crust

Before any solid crust formed on Earth it was covered by a deep ***magma*** ocean of liquid rock. It's chemical composition was similar to that of lithospheric mantle today, a coarse-grained rock called peridotite. As that ocean cooled from the top down, glazes of solid crust formed on the surface, a rock called *komatite*. Being denser than its parent liquid, however, these crusts sank to remelt at depth. Minerals richer in iron and magnesium had the highest melting temperatures, so they began to crystalize and sink in a gradual process called fractional crystallization. This left behind a slightly less-dense magma richer in silica that crystallized into a rock called *basalt*, which was light enough to float. Earth finally had a solid surface floating above magma like lake ice in winter. Basalt is Earth's most common rock, the stuff from which moon rocks, shield volcanoes, oceanic crust, and floods of lava are made.

If you keep fractional crystallization going ***long enough*** inside a magma chamber ***big enough***, all of the heavy minerals like olivine and pyroxene settle out. These magmas became so silica rich that they crystallize into lighter-colored rocks rich in feldspars and quartz, creating granites and related rocks. Being less dense, this granitic slag floated higher than the basalt of the oceanic crust. Once formed, it couldn't sink or be thrust back down into the mantle in any appreciable quantity. This is the stuff from which continental crust was made, mostly during the Archaean Eon of Earth history prior to 2.5 billion years ago.

The oldest of these silica-rich continental rocks occur in the Great Bear Lake region of Northwest Territories, Canada. Known as the Acasta Gneiss, they are 4.0 billion years old, younger by half a billion years than the earth itself.

Global Ocean

At some point, Earth's surface cooled down to the tipping point where water vapor could condense into visible droplets to form clouds. This created a bank of stratus clouds so dense and thick that light from the sun couldn't penetrate down to the still-hot surface. As with Venus today, rainfall was continuous, lighting was constant, and turbulent storms were intense. Drops falling too low, however, would quickly steam back into vapor. Then came a second tipping point when a drop of liquid rain splashed on the black crust and skittered as if on a hot skillet before disappearing back to vapor. This local evaporation rapidly drew heat away from the surface. Finally, there came a third tipping point when a drop lasted long enough on the warm basalt to be joined by another, and another, and so forth to create a global ocean.

Earth remained like a sauna for quite a while. As fractures opened up in the thin crust beneath the deepening oceans, or as new volcanoes were born, the surface water would have locally boiled back to steam to fill the air with billowing clouds similar to those we can see today when molten lava reaches the sea.

Eventually, the global ocean rained itself out of the sky. The end result was a continuous film of distilled water that today weighs less of one fifth of one percent of Earth's mass. It wasn't yet salty because there were no continents to weather that salt from. It was deeper than at present because there was probably more water to be held. It's possible that there were no islands of land, though it's more likely that some volcanoes stood above the sea.[50]

As Earth's mantle cooled, some of Earth's water became trapped within it. At a depth between 250 and 400 kilometers is a transition zone in the mantle. In that zone is a common mineral called Wadsleyite containing up to 3 percent water by mass. Within this zone is enough water to fill 9 modern oceans. Because a hotter mantle can hold less water, it's very likely that Earth's original global ocean was at least twice as deep, a conclusion supported independently by evidence from chondrite meteorites.

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[50] Voosen, 2021, Ancient Earth was a water world...

Some of earth's early water was also lost to space as the gain of water from water-rich asteroids diminished. Volcanic shields and cones began to poke their way into the sulfurous air. Eventually, there were thousands of steaming and lifeless islands with rubbly black beaches dotting the sea under hazy skies.

Earth's global ocean is the oldest feature on Earth. Our earliest date for it is 4.404 billion years. The evidence comes from a sandstone outcrop in Jack Hills Australia that contains a sand grain composed of the resistant mineral zircon. Within that grain is an inclusion with oxygen isotopes indicating the presence of liquid water at a temperature 90° C (200° F. This is only slightly below its boiling point. Earth's earliest water ocean was as hot as a simmering soup.

This liquid water saved our planet from the climate fate of our twin planet Venus, whose atmosphere is about 95 percent CO_2 by weight. Our atmosphere, in contrast, contains only about 0.04 percent CO_2 by weight. The difference is due to rainfall. Earth's raindrops were able to dissolve carbon dioxide from the atmosphere to produce carbonic acid, which was able to leach calcium ions from the basalt crust. When these ions were combined in the sea, they were able to precipitate the common carbonate mineral, calcite, the dominant constituent of limestone. The equation: ***carbon + water + basalt = limestone*** is the same one being used today by carbon sequestration startup companies like *Climeworks*, which I contribute to.

Much of Earth's original atmosphere was transformed into other things. It's water vapor precipitated as the ocean. It's carbon dioxide precipitated as limestone. Its organic gasses remained as a haze. It's molecular nitrogen (N_2) couldn't precipitate because this gas is fairly inert. Molecular oxygen would be delayed for another billion years to the time when photosynthesis kicked into high gear.

The Future

Earth is often called a Goldilocks planet, orbiting just the right distance from the sun to allow liquid water, the most fundamental requirement for life, to be continuously present. Were Earth closer to the sun, it would be too hot, and the solar wind too strong. Were it further out Earth would freeze solid like modern Mars. Our "just right" condition has been maintained for the last four billion years, even as Earth has been steadily cooling down from its fiery origin, and even as our sun has been steadily warming up as a predictable consequence of being a main sequence star. Barring a few hot and cold climate hiccups, this "just right" condition has been maintained at the billion year scale by a negative feedback mechanism involving carbon dioxide. The steadily warming sun has been offset by a steadily weakening greenhouse.

But nothing lasts forever. As the sun continues to warm, the carbon concentration of Earth's atmosphere will continue to drop. At some point, estimated to be between 500 and 800 million years from now, there will be too little carbon dioxide for photosynthesis, ending the primary production on which all animal life depends. The death will not be from climate, but from carbon starvation. That's an odd thought for a world concerned about a carbon excess.

Moving further out in time, when the sun eventually begins to run out of hydrogen fuel, and begins to burn more helium, the outward thermal expansion pressure will begin to exceed the inward gravitational pressure, causing the sun's corona to expand.

El Sol will swell to become a pulsating red giant whose corona will engulf the Earth. All of earth's atmosphere will vaporize and burn away. If the outward stellar pressure is high enough, it may push our planetary cinder out into the empty iciness of outer space.

This will be the most dramatic climate change for Earth that I can imagine.

13 - RUNNING THE SHOW - 3042

TAKEAWAY

The three great physical forces of gravity, centrifugal force, and geothermal heat operate from Earth's center, and create the climates powered by the sun.

KEY POINTS

Gravity runs the convective circulation that drives the electrical dynamo in Earth's outer core, the tectonics of its mantle, and the weather of its troposphere.

Centrifugal force runs the: orbits of Earth and moon, the spin of the earth, and flattens our sphere to a spheroid. The resulting Coriolis force acts on atmospheric and oceanic currents spanning five orders of magnitude from the equatorial Trade Winds to dust devils.

The flow of heat from hot to cold is the third great force. It powers the magnetic field that keeps the atmosphere here and the plate tectonics that locates our climates and exhales volcanic gas.

These three forces created the places and terrains on which sunlight falls. There, the solar-powered biogeochemistry of life circulates the volatiles our atmosphere is made of.

Cyclical climate change at a range of time scales arises from the revolutions, tiltings, and wobbles of our spinning earth.

SCRIPT AND TEXT

Pause.....

Episode 13 - Running the Show

Pause ......

Welcome to Climate Underground

I'm your host, Robert Thorson

Thanks for joining us.

Pause

Bathroom Scale

When you step on a bathroom scale to measure your weight, you create a vector force, meaning one with magnitude ***and*** direction. We pay lots of attention to the *magnitude*, the number of the scale, the strength of the gravitational attraction between the mass of your body and that of the Earth. We take for granted the *direction* of that force, in this this case pointing straight down toward Earth's center more than six thousand kilometers beneath your body. If you walked to the nearest coffee shop, the direction of that force would change slightly, but the place it's pointing toward would not. If you ascended in an elevator, the magnitude of that force would change, but it's direction would not. Earth's sweet spot is command central for all things gravitational.

When you step on a spinning carousel or playground merry-go-round, you feel a different force, an outward-directed ***centrifugal*** force. Move in toward the center and you'll feel the magnitude of that force diminish. The same changes happens on our spinning Earth. The further away you are from its center, the stronger the centrifugal force. At Earth's center, the force falls to zero. Earth's sweet spot is command central or all things centrifugal such as its spins, wobbles and tilts.

When you stand in front of a campfire, you feel the heat of thermal radiation. The closer you get, the hotter it feels. Circling the fire at the same distance, the heat feels the same. This same physics applies to Earth's heat. It's hottest and steadiest at the center of its metal core where the temperature is estimated as close to 5000 degrees Celsius or 9,400ºF, perhaps exceeding that of the sun. Within the earth, heat is always flowing ***upward*** and ***outward*** at a diminishing rate to a value close to that of the mean annual temperature. The gradient of that temperature change, the geotherm, is fairly low within Earth's great bulk, and much faster within the crust. Earth's sweet spot is central command for all things geothermal.

These three great forces --gravity, centrifugal, and thermal-- are the ultimate drivers for Earth's many climates. All three arise from the same sweet spot: the center of mass, the origin of rotation, and the highest temperature. All gradients point upward and outward from the geocentric frame of reference. We can't go there physically because our bodies would be instantly annihilated. But we can go there in our minds as a thought experiment.

Earth's sweet spot is the only place on Earth where nothing changes except for the occasional radioactive disintegration. It seems as if time and space were locked away in an enormous spherical metal vault. At the center, there are no material differences, no motions, and no histories. Just a superhot dot that will eventually cool down to the ambient temperature of empty space, the last place on Earth to do so.

Above its sweet spot, Earth is a series of concentric spheres that enlarge in surface area and decrease in curvature all the way out to the edge of space. From that center, a ray pointing outward in any direction travels through pretty much the same thing for 99.5% of the distance until you get to a depth of about -35 km, the average to the base of Earth's continental crust. Between that depth and +13 km, the average height of the troposphere, Earth is much more heterogeneous in material, elevation, and behavior. It's solid outer crust is greatly differentiated. There are patches of ice here and there. It's film of liquid water is discontinuous. It's film of rooted vegetation is sporadic. And though the veil of its atmosphere is continuous, it's in constant flux.

Earth's surface topography spans only about three tenths of one percent (0.3) of this radial distance, 20 km in all. The range is from about +9,000 meters for Mount Everest to -11,000 meters for the Challenger Deep of the Marianas Trench. Earth's lower atmosphere, the troposphere, spans about half this radial distance.

Earth's weather manifests mainly as horizontal movements. We forget that blowing winds and traveling weather fronts are ultimately driven by vertically directed gravitational forces targeting Earth's center. Cold air is pulled more strongly downward than warm air. When it meets solid land, that descending air spreads out like an underflow, pushing the warmer, usually moister, air upwards to make rain. The physics is broadly similar to the downward pull of cold ocean water spreading outward as marine currents, pushing warmer water upward.

The meteorological weather of our troposphere, the magnetic weather of our outer core, and the liquid weather of our ocean are all driven by thermal convection, a meta-process that involves all three of these great forces acting on fluids: gravity, centrifugal, and thermal. The same three forces also drive the tectonic weather of our mantle, but at much, much slower rates because the convection occurs within a plastic solid, rather than a true fluid.

Three Forces

The first great force is the *gravity,* the relentless inward pull of everything downward toward the center of our planet. Without this gravity, our atmosphere would have drifted off into space, as it did on the moon. And without an atmosphere, there would be no climate to make from the underground.

Earth's gravity is a relentless force between two objects. The magnitude of that force on Earth depends directly on mass of the other object in consideration, and inversely on the square of its distance from Earth's center. A mountain is pulled more strongly than a feather at the same average distance because it is more massive. A fist-sized stone at the top of that mountain is pulled less strongly than a stone of the same size in the valley below because it is further away from Earth's center. Salty water us pulled more strongly than freshwater. A molecule of carbon dioxide is pulled too weakly to come to rest on the soil, but too strongly for it to escape to empty space.

Niagara Falls provides a good example of an earthly gravitational process. As the Niagara river leaves Lake Erie, it flows northward down the Niagara River because every downstream inch brings it closer to the center of the earth. When it flows over the Niagara escarpment, a cliff of dolomite, the water's forward momentum gives it an outward curve that quickly disappears. From that point on, the flow is straight down toward Earth's iron core. When the water hits the plunge pool below, it re-organizes to become a river again, relentlessly seeking Earth's core.

The pair of Great Lakes bracketing Niagara Falls also prove that the force of gravity is straight down. Lake Erie and Ontario have nearly horizontal surfaces because that direction is perpendicular to the gravity vector. Any differences in elevation are due to local details associated with the inlet and outlet, tides, and transient weather-related effects.

Rock, when warm enough and soft enough, follows the same gravitational rule as water. When mountains get too massive, gravity pulls down on them so strongly that the hotter, softer, lower-crust gives way and flows plastically sideways, carrying the upper crust along for the ride. The Himalayas have reached that upper limit. To the east, southeast Asia is being squeezed and sheared away from the continental collision. To the west, the same is true for Pakistan. The maximum height of mountains on Earth is limited more by the ability of the crust to support that weight than by the tectonic forces lifting them up.

Gravity is also responsible for earth's tides. The rise and fall of the sea against the shore is an illusion. What's really taking place is the combined gravitational pull of the moon and sun create a stationary bulge on the ocean. When the edge of a continent rotates into and out of that bulge, the tide appears to rise and fall. Each place on Earth's surface modifies this effect in its own way to amplify or diminish the tide. Each place has its own tidal climate.

The crushing gravity of the sun's great mass is what keeps its nuclear fires burning. When the inward pull of solar gravity falls below that of the outward push of nuclear fusion, the sun's corona will expand outward to engulf our planet, vaporizing our atmosphere, and ending climate history.

The second great force is the *centrifugal* force associated with Earth as a planet -- its relentless outward pull caused by Earth's orbit around the sun, its rotation around a spin axis, the wobble of that spin axis around a fixed frame of reference, and the orbit of the moon. Centrifugal force is the mathematical product of three terms, the mass of a rotating object, its radial distance away from the center of rotation, and the square of its angular velocity. The bigger something is, the further out something is, and the faster something is rotating, the greater the centrifugal force. When figure skaters extend their limbs outward, their speed of rotation slows down to compensate for the greater radius.

Like all orbits, Earth's orbit around the sun is a steady-state balance between the gravitational force pulling earth toward the sun and the centrifugal force pushing it outward away from the sun. The result is a dead heat of distance, as if Earth were tethered to a string. If the sun's gravity were to instantly cease, its planets would fly off in parallel straight lines into outer space like a flock of geese flying side by side. If the *centrifugal* force were to instantly cease, Earth would plummet straight down into the solar fire.

Earth's climates are profoundly influenced by the balance between gravitational and centrifugal forces. Recall that the speed of Earth's spin, the tilt of the its axis of rotation, and the wobble of that axis around a fixed point in space were all started by the Great Thwack, the moon-forming collision of a Mars-sized planetary embryo and a newborn Earth.

Let's start with Earth's spin rate, which controls the length of its days. Recall that the sun does not actually rise and set. Instead, every spot on the surface is constantly rotating into and out of the shadow of the sun to create what we call day and night. Earth's days were initially very short, probably only 6 hours long. The moon, being very close, spanned much of the sky and set up enormous tides, first on Earth's magma ocean, and then on its water ocean. Since then, tidal friction has gradually slowed down Earth's rotation rate. To conserve angular momentum, the moon has migrated further away to its present distance.

An extraordinary new paper in *Science* paper suggests that the slowdown in the Earth's spin wasn't gradual, but was instead punctuated by reconfigurations elsewhere in the solar system.[51] In the early Archean about 3.5 billion years ago, the day length was about 14 hours. It then increased gradually until 2.4 billion to a day length of about 21 hours. After holding constant for about billion years, during the last 0.7 billion years, the day length again began to increase to the present value. Remarkably, these two ***slowdowns*** in earth's spin about 2.4 and 0.7 billion years ago coincide with abrupt ***jumps*** in the abundance of atmospheric oxygen, the exhaust gas of photosynthesis from cyanobacteria. The first jump transformed planetary chemistry everywhere at the surface, clearing the sea of dissolved iron and rusting the land with brown soils. The second jump set the stage for complex multicellular life. Essentially, the speed of Earth's spin was a fundamental control on the chemical composition of the earth's atmosphere, from which climate arises.

If Earth had the density of a marshmallow, the angular momentum of its spin would be trivial. As with the moon, one side would likely continuously face the sun, locked a permanent gravitational embrace. With no spin, there would be no Coriolus force, no spinning fluids, and thus no climates as we know them today.

The angular velocity of Earth's steady spin is greatest at the equator and least at the poles. Because the bulk of its volume is the dough-soft mantle, these differences centrifugal force bulge Earth outward at the equator and flatten it at the poles. The result is a flattened sphere called an oblate spheroid with a radius 13 km wider at the equator. Owing to this effect, large, low-gradient rivers flowing toward the equator actually flow slightly uphill relative to the sweet spot at earth's center. Being flattened at the poles also exaggerates Earth's seasonality. Sometimes, is fun for me to imagine Earth spinning so fast that it assumed the shape of a disk. Think how weird our climates would be then.

Climatically, the most significant result of Earth's spin is the Coriolus Force. From the geocentric frame of reference, objects moving on Earth's surface move in a straight line. From a surface frame of reference, however, objects moving in the northern hemisphere appear to be steered to the right, and those in the southern hemisphere to the left. This steering is as relentless as the inertial spin causing it, creating spirals in earth's fluids ranging in scale over five orders of magnitude, from continents to dinner plates. In the atmosphere they are air masses, cyclones, tornadoes, whirlwinds, dust-devils, and swirling gusts. In the ocean they are gyres, currents, Ekman spirals, and whirlpools of all sizes. In the liquid core, they are the elongated vortexes giving rise to our magnetic field.

When the heliocentric model of Nicolas Copernicus replaced the geocentric model of Ptolemy, Earth's orbit was assumed to be perfectly circular. Kepler, and then Newton showed that its orbit was instead an ellipse, a geometric shape with two foci. The sun occupies one of these foci, meaning that it's off-center relative to the otherwise symmetrical orbit. Additionally, the shape of the ellipse oscillates at a regular rhythm of 100,000 years from being more spherical to less spherical, meaning from less eccentric to more eccentric.

This variation in eccentricity creates a mechanism for changing Earth's climate by enhancing and diminishing its seasonality with the regularity of a metronome. Recall that our seasons result from having a tilted planet revolve it's governing star. At the summer solstice, one hemisphere leans

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[51] Pennisi, 2021, Totally New Idea suggests....

directly toward the sun, maximizing daylight. At the winter solstice, it leans directly away, minimizing daylight. This sets up two midpoints when night and day are of equal duration, the vernal equinox when the days begin to lengthen, and the fall equinox when they begin to shorten.

This orbital theory of ice ages was initially proposed by James Croll in the 1860s and then rigorously improved and tested by Milutin Milankovich in the early 20th century. Interest was lost when there seemed to be no way to test it. This all changed in the 1970s, when I was a graduate student studying glacial geology. Refinements in isotopic analysis, combined with access to deep sea cores led to convincing proof of the orbital theory, especially at the roughly 40,000 and 20,000 year periodicities.

In one of the great achievements of climate science in the 20th century was to match the clockwork regularity of orbital parameters to the regular advances and retreats of Earth's ice sheets during the last million years, though one recent study suggests that the 100,000-years-beat is more apparent than real, and is instead the sum of other orbital influences at shorter time scales.[52]

The differences in radiation due to orbital changes are small, but apparently enough to trigger positive feedbacks in Earth's climate system into action -- the albedo effect during the growth of glaciers and the greenhouse effect during their retreat. These are the same two positive feedbacks that, one eon ago, sent Earth into and out of a deep-freeze called Snowball Earth.

Critical to this mechanism are two important facts. First, the bulk of Earth's land mass on which ice sheets might grow lies in the northern hemisphere between about 40° and 70° latitude, where cool temperate and subarctic conditions prevail today. Second, thermal melting of glaciers in the summer plays a greater role in their annual budgets than the snowfall accumulations in winter. Thus, times when the northern hemisphere summer receives more sunlight will be times when it deglaciates and vice versa. This is the main orbital pacemaker of ice ages.

Three other important orbital mechanisms also influence the amount of seasonal radiation received by northern hemisphere, and thus the climate.

Earth's tilt is known as its obliquity. From the sweet spot at its center, the northern and southern parts of that axis are currently tilted 23.4° away from vertical. But this tilt is not constant. In 1437, the great astronomer Ulugh Beg accurately measured a tilt of 23.3 degrees. Calculations show that Earth's obliquity has varied from 22.1 and 24.5 degrees during the last five million years with a mean periodicity of about 41,000 years. This tilt affects our climate by enhancing and diminishing Earth's seasonality independent of the oblateness of its doughy shape and the eccentricity of its solar orbit. When amplified by albedo and greenhouse feedbacks, these variations in tilt played an important role in regulating Earth's climate. In fact, obliquity was the dominant forcing agent during the first half of the Pleistocene ice age. During the last million years it's been co-dominant with the 100,000 year cycle, forcing higher-frequency advances and retreats within the larger cycles.

Earth's wobble is the third important orbital influence on Earth's climate. As earth spins on its tilted axis, that axis itself rotates in a circle against distant stars in the same way the spin axis of a gyroscope or top rotates around the fixed frame of reference on the ceiling of a room. Historically,

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[52] Science article.

this was first recognized in the second century B.C. by the Greek astronomer Hipparchus, who observed that the timing of the equinoxes was changing slightly against the backdrop of the stars. This wobble, called axial precession, when lumped with much smaller terms called planetary and lunisolar precession, has an average periodicity of 21,000 years. The timing of this precession either adds to, or subtracts from, the climatic influences of obliquity and eccentricity.

The third great force emanating from the center of the earth is heat. Earth's temperature reaches its maximum in its inner core. No one knows how hot it is, but calculations indicate it exceeds 5000°C. The three main sources of that heat are residual heat left over from planetary formation, radioactive heat from decay, and frictional heat, mainly from dynamic motions within the core and mantle owing to circulation and to tides.

The geothermal gradient in the core is very low because iron is an excellent conductor. At the core-mantle boundary, the temperature has diminished to about 3500 °C. The cooling gradient is steeper in the mantle, and very steep in the outer crust, where the gradient varies between about 20-30 °C per kilometer.

Working in the other direction, from familiar to unfamiliar, Earth's average surface temperature is about 15°C (59°F). In its deepest goldmine about 4 km below the surface the temperature is about 60°C or 149 °F. At the base of the crust about 35 kilometers down, the temperature rises to about 400-700°C.

Though the sun provides the ***energy*** for Earth's climate system, the system itself is mainly created by the three great forces of gravity, centrifugal, and heat emanating from the center of the Earth. These three forces work together in the troposphere, global ocean, mantle, and outer core to create the climates we know and love.

14 - CARBON UNDERGROUND - 3758

TAKEAWAY

The vast majority of carbon in circulation on Earth is stored underground as limestone and buried organic carbon in the form of coal, oil, and gas that is often tapped as fossil fuels.

KEY POINTS

Fossil fuels are organic remains that are dug up, pumped up, or vented up from earthly reservoirs to be burned for the energy of combustion. They are as natural as water.

Fossil fuels arise from three detours away from routine geological processes: organic matter must accumulate rather than decompose; that organic matter must be buried; and it must later be re-exposed naturally or by human contrivance.

Coal is the burial, dewatering, compaction, and chemical transformation of solid organic matter within sedimentary rock.

Natural gas, mostly methane, is produced by bacterial decomposition of organic matter. Pockets of gas trapped underground in reservoirs or fracked from black shales are the primary fuel sources.

Petroleum is a liquid oil that comes from the organic mud of a source rock, seeps upward until blocked as a trap rock, and accumulates in a porous reservoir rock called an oil field.

Limestone is an inorganic carbon-rich rock composed mainly of the mineral calcite, and precipitated mainly by marine organisms.

SCRIPT AND TEXT

Pause.....

Episode 14 - Carbon Underground

Pause ......

Welcome to Climate Underground

I'm your host, Robert Thorson

Thanks for joining us.

Pause

I bought my first car in 1969, an old, beat-up, gas-guzzling, Chevy Biscayne with a powerful V-8 engine, bench seats, and a stick-shift manual transmission. My love affair with that car lasted 2 years until I learned, in 1971, that my car's exhaust emissions were raising Earth's planetary temperature. So I junked my car, naively promised myself that I would never buy another, and bought a bicycle instead. Seven years later, I came to my senses, broke my promise and bought the first in a long series of purely functional family cars, all Volvo station wagons.

But with the kids now gone, I made a decision to avoid cars as much as possible, living a village lifestyle where I walk work and nearly everywhere else. Weeks go by without me getting in the car. I haven't flown in this millennia, except for two family emergencies.

Though modern culture is also beginning to move away from fossil fuels, our modern economies and lifestyles remain addicted to them, owing to their their energy density, portability, and price. Nowhere is this dependency more compelling than with international air travel and international shipping. It will be quite a while before overseas flights and ocean freighters go electric.

Fossil fuels are, by definition, the remains of ancient life. In the grand scheme of geological history, they are unusual, requiring a triple detour events. In the ***first*** detour, local geological circumstances must shunt oxygen away from organic matter so that it can accumulate instead of decompose. In the ***second*** detour, that organic matter must be locked away into some underground reservoir, usually a sedimentary basin created directly or indirectly by tectonic activity. ***Third***, that underground reservoir must later be exposed in some way, whether uplifted, or accessed by us going down to get it by mining or drilling.

The root word for fossil is *fossilis*, which means something dug up. Though the term originally applied to anything dug up like minerals, modern usage restricts the word to evidence of past life. The term groups all three phases of organic matter --solid, liquid, gas-- under the heading, *fossil fuel* because they share a common biological origin. Solid coal is ***dug*** up. Liquid petroleum is ***pumped*** up through drillholes Gas is a gas, ***leaked***, ***vented, pumped, or sucked*** up from drill holes and from underground fractures created by fracking. The label fossil fuel also stuck because it's alliterative, as with Dunkin Donuts, Seven Seas, M & Ms, Captain Crunch, and so forth. The journey of all fossil fuels consists of two steps: upward to the ground surface where we burn it, and upward to the atmosphere where we exhaust the waste gasses.

The story of fossil fuels begin with ancient life. Sunlight streamed to Earth during some past piece of earth history, perhaps the Carboniferous, a geological period named for its high carbon content, or the Cretaceous, during which the dinosaurs were far more famous that the organics accumulating throughout globe. As with photosynthesis today, photons of solar radiation were absorbed by the chloroplasts of plants. These photons, tiny quanta of energy, were used to take carbon from CO_2 in the air, combine it with hydrogen taken from soil H_2O to make a simple sugar called glucose. The waste gas from this process is molecular oxygen, O_2. From this sugary beginning, all of the more complex organic materials were then made; starches, lipids, fats, proteins, and so forth. From these compounds, plants made leaves, which were used to make more energy, which was used to make more complex things like wood, flowers, seeds, and cones. Ecologists call this creation of organic matter from inorganic raw materials *primary* production. In ecosystems, photosynthesis is like it's putting energy money in the bank.

The plant holds on to that organic matter until it dies or is eaten by something else. In terrestrial settings, some leaves are shed and some are consumed by all manner of herbivores who excrete the remainder to the ground. Within a geological microsecond, much of that organic tissue goes underground into the soil. There, a miniaturized ecosystem of bacteria, fungi, invertebrates and small vertebrates combines that organic matter with gaseous oxygen to release little jolts of energy, this time as electrons rather than photons. The waste gas from this process is carbon dioxide vented back to the air. Ecologists call these living things *consumers*. They spend the energy money put in the energy bank by producers.

The best global expression of this incorporation and release of carbon dioxide into and out of plant tissue are the annual ups and downs of the Keeling curve on Maun Loa. The carbon balance of the atmosphere in the northern hemisphere falls in spring and summer because that carbon is being used by producers to create organic matter. The carbon balance rises in the northern fall and winter when consumers burn that organic matter, which releases CO_2. Under normal circumstances, and during intervals of steady state, the carbon balance changes little. Some years there's a gain, big or small, and some years there's a loss, big or small. Over time, the trend of the curve stays flat because there's no net storage or loss of carbon.

This is where the first geological accident comes in. If the decomposition hemicycle is shut off for any reason, there's a net gain in organic matter, meaning a net gain in captured energy, as with a battery being recharged. Usually this gain in carbon requires that the oxygen supply be cut off, usually because the site is submerged in stagnant water. Any gain in organic matter will remain locked away from the atmosphere, reducing the carbon concentration until that organic matter is re-connected to an oxygen supply. Detour #1 is complete.

Fossil Fuels

My most intensive experience with coal was at the Usabelli Coal Mines of Healy Alaska. For several days during the summers of the mid 1970s I walked its badland gullies, counting seams of coal, and studying the sediments that lay above and below each. There, a package of sediment, clay, mud, gravel and coal several thousand feet thick and many miles long had been tipped northward in a single crustal block during the recent rise of the Alaska Range. Two big geological events were required: one to create the basin in which the sediments would accumulate, and another to uplift and expose it. Within the seams were abundant recognizable plant fossils, mainly moss, ferns , leaves, and wood. The same is true for coal seams every everywhere.

It's easy to understand the first step in making coal. Any swamp or marsh or bog will do. Poke a stick in deep enough and the rotten-egg odor of hydrogen sulfide will likely waft up, confirming the absence of oxygen at depth. Whatever organic material fell into the water and remained undecomposed is the raw material. In normal circumstances, only a small accumulation takes place, one that's easily reversed if the local area became drained. But in order to accumulate of lots of organic matter, a second detour has to take place. We need a sedimentary basin.

Geology is full of tectonic sags, rifts, and down-warped depressions for coal to accumulate. Chief among these, and most important for fossil fuel recovery of all sorts, are *foreland basins*. They occur when relatively undisturbed crust beyond a growing mountain range is flexed downward on account of the extra weight of the mountains, for the same reason a sheet of plywood is flexed downward by a stone placed on one end. This situation is perfect for having broad swampy deltas build outward into calm inland seas.

A layer of peat at water's edge accumulating when the water level is water level is low, can easily become buried by the muds of the rising sea. When the basin is sinking slowly, each cycle of rise and fall can give rise to a discrete seam of peat. Over time, the peat and sediment descend deep enough into the crust for it to become compacted and heated into successively higher grades, from peat to lignite to sub-bituminous, bituminous, and anthracite coal. At each heating step, more and more of the volatiles are driven off, the molecules transform into more energy rich arrangements, and the carbon content rises.

Because of its sedimentary layering, coal mining is essentially the mechanical removal of an organic sedimentary layer known as a seam. From the miner's point of view, the ideal is to have one or more seams lying flat on the surface or parallel to it at shallow depth. These can be easily stripped of overburden, excavated or ***strip-mined*** with loaders, and trucked away to be burned, with no refining necessary.

Mountaintop removal is little more than the strip-mining of seams at high local elevations near upland summits. It's bad reputation comes from being so plainly visible, and being a source of pollution in all directions, both a consequence of topography.

Open pit mining is the strip mining of seams well below the general land surface. ***Underground*** mining is done when there's too much overburden to strip away, usually because the seam is low on a hillside or is well beneath the topographic surface. Though less unsightly and environmentally damaging than strip mining, underground mining the most expensive and most dangerous, and hardly done at all anymore.

One of the most interesting ironies of the current climate crisis is that global warming began in earnest with a positive feedback loop involving coal. The coal-fired steam engine --invented in 1712 by Thomas Newcomen, and greatly improved in the 1770s by James Watt-- was first put to serious use to pump water from underground coal mines. Here was a case of coal being burned to mine coal, which raised both the demand for more coal and the opportunities to mine it economically. It's no wonder that the industrial revolution took off rapidly.

Being solid, coal is fairly easy to trap below the surface. All you need is net burial. The fluids of natural gas and petroleum, however, require special conditions of entrapment because they are less dense than any surrounding sediment, brine, or aquifer, and therefore rise upward.

Natural gas is the next easiest type of fossil fuel to understand. It's mainly methane, a simple gas given off when organic matter is decomposed by bacteria in the absence of oxygen. This situation is most easily and broadly met in the so-called dead zones at the bottom of lakes and seas wherever the oxygen content falls to near-zero. Dead zones form when the basin holding the water has restricted, circulation and when the water column is stratified with warm surface water floating over cold bottom water. If the surface water is laden with nutrients, the biological productivity of phytoplankton is high. Microscopic algae and other plankton grow profusely, creating living organic matter that eventually sinks into the cold layer at the bottom as dead organic matter. The result is black muck. With limited oxygen, anaerobic (anoxic) bacteria called methanogens get busy. They decompose that organic matter to produce methane. If that methane escapes and bubbles up to the water surface, the bubbles pop into the air and are eventually oxidized back to carbon dioxide which can then be extracted by plants. If the organic matter gets buried, however, it becomes trapped in the growing pile of sediment where it will remain until somehow released.

Most of the gas being fracked today in the United States comes from the deep black marine shales of the foreland basin of the ancient Appalachians. Gas produced by methanogens was trapped in the impermeable mud. To access it, frackers drill miles of horizontal boreholes in the rock, explode those tube-shaped-cylinders to create adjacent fractures, inject fine sand into those fractures to prop them open, and allow the gas to vent upward to the surface.

Gas is also trapped in other ways. Prior to the recent gas boom, most of it was associated with petroleum reservoirs where pockets of gas were trapped above the oil, which was trapped above watery brines. Uncontrolled leaks of methane from sites of petroleum production is a major problem for climate pollution today. During the Pleistocene, Earth was cold enough for to trap vast quantities of methane within and below permafrost. This stuff is now bubbling up from Arctic lakes, and has even caused a few explosions that left what look like meteorite impact craters. The greatest concern gaseous carbon and the climate crisis comes from a solid or "ice" form of methane called a clathrate-hydrate that is common in cold muds beneath shallow seas at depths of 300-500 m.

Petroleum often starts with the same source rock as gas, the recipe is more complex. It starts with a rich organic rain of plankton falling to the bottom of an oxygen-starved, restricted basin, usually in tropical climes. But instead of staying in the source rock as a black shale, it's buried deeply enough in geothermally warmed rock for a long enough time to "cook" into petroleum. Within the source rock, the original organic material, mainly cellulose, transforms into a waxy solid called kerogen. In the next step, that kerogen is transformed into a liquid called oil and a gas called natural gas. Being less dense than the overlying rock and its pore water, both liquid and gas migrate upward through the overlying crustal formations following pore spaces and cracks, either escaping as oil seeps and gas leaks, or being trapped.

Asphalt roads are made of bitumen, the black, tarry residues remaining after petroleum is refined for gasoline, diesel, and fuel oils. Prior to widespread oil refining, where tar is a byproduct, asphalt roads were initially made from bitumen imported from natural lakes of oil, the so-called "pitch" lakes of Trinidad and Venezuela. The first "tarred" road in the United States was built in 1870 in front of City Hall in Newark, New Jersey was made of such natural tar. Imagine water skiing or swimming a lake of tarry oil, rather than water.

Oil Creek, near Titusville, Pennsylvania was once the most famous natural oil-seep in the United States. The name Oil Creek describes itself. Oil seeped up into the creek through the bed of a stream channel to join the water flowing down from above. Here, and elsewhere throughout the world, indigenous peoples used this odiferous material for many purposes such as for ornamentation, glue, sealants, and as a source of heat. The fame of Titusville comes from its role in launching America's petroleum industry. There, George Bissel and Edwin Drake successfully drilled a well to produce petroleum to be distilled into oil to be burned for light and heat. The global market for whale oil crashed almost immediately.

The most famous oil seep is in Rancho La Brea near Los Angeles. There, the upward-leaking black crude oil formed a pitch lake that gradually stiffened in viscosity as its volatiles evaporated. The result was a gooey tar that trapped and preserved ice-age animals. Something similar happened with the infamous Athapaskan Tar Sands of Alberta, Canada when the oil moving through porous sandstone became too stiff to move. Instead, it was locked in place like water frozen in an aquifer. Being too stiff to pump, the tar is heated with steam until it turns to dark oil that can easily flow.

Think of oil seeps as mineral hot springs having a different liquid (oil instead of water) and a different gas (methane instead of hydrogen sulfide). The physics are broadly similar. When natural oil seeps reach the surface, the methane and oil are brought back into contact with atmospheric oxygen, so they decompose quickly back into carbon dioxide, completing the loop. This makes petroleum no less natural than spring water. Thousands of seeps occur all over the world, many of them undetected.

The infamous Deepwater Horizon oil spill in the Gulf of Mexico in 2010 can be thought of as a super-fast oil seep. The main problem was not that oil entered the marine environment, but that the rate its entry was much higher that the rate at which it could be decomposed. Since then, much of the oil that soaked into beach sands has been oxidized by hungry bacteria and vented back up to the atmosphere. Pollution by organic compounds and metals continues.

The Deepwater Horizon spill offers us a wonderful parable for the uber problem of the climate crisis. The problem is not the oxidation of fossil fuels, because that's been happening throughout the last half-billion years of the Phanerozoic Eon. The problem is the ultra-rapid rate of oxidation caused by the collective bonfire of combustion in our furnaces and engines. The exposure of coal by erosion, the leaking of petroleum to the surface, and the venting of gas to the atmosphere are every bit as natural as the fall of the rain and the flow of a stream.

The Little Missouri River in Theodore Roosevelt National Park in North Dakota, provides another fossil fuel parable for modern times. When I visited there in 2009, I noticed that the pebbles and cobbles of the stream bank, riffles, and gravel bars were dominated by a pinkish brown rock called clinker. These harder fragments had been weathered out of the weaker silty and sandy strata of the badlands before being rolled, rounded and concentrated by the channel. What was the source of the clinker? Ancient underground coal fires had baked the sediment bracketing the coal seams, converting it into natural brick. Ironically, the natural burning of fossil fuels created the oxygenated riparian habitat needed for the local trout to thrive.

For a petroleum reservoir to develop, the upward seeping oil must be trapped underground by some impermeable geological formation. An umbrella held correctly sheds the rain. One held upside down collects the rain into a growing volume. Now imagine that a rain of petroleum drops is falling upward. Any geological circumstance creating the shape of an umbrella held in its correct orientation would trap oil rising up from a source rock being cooked at greater depth. And any gas migrating ahead of that oil would be compressed at the apex of the umbrella. If there's enough pore space in the rock to hold sufficient oil, and if the reservoir is big enough, the result will be a volume of trapped oil, a.k.a. an oil field.

A good petroleum reservoir requires three very different kinds of rock arranged in the right sequence. A *source* rock to produce the petroleum, a *cap* rock that prevents it from escaping up to the surface, and a *reservoir* rock to hold enough in the pores to make it commercially worthwhile. The cap rock is usually an impermeable shale or salt or angled stratum where upward flow is blocked by a fold or fault. The reservoir rock is usually some sort of porous sandstone or limestone, and the source rock is usually an anoxic mudstone or shale.

Our ingeniousness in ***tapping*** the ancient ***traps*** of fossil fuels --coal, oil, and gas-- continues to play a huge role in the current climate crisis. Essentially, we are spending down the energy that was saved during former chapters of the earth's story.

Limestone

Earth's limestone is by far and away the largest reservoir of carbon within sedimentary rocks, an estimated 40 million gigatons. This is four times more than all the organic carbon sources combined. Limestone is not a fossil fuel, because it doesn't release energy when burned. But it has always played a critical role in earth's carbon cycle.

Historically, the word limestone is any rock that can be burned to make lime, the gray-white powder of cement that has held concrete together since the days of Rome. This vernacular usage of the term includes marble , which is a metamorphic rock, and coquina, which is little more than broken shells so weakly stuck together they crush when wallked on. Making concrete is a climate double-whammy because carbon dioxide is the exhaust gas released when the limestone is baked to make lime, and because carbon dioxide is the exhaust gas released when fossil fuels are burned to fire the kiln.

The world burns an astonishing amount of limestone to make concrete. In 2014, the United Nations Environmental Programme noted that the world uses enough concrete each year to build a wall around the equator that is 88 feet high and 88 feet wide.[53] Worldwide, 30 billion tons are manufactured each year, more three times the amount when I started college teaching in 1979. [54] Global CO_2 emissions from limestone production now exceed 8 percent of the global total and the pace is picking up as cities grow and infrastructure is replaced.

The main mineral of limestone is calcite with a simple formula $CaCO_3$, composed of a calcium ion of Ca^{+2} and a carbonate ion of CO_3^{-2}. Chemically, it may help to think of the carbonate ion as an ultra-oxidized molecule of carbon dioxide. Calcites cousin, the related mineral aragonite has the same chemical composition as calcite, but a slightly different crystal structure. Calcite's other cousin, dolomite has some magnesium replacing some of the calcium, creating a more resistant result.

Most of the limestone deposited in the last half billion years was biomineralized by marine organisms. I'm talking about every coral reef and shelly beach, and every inch of the Florida Peninsula and its Keys. Limestone formations that many people actually know by name include the Kaibab Limestone rimming the Grand Canyon and the Niagara Dolomite forming Niagara Falls. It's hard to walk anywhere near Cincinnati without stepping on billions of perfectly preserved fossil

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[53] Pascal Peduzzi's report for the

[54] Nature, 2021 in sources.

shells because that's what all the local rocks are made of. All these shelly organisms building up all these formations are responsible for sequestering enough carbon out of the air to make the last Eon of Earth history quite habitable.

The Cliffs of Dover are made of a weak limestone consisting almost entirely of dead calcareous plankton called coccolithophorids. Paris, the city of light, is built almost entirely of a light-colored limestone quarried from beneath the city. It's many underground chambers, grottos, catacombs, and hiding places are like a negative image of the positive city. In the United States, the most widely distributed is the Salem Limestone, which is so perfectly suited for quarrying that it's being sold the world over. From it were built the Empire State Building, the Brooklyn Bridge, and the dimension stone of the campus I work at. What is now the flat farm country of central Indiana was once the vast, flat floor of a warm, shallow sea.

The biomineralization of lime helped jump-start the diversity of life during the fierce competition of the Cambrian explosion. Calcite was the mineral of choice to make hard parts, whether for teeth, or for armor against teeth. From the contest emerged nearly every phyla today, including clams, snails, corals, squids, sponges, vertebrates, and creatures you may not know of, bryozoans and brachiopods. These are the macroscopic organisms we can see with the naked eye. Much more important to the carbon cycle are the many kinds of plankton that secrete lime shells (called tests). Every single one that ever lived has played a role in earth's climate.

Limestone can also precipitate inorganically directly from a concentrated water solutions. In lakes and marine basins where evaporation is strong, limestone precipitates like salt, forming beds of strata. At smaller scale, it precipitates as the stalactites of caves, the glistening travertine of hot springs, and spongy tufa in lakeshore settings, and the scale in our teapots and toilets.

For earth's ***long-term*** climate, there is no more important rock than limestone. For its ***short term*** climate there is no more important material than buried organic carbon.

15 - VULCAN EXHALES - 2556

TAKEAWAY

The carbon in Earth's underground reservoirs is returned to its atmosphere by the release of volcanic gasses at a rate that varies greatly. Without these exhalations Earth would have long since frozen over.

KEY POINTS

Everything about Earth's climates are related to volcanic activity in some way: the creation of the atmosphere by venting from below, the origin of life, gas belches leading to mass extinctions, and the ongoing degassing that makes life possible.

Volcanic degassing impacts the climate with four basic tempos, during: the staccato of notable historic eruptions, the crackle of constant small scale eruptions; the continuous background noise; and great belches from superplumes.

The intermittent great belches from large provinces of flood basalts all created catastrophic loads of carbon dioxide leading to super-greenhouse climates --and related effects of acidification and anoxia-- associated with all five of Earth's five major mass extinctions.

The burning of fossil fuels and explosions of trapped natural gas are completely natural, and are routine occurrences in many volcanic terrains.

SCRIPT AND TEXT

Pause ......

Episode 15 - Vulcan Exhales

Pause

Welcome to Climate Underground

I'm your host, Robert Thorson

Thanks for joining us.

Pause.....

When I was a teenager, I worked summers as farmhand in North Dakota. Our prairie homestead still had a working forge like those you might see in the blacksmith shop of a living history museum. I used it only once --to straighten the steel tooth of a cultivator I had mangled out of shape by dragging it over a boulder lurking in the loam. I remember lighting the coal fire and pumping the bellows to raise the temperature high enough to make the metal glow yellow-hot so it could be hammered back into shape on the anvil.

That's the closest I ever got to role-playing Vulcan, the Roman god of fire, namesake for the earth's most fundamental process, Vulcan-ism spelled with a " u," now volcanism spelled with an "o". His human incarnation is that of a blacksmith in a forge with a hammer. From his underground forge, Vulcan used geothermal heat to make all other earthly things, including the mountain where Jupiter, god of the atmosphere, looked down from above.

As I worked at the farm forge, I exhaled two important gases: water vapor and carbon dioxide. Earth's volcanoes do the same.

No aspect of Earth's biota or its natural climates are unrelated to volcanic activity. Earth's early atmosphere was almost entirely volcanic gas. The ocean is condensed volcanic gas. Ice sheets are crystallized volcanic gas. The continents that merge and disperse to create regional climates are ultimately volcanic in origin. The living things now tweaking the carbon cycle got started with volcanic heat and chemistry.

Four Tempos

Volcanoes influence the climate on four basic tempos.

The *best known* volcanic tempo is the ***irregular staccato*** of booming historic eruptions that make the news or the past news, those that are well catalogued and carefully researched. Famously, the 1815 Eruption of Mount Tambora in Indonesia created the Year without a summer in 1816, and set the stage for the dark novels of Dracula and Frankenstein. Most memorable to me was the May 1980 eruption of Mount St Helens in the Washington Cascades, which claimed the life of vulcanologist David Johnston who had been my office-mate in graduate school and fellow employee of the U.S. Geological Survey. Most well documented is the 1991 eruption of Mount Pinatubo which injected nearly 20 million tons of sulfur dioxide into the stratosphere, cooling the Earth by 0.5°C for about two years. Most disruptive for Europe were the April 2010 eruptions of the barely pronouncable Icelandic volcano [hay-uh-**ftaat**-laa-yow-kl] Eyjafjallajokull which forced the shutdown of airports in 20 countries for up to a week.

Most recent --as of the time of this writing-- was the unexpectedly powerful eruption of Hunga Ha'apai undersea volcano in Tonga on January 15, 2022. Submarine volcanoes usually don't erupt violently because the overlying water pressure prevents this from occurring. But this eruption in Tonga occurred in water shallow enough to explode but deep enough for the eruption to involve lots of water. The blast blew through the stratosphere into the ionosphere more than 90 miles up. The boom was heard thousands of miles away and the shock wave of compressed air travelled around the world. Gravity waves of atmospheric pressure created strange tsunamis that were unexpectedly damaging thousands of miles away. Despite its power, the eruption had little short-term meteorological climate impact because there was little sulfur dioxide gas dissolved in the magma.

An earlier Tongan eruption in 2019 left a raft of floating rock covering 40 square miles that wasn't discovered until a ship sailed through it. The gas in that rock, called pumice, literally outweighs the glass that trapped the bubbles inside.

In every case, the driving mechanism for explosive eruptions is the rapid expansion of gas, mainly coming from within the magma, but also involving nearby water. Exceptionally large blasts billow upward as clouds of ash and gas before punching their way through the troposphere.

With each eruption, a pulse of carbon dioxide is emitted into the atmosphere. Pulses of water vapor and sulfur dioxide create mists of sulfuric acid droplets that become sulfate aerosols that merge with the tiniest ash particles to encircle the earth as a thin cloudy veil. At stratospheric heights, these aerosols reflect incoming sunlight, cooling the earth for a year or two before settling back down to the top of the turbulent troposphere, where they are quickly rained back to earth's surface.

Fuming away in the background of the irregular staccato of notable historic eruptions are thousands of smaller eruptions that receive only local notice or trivial media mentions. In any given moment, an average of ***thirty to forty*** eruptions are taking place somewhere on Earth that are being carefully monitored for signs of danger. In most cases, they puff away visibly but silently, but some rumble with seismicity, and others spurt magma near the main vent. Evacuations are sometimes necessary. But, after the excitement, the volcano calms down and things go back to normal. The eruptions at tempo, we say, have ended.

The ***fastest*** *and most* ***continuous*** *tempo* involves the, relentless, and often invisible exhalation of greenhouse gases --carbon dioxide, water vapor, nitrous oxide, and methane-- from volcanic terrains that are too nonviolent to be considered eruptions. The bubbling mud pots of Yellowstone render such invisible outgassing visible. More often these exhalations are completely invisible as they leak from fractures and diffuse upward through the soil. Some streams in the East African rift bubble continuously from below with volcanic gas seeping into the streambed. Not one second of Earth history has occurred without volcanic gas leaking upward from the planetary interior, a process that began with fuming fury of the Big Melt and will continue until our planet is stone cold.

On land, we monitor invisible gas seeps with satellite imagery, data loggers, and field sampling. In the deep ocean, they remain generally undetected because the pressure is high and gas bubbles rising upward are quickly rendered invisible by the constant motion of waves and the windswept froth of whitecaps. The ocean is where the vast majority of volcanic activity takes place on earth, most of it concentrated along Earth's largest mountain range and largest volcano, the uninterrupted system of mid-ocean ridges that sum to nearly 60 thousand kilometers in length (37,000 miles). There, sea-floor spreading is taking place at rates up to 3 inches (8 cm) per year, roughly the width of your hand. Each year, mantle magma rises up to fill the stretching gaps, crystallizes into basalt, and release gas into the ocean and eventually the air. Every year, those gasses enter the atmosphere.

The *longest tempo* by which volcanoes change the climate are the super-colossal belches of gas that accompany the great outpourings of lava known as Large Igneous Provinces, LIPs for short.

Five are known in the last half-billion years, yielding an average frequency of once every 100 million years.

Each belch began above a hot spot on the core-mantle boundary. Above it rose a vertical plume of magma more than a thousand miles high that is analogous to the giant tropical cumulonimbus clouds that rise tens of thousands of feet above the intertropical convergence zone. In the atmosphere, these plumes of meteorology form and disappear within hours and days. In the mantle, they rise for many millions of years.

Upon reaching the top of the mantle, they burn their way through the crust like a blow torch to flood the surface with extensive lava lakes that coalesce and freeze into vast sheets covering at least a million square kilometers, a patch of land larger than India or Argentina.

Climatically, each of the five belches contained almost unthinkable loads of carbon dioxide released during a time frame of a few tens of thousands to a million years. The best estimate for the average volume of each is 30 thousand gigatons of carbon, roughly 70 percent of the total contained in the modern atmosphere, land, and oceans. This is about 750 times greater than the current annual global release of carbon by humans of about 40 gigatons per year.

After being eroded, the flat lavas of Large Igneous Provinces usually produce a stairstep landscape known as traprock. Famous ones include the **Columbian River Basalt** plateau of Washington state and adjacent Idaho and Oregon, which buried over 81,000 square miles beneath up to a mile of lava. These flood basalts were later eroded into stairstep canyons by torrential floodwaters of the last glacial maximum. The [**Deh**-Kin] ~~Deccan~~ traps of central India are a high plateau of basalt also more than a mile thick but covering twice the area.

The Palisades Sill of the Hudson Valley, the Watchaung hills of New Jersey and the elongate traprock ridges of Connecticut were part of an even larger outflow, the **Central Atlantic Magmatic Province** (CAMP), which extended from Brazil to Europe during the initial breakup of Pangea. Staggeringly, CAMP covered 11 million square kilometers with a volume of ~8 million cubic kilometers of magma. Recent work confirms four colossal pulses of vulcanism within an interval of only 600,000 years, associated with an enormous flux of "new," isotopically light carbon into the air, mass extinction, dramatically rising temperatures, and the collapse of coral reefs caused by ocean acidification, and [55]

Each of these LIP eruptions ignited whatever fossil carbon was nearby, whether seams of coal, reservoirs of petroleum, pockets of natural gas, or black shales. All five great extinctions deduced from paleontology coincide with these outpourings. All five great extinctions involved an abrupt greenhouse warming.

Most famous are the Siberian Traps, which erupted about 252 million years ago to flood the continent with somewhere between 10^5 and 10^6 cubic miles (3-5 million cubic kilometers) of new rock, enough to cover more than 2 million square miles (5 million km^2), enough to flood the US with lava an average of a half mile deep. The thickest point in Siberia was five times that depth. Imagine sheets of frozen lava much further than the eye could see cut by rivers to a depth three times greater than the Grand Canyon. To put this mass into perspective, Earth's largest known historic eruption was Tambora, in the Sunda Arc of Indonesia, which blew its top in 1815 to make

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[55] Zircon U-Pb Geochronology Links the End-Triassic Extinction with the Central Atlantic Magmatic Province TERRENCE J. BLACKBURN et al, Vol 340, Issue 6135 • pp. 941-945 • DOI: 10.1126/science.1234204

1816 the year without a summer. Though this released only an estimated 175-215 cubic kilometers (up to 52 cubic miles) of material, it was only one 20-thousandeth as massive as the Siberian trap eruption.

Coal fires

To make things even worse, the Siberian Traps erupted through the Tunguska sedimentary basin up to 12 km deep that was full of flammable things. Limestones baked into calcium oxide released staggering quantities of carbon. Coal, black shale, oil, and gas burned to release soot and toxic gases. The belch of sulfur was high enough to send Earth on an acid trip. Rain fell with the pH of vinegar to acidify the oceans beyond anything we're seeing today. Beds of salt with halides, bromides and chlorides to waft up to the stratosphere and consume the ozone layer. Nasty upon nasty. Science writer Richard Kerr called this scene a "vast, subterranean, coal-fired inferno that belched metal-bearing ash into the stratosphere." Giga-tons of coal fly ash — the toxic stuff being regulated today at power plants — fell as dust contaminated with mercury, radionuclides and other toxic metals. Perhaps life on Earth went insane before it died from acid rain.

Imagine a world where the carbon dioxide pollution from that one-two punch of volcanic gas and burnt organic material caused a rapid temperature rise of at least 8°C. This exceeds by eight times the measured amount of global warming created by humans since the Industrial Revolution, when the burning of fossil fuel began in earnest. It exceeds by four times the 2°C warming the IPCC hopes we will remain below. This end-Permian warming was abrupt enough to keep Earth's system's out of whack for many millions of years.

The next Large Igneous Province eruption on Earth could start at any moment and continue for thousands of years, overshadowing the carbon we're projected to burn, though almost certainily at slower rates. The good news is that we would get lots of warning, and the greenhouse emission rates would be slow enough for us to adapt. The bad news is we would be powerless to stop them.

The *world* of human beings is now hell-bent on phasing out coal. But other actors on planet *Earth* see are not part of the negotiations. Coal fires have been burning on this planet since this material first came available about 300 million years ago. They were ignited by volcanism, flashes of lightning, drops of molten rock from meteorite impacts, and even spontaneous combustion. Once, ignited, natural coal fires are very hard to extinguish, even in settings with lots of rainfall because there's enough oxygen in adjacent sediments feed slow-burning embers.

In 2021, the U.S. Office of Surface Mining Data reports 259 known underground coal fires smoldering away in more than dozen U.S. states. Hundreds to thousands more are not yet discovered and documented. The U.S. Geological Survey has estimated that, in China alone, somewhere between 10 million to 200 million tons of coal are burning naturally either underground or as surface fires that cannot easily be put out. None of this is counted in emissions scenarios in climate reports.

In December, 2021, Colorado experienced its most destructive wildfire in state history, a surprising wildfire in Boulder Colorado that destroyed more than 1000 homes and buildings. Though the surface fire was soon extinguished, underground coal fires continue to burn. It's quite possible that the blaze was ignited by a burning underground coal seam, one that continues to burn today.

Centralia, Pennsylvania has become poster-child for underground coal-seam fires. First noticed in 1962, toxic smoke, surface subsidence, and general uncertainty associated with an underground coal-seam fire that extends over a distance of 8 miles (13 km), covering more than 3700 acres (15 km2), and burning to depths of at least 300 feet (90 m). Though there were multiple attempts to extinguish it, the town eventually gave up and abandoned the area in 2017, leaving only a few residents in a community that had numbered ~1500. It's still there, burning away.

If humans are natural creatures, which they are, then our burning of coal and other fossil fuels can be thought of as a sixth great belch of carbon dioxide in Phanerozoic time. Despite decades of caution, humanity is still dumping an almost inconceivable 40 gigatons of carbon dioxide per year into the atmosphere. That's a hundred times faster than the annual ambient rate of volcanic degassing. Having overwhelmed Earth's carbon thermostat, we've created a nearly perfect linear relationship between CO_2 emissions and global surface temperature. The rate is +1.0°C–2.3°C for every 1000 gigatons of carbon. The more we burn, the hotter it gets. The math is simple.

Let's say that we did nothing to curtail greenhouse emissions. Massive coal burning began in the mid 18th century, petroleum got serious in the 19th, and natural gas in the 20th. What about the whole of the 21st century beyond the year 2100? Counting everything we've burned already, the entire known reserve of fossil fuels would release about 5000 gigatons total. At the current rate, this would last about 125 years.

Though this tonnage is staggeringly high, it's only about one sixth the largest geological carbon belch of the end-Permian extinction. Peak concentration of CO_2 may have reached 8,000 parts per million, toughly 20 times the current amount. Average surface temperatures may have jumped 16ºC within a million years. The hottest summer months in continental interiors likely exceeded 140ºF. The uppermost ocean may have reached 40ºC, the temperature of a hot tub. [56] Though earth survived all this, it wouldn't have been a pretty sight.

The rate at which we're emitting carbon from our smokestacks and fires, when summed, qualifies as a colossal eruption big enough to make Vulcan jealous. This is not a good thing.

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[56] Brannen. Search for hot tub.

16 - EARTH'S THERMOSTAT - 3186

TAKEAWAY

Earth's average surface temperature has been kept within a fairly narrow range owing to a stabilizing, feedback loop in which a rise in CO_2 increases the rate at which it is removed by rock weathering

KEY POINTS

Volcanoes play the lead protagonist role in maintaining an equilibrium greenhouse temperature for much Earth history. The co-star antagonist is the weathering of volcanic rock, which removes the carbon that volcanoes release.

Earth's carbon thermostat works in a negative feedback loop to keep the carbon dioxide concentration in the atmosphere within a limited range at the time scale of a million years. The higher the concentration of carbon dioxide in the air, the faster it is removed by weathering, and vice versa.

The chemistry involves the dissolving of carbon dioxide in water to make carbonic acid, the application of that carbonic acid to calcium-bearing silicate rock, the release of calcium and bicarbonate ions to the sea and the biogenic precipitation of those ions back into limestone.

The set point of the thermostat for the last half-billion years has averaged about 67°F as the threshold between icehouse and greenhouse conditions. This is about 8 degrees warmer than the present average temperature.

On two occasions, Earth came close to permanently freezing over, as did Mars, or close to developing a permanent super-greenhouse, as did Venus.

SCRIPT AND TEXT

Pause ......

Episode 16 - Earth's Thermostat

Pause

Welcome to Climate Underground

I'm your host, Robert Thorson

Thanks for joining us.

Pause.....

In the early years of my adult life, I spent years living without a thermostat. When my house got too cold in winter, I'd throw another log on the fire or adjust the damper on the wood stove. When it got too hot in summer, I'd open a few windows and turn on the fans. Though I now live in a fairly modern house with an excellent thermostat, I never take that electronic gizmo for granted because I know how much hassle it's saving me. Without thinking, it does its job of keeping the temperature of the house within a fairly narrow range better than I was able to do when thinking.

A thermostat doesn't make heat or cold. It regulates the balance between a heat ***source*** and a heat ***sink***. When the temperature falls too much, it tells the furnace to make heat. When it rises too high, it tells the air conditioner to make cold. The job of a thermostat is the ***stat*** part of the word, to achieve ***statis***, to maintain a ***steady state*** equilibrium temperature with a negative feedback between two opposing tendencies. When my HVAC system --my heatint, ventilatoin and air consitioning system-- drifts too far away from equilibrium my thermostat pulls it back in line.

Earth has a climate thermostat so beautiful one might think it was intentional. It has kept the average global temperature of its atmosphere within a very limited range for all of the last half-billion years of Earth history. Earth's thermostat is much more complicated than my house thermostat, but works using one simple idea: the greenhouse effect. When the temperature rises too much, it reduces the strength of the greenhouse effect by moving carbon from the air to the underground. When the temperature falls too much, it strengthens the greenhouse effect by moving carbon from the underground back to the air.

Active volcanoes are always slowly leaking gas somewhere in the world, whether we can see it or not. Of the 1,500 volcanoes known to have been active in the last 12 thousand years, all either did vent or are venting carbon dioxide to the sky. Of these 400 are discrete point sources of carbon gas emission where we can measure the flux, and 670 are diffuse non-point sources whre we have little idea of the flux. These places of observation don't include regions lacking visible volcanic features, but which are known to be degassing away. And then there are problems like Lake Nyos in Cameroon, which may store carbon quietly for years before belching a big burp of it up with deadly consequences.

Throughout all of geological time back as far as the Archaean, the average global rate of volcanic leakage was one main control on the strength of greenhouse effect, which controlled the heat balance of the troposphere, which controlled the behaviors of Earth's many climates.

At the ***long-term*** time scale from millions to billions of years, the link is perfect. Vulcanism saved the day by pulling Earth out of its most extreme cooling, the late Proterozoic Snowball Earth. And though volcanism contributed greatly to Earth's most extreme warmings, another factor that I'll explain later, pulled those hot house conditions back in line .

At the ***short-term*** time scale of years, the link between volcanoes and climate change is also perfect, but for a completely different reason. When volcanoes blow up, the injection of aerosols of droplets and ash into the stratosphere blocks incoming radiation and cools the Earth like a sunshade. This is very notable at the scale of a few years following stratosphere-punching eruptions. The 1991 eruption of Mount Pinatubo is a case in point. This second largest eruption of the 20th century, cooled the whole earth about half a degree C for a few years, temporarily offsetting greenhouse warming.

At the ***medium-term*** time scale of decades, the link is also perfect. In an exciting new paper by climate scientist Michael Mann and colleagues, they showed that a "quasiperiodic variation of climate centered in the North Atlantic called the Atlantic Multidecadal Oscillation (AMO), was due to the lasting impacts of explosive volcanism.[57]

All three of these links --slow, medium, and fast-- come from the underground. That's where 99.8 percent of Earth's carbon is stored, its whopping 1.85 billion gigatons (Gt). The remaining 0.2 percent is held in its surface reservoirs of land, oceans, and atmosphere. Based on volcanic monitoring today, the annual outgassing rate from volcanism and other geothermally driven geological processes is 0.3 to 0.4 gigatons per year. This is only about 1 percent of the ~40 gigatons released annually by humans today.

But from where does volcanic carbon come? Half or more probably comes deep within the mantle and is so-called new carbon. The rest is old carbon, fossil carbon that's being recycled into and out of the mantle by tectonic processes. Flowing lava with new carbon can ignite a forest or a seam of coal to release old carbon. Rising magma can bake an underground limestone formation causing it to release old carbon to the surface.

The sediment accumulating on the floor of the ocean is obviously rich in water, which fills all the pore spaces. It's also carbon-rich, whether in the form of organic muck or planktonic carbonate. As wet, carbon-bearing sediment layers accumulate above one another, both materials leave the realms of exchanges and enter the realm of dead storage. In subduction zones where one tectonic plate dives beneath another, these water- and, carbon-rich sediments are eventually dragged down to the depths where higher pressures and temperatures prevail in the shallow crust. The pore water is squeezed out like a sponge, flows upward, and acts as a flux to lower the melting temperature of adjacent rocks. The result is magma, a mixture of molten rock and dissolved gas. Being liquid, it's less dense than surrounding solid rock, so it rises upward. Then, as the pressure drops, the main gases of water vapor and carbon dioxide bubble out. When this happens slowly, volcanoes are dubbed effusive, meaning non-threatening. When this happens rapidly, they explode catastrophically. It's the gasses that makes volcanoes explode, not the melted silicate.

In geothermal fields, the steam we see is only half-volcanic. It's water is rain and snowmelt circulating in rock fractures. It's heat is enough volcanic heat to bring water to a boil. Geysers erupt fountains of water for the same fundamental reason that volcanoes erupt fountains of lava. The positive feedback that occurs when higher up means lower pressure, which means more gas exsolves, which reduces the bulk density, which causes the fluid to rise faster, and so forth until it explodes.

The most striking thing about Earth's climate state is not its ***average*** temperature, but how stable that average temperature has been over the long haul of geological history. For the entirety of the last half billion years, it's average surface temperature has stayed within a fairly limited range

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[57] Mann, 2021, Multidecadal.

between ***peak*** icehouse at about 13 ºC, and ***peak*** greenhouse conditions at about 32 ºC. That's well above the freezing point of water at 0ºC, and well below the boiling point at 100ºC.[58]

Compare Earth's surface temperature range with that of Venus and Mars, its nearest neighbors. The surface temperature of Venus was measured by Mariner 2 spacecraft broiling plus 260 ºC or 500 ºF before the instrument failed. This is due to a thick, dense, suffocating atmosphere of 95 percent carbon dioxide and a surface pressure 75 times that of Earth. The average temperature of Mars is a frigid minus -81º C or -113 ºF, thanks to a negligible atmosphere with a surface pressure less than one percent that of Earth's. Though the Martian atmosphere is composed mainly of CO_2, there's too little to make much difference. Much of its carbon is locked away in polar ice caps consisting of dry ice. It's cold enough there for carbon snowflakes.

Early in Earth's history, the sun was about 30 percent less luminous or dimmer than today. Without its greenhouse blanket, Earth would have had an average surface temperature of about -18ºC or about 0 ºF, much colder than at present. Yet we know from geological evidence that liquid water has been present since about 4.4 billion years, continuously since ~4.0 billion. As the sun brightened, Earth's surface stayed within the Goldilocks range, avoiding the path of Venus's super greenhouse or the path of Mars's deep freeze. Staying within the range required that Earth have a dependable thermostat that kept the heat in balance.

The key to Earth's thermostat at long time scales of a million years or more is a holistic balance first glimpsed by the Scottsman James Hutton in the late 18th century: the balance between internal geothermal forces creating rock from below versus the external meteoric processes destroying that rock from above. More specifically, the creation of new, chemically reactive rock from below versus the destruction of that new rock by the aqueous biogeochemistry of weathering and sediment transport from above.

Understanding how this earthly thermostat works in more detail requires that we unpack four basic concepts of the Earth system before putting them back together. These are: carbon dioxide, silicate minerals, water, and soil.

The ***first*** piece of Earth's thermostat is the gas carbon dioxide. Understanding it begins with the element carbon, abbreviated C on the periodic table. Its atomic number is 6, meaning it has six protons. Normally it has six neutrons, giving it an atomic weight of 12. Carbon is the fourth most abundant element in the universe (after hydrogen, helium, and oxygen), created in the nuclei of massive stars by the fusion of three helium nuclei before being blasted into space by supernovae explosions. Of all the elements, it's melting temperature (~3550°C) and sublimation temperature (3800°C) are the highest known.

The name "carbon" is derived from the Latin word *carbo*, meaning charcoal. It's the basis for all organic chemistry, and is present in all living organisms, usually bonded to hydrogen, oxygen, nitrogen, phosphorus, and sulfur. In pure form, it's the mineral diamond, the mineral graphite, and black soot. Crystals of diamond and graphite dust make up some of the earliest minerals of the universe. Carbon's simplest molecule is methane, a single, symmetrical atom of carbon surrounded by four hydrogens. Its most complex molecules are long chains, importantly the master chemicals of

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[58] *Science,*

life, DNA and RNA. There are also fullerenes, graphene, carbon nanofoams, carbon glass, and weirder forms. Because it can form more compounds than any element --greater than ten million and counting-- it's often considered the king of the elements.

The most primitive chondrite meteorites --the stuff from which Earth was assembled-- average more than 3 percent carbon. Only a tiny fraction of Earth's carbon is in the atmosphere today, currently 0.004 percent of the total, mainly as carbon dioxide.

So, what is carbon dioxide? Physically, it occurs in three phases. As a solid, it's dry ice, created by forcing the temperature below -109 ºF. As a liquid, it travels in pressurized tanks that carbonize our beverages. As a gas, it's an invisible, but highly reactive gas. Chemically, it's a simple molecule of one atom of carbon and two of oxygen. Biologically, it's the main raw material for plant photosynthesis and the main exhaust gas of all animal breath. Geologically, it's an important volcanic gas and the main ingredient of limestone, whether in shells, reefs, or strata.

In Earth's atmosphere, carbon dioxide ultimately comes from underground volcanism, the continuous upward leakage of gas. I t's usually co-dominant with water vapor, and other carbon-, sulfur-and nitrogen- gases. If Earth's volcanoes stopped venting carbon dioxide, Earth's atmosphere would quickly and permanently be chemically stripped of carbon dioxide, probably within a million years or so, sending us into the deep freeze. If the surface processes that remove carbon dioxide were stopped, the concentration would build back up to send us into the hot greenhouse state.

The ***second*** piece of the thermostat are silicate minerals, which overwhelmingly dominate the crust and mantle. The simplest is quartz, with a composition of SiO_2, meaning one part silica to two parts oxygen. Because quartz lacks other elements, like calcium, sodium, aluminum, magnesium, and iron, and because the silicon-oxygen bond is arranged in pyramid-shaped tetrahedrons, quartz is very resistant to chemical breakdown. This is why the bulk of sand on beaches in made of quartz. Nearly everything else has weathered away.

The most common group of minerals on earth are called feldspars, which add aluminum and one or more cations to the forumula of quartz. Those feldspars that crystallize at lower temperatures in more silica-rich rocks like granite are called alkali feldspars because the cation of choice is usually potassium, though it can be sodium. Such rocks are called felsic as shorthand for, *fel* + *si* for their feldspar and silica. Those much more common feldspars that crystallize at higher temperatures in rocks like basalt are called plagioclase feldspars. For these, the cation of choice is usually calcium, but sodium is also important.

The other mineral group of concern here are called mafics as shorthand for *ma* + *fi*, minerals rich in magnesium and iron. These are what gives primitive rocks their black or greenish-black color. The two most abundant subgroups are *pyroxene*, which swaps magnesium and iron in place of calcium, sodium, and potassium, and *olivine*, which takes the additional step of shedding the aluminum.

The upshot is that the *felsic* rocks, being fairly rich in silica and quartz rich are fairly resistant to chemical weathering, and, importantly, have no calcium to offer. In contrast, the *mafic* rocks are much more easily weathered, and provide abundant sources of calcium. These mafic and ultramafic rocks are the key to earth's thermostat, especially when they exposed in high-relief volcanic arc settings in warm, wet soils like those of the tropics. On balance, writes geologist Francis McDonald, "Earth's climate state is set primarily by the balance of volcanic outputs and global weatherability."

The best known case of how the thermostat works began about 45 million years ago when India, heavily freighted with primitive volcanic rock rich in easily weathered plagioclase feldspars, pyroxene, and olivine, crashed into Asia. Thus commenced the long, slow cooling that sent Earth into its present icehouse state, meaning one with significant ice in its polar regions. The cooling intensified when Antarctica broke away from Australia about 34 million years ago and began migrating toward the South Pole, and culminated with the vast expansions and contractions of glacier ice in the northern hemisphere. We're now just beginning to exit this icehouse state because we've reversed the long-term cooling trend and are now heading back into Earth's default condition of a *greenhouse* thermal state, meaning ones without polar ice. This exit will likely take millions of years.

The ***third*** piece of the thermostat involves carbonized water. If distilled water fell on fresh rock, little weathering would take place. But all rain is naturally acidic because each freshly condensed drop falls through an atmosphere with reactive carbon dioxide. Raindrops are thus weak carbonic acid, in which the hydrogen ions of (H^+) displace the positively charged cations of silicate minerals in a process called hydrolysis, meaning water breakage. When this happens, the dissolved calcium ion (Ca^{+2}) is liberated from a feldspar mineral lattice to flow downstream, and the carbon dioxide travels with it as the dissolved bicarbonate ion (HCO_3^-). After reaching the sea, these become the building blocks for plankton exoskeletons, shells and corals. All other things being equal, the more carbon there is in the air, the faster it is removed.

The ***fourth*** and final piece of the thermostat is the soil. During the last 400 million years, the complex process of rock weathering takes place mainly beneath a rich, biologically active soil. Terrestrial plants harvest carbon from the air and water from the ground to create organic matter. There's no shortage of carbon, and usually no shortage of sunlight and water. Biologically active nitrogen is easily fixed from the inert nitrogen in the air by bacterial processes. What plants still need are the vital phosphorous and potassium that can only come from minerals. So, plant roots work with microbes and strands of fungus (mycelia) in the soil that have evolved physical and chemical mechanisms to break up rocks and dissolve them in search of nutrients. Weathering rates rise with temperature increases, provided there's enough moisture. Conversely, weathering rates go down when it's too cold or too dry, or when organic topsoil is absent, as they were for most of earth history.

Over time, the buildup of an organic topsoil creates an efficient recycling system in which new organic litter falls to the forest floor where it is decomposed in the presence of oxygen. This creates abundant carbon dioxide within the soil that builds up to concentrations of up to 40 percent by volume, which is orders of magnitude more than in the atmosphere. Rain trickling through gas-rich topsoil becomes very acidic and is very aggressive in dissolving rock. The resulting chemical destruction greatly increase the rate of chemical weathering of silicate rocks over background rates.

Now, with all four pieces of the global thermostat are in place --carbon dioxide, silicate minerals, water, and soil-- we can re-assemble them.

Except for short-lived great belches from LIPs, vulcanism sends a generally steady stream of carbon dioxide into the atmosphere, which mixes globally within a matter of weeks. Rain falls first through that atmosphere, dissolving carbon dioxide and then through the topsoil, which dissolves even more. The resulting carbonic acid, in concert with soil organisms, reacts with silicate rock to create two stable dissolved ions, calcium (Ca^{+2}) and bicarbonate (HCO_3^{-}), which wash to the sea. Marine organisms pull carbon dioxide and bicarbonate from the sea and combine it with the calcium ion to create macroscopic shells, reefs, and beaches or microscopic plankton in shallow seas to create marine platforms. Though the carbon is now sequestered from atmospheric circulation, it will eventually recycle back to the air when released again by volcanic degassing. The cycle is complete.

Things will hum along without much abrupt change until there's a global rise in volcanic activity for whatever reason. This loads the air with extra CO_2, which enhances the greenhouse effect, warming things warm up temporarily. The increased warmth increases the vigor of the hydrological cycle and the rate of chemical reactions within the soil. The extra CO_2 enhances the reactive thickness of soils and the acidity of soil water. The combination of these four effects drives up the rate of weathering, which sucks more CO_2 from the air. Things return back to steady state.

No consider the reverse, a time with less volcanism than usual. With less CO_2, the greenhouse, becomes weaker, and things cool down. This decreases the vigor of the hydrological cycle and of biological reactions within the soil, and lowers the acidity. This drives down the rate of weathering, which pulls carbon out of the air at a declining rate, which cools the climate down to a new steady state controlled by baseline volcanic CO_2.

An excellent example of this effect happened during our present Cenozoic Era. About 15 million years ago and again about 7 million years ago, there was a global slowdown in the rate of plate spreading from mid-ocean ridges. The result was a global slowdown in volcanic CO_2 emissions, which led to a 10 degree C drop in temperature over Antarctica and a substantial thickening of ice. A cooler global temperature reduced the rate of weathering, bringing the system back into steady state.

The almost magical thing about the earthly thermostat is that it buffers otherwise wild swings in carbon caused by pulses of tectonism. Each pulse simultaneously intensifies both the carbon source and the carbon sink, setting up a negative feedback that brings things back to steady state. The extra source of volcanic degassing is simultaneously compensated for by the extra sink of higher rates of weathering sequestration because most of the new rocks being exposed are volcanic in origin. Thus, volcanoes *giveth* in terms of gas and *taketh* away in terms of weatherable rock.

At the multi-million year time scale, writes geologist Francis McDonald "Earth's climate state is set primarily by global weatherability," which is linked to volcanoes in two ways acting opposite each other. In one direction, the weatherability is set by the amount of CO2 and moisture in the air, both of which are volcanic gasses. In the opposite direction, the weatherability is set by the uplift and exposure of volcanic rock as a consequence of plate motion. The evidence is compelling. The four ice ages of the last half billion years map directly on four mountain building episodes in the tropics and subtropics. [59]

On five occasions within the last half billion years, belches of extreme vulcanism overwhelmed the thermostat. It was the excess of gas, not the deficit of weatherable rock that resulted in the five great mass extinctions known from the fossil record. After each extinction, the thermostat

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[59] Mcdonald, 2019, Arc Continent collisions...

mechanism, which never stopped working, eventually brought the carbon content of our atmosphere back to normal.

Understanding the thermostat suggests the possibility of a better baseline for climate change than the pre-industrial climate of 18th century history, which is anomalously colder and more variable than average for Phanerozoic history. The threshold temperature between Earth's alternating icehouse and greenhouse states during the last half billion years was about 20ºC (67ºF). Earth's 20th century average temperature was about 6 degrees lower at 14 ºC (57 ºF). Seen this way, the ongoing global warming is a return to a more normal conditions.

By no means does this suggest that warming is a good thing. It clearly is not relative to the cooler Holocene in which human civilization emerged, and for other species who enjoyed this last interglacial. But what it does suggest is that a hotter planet is closer to the Phanerozoic baseine than the present.

Planet Earth is not about to go up in flames.

17 - CLIMATE CLOCKWORK - 3272

TAKEAWAY

Earth history plays out with four kinds of time: the arrow-time of story narrative, the cycle-time of repeating events, the one-time of unique events that never happen again, and the all-time of universal constants that never change.

KEY POINTS

Earth's climate history is dominated by four main narratives that interact with one another through time: the slow warming of the sun, the slow cooling of the earth interior, the slowing of Earth's rate of spin, and the diversification of life during organic evolution.

My family's homestead farm in North Dakota contains clues to a typical climate narrative in arrow time. The sequence is from Paleocene subtropical coal-bearing floodplain swamps to the drought-prone continental climate of the Anthropocene.

Earth's cycles of time are nested one within the other from the super-continent of a half-billion years to the daily sunrise. This includes Earth's alternations between greenhouse and icehouse states, and the 100-thousand-year-long-beat of major glacial advances.

Earth's great singularities punctuate Earth history, and change it forever. The origin of life about 4 billion years ago. The great oxidation event at 2.4 billion. The emergence of our dominant species about 300 thousand years ago.

There is no history in universal constants, which never change. Carbon will always have six protons. Ice will always melt at 0°C. The gravitational constant will always be the same. Time doesn't matter.

SCRIPT AND TEXT

Pause ......

Episode 17 - Climate Clockwork

Pause

Welcome to Climate Underground

I'm your host, Robert Thorson

Thanks for joining us.

Pause.....

Each time the bicycle wheel turned, I heard a faint sound like the ticking of a clock inside a sleeping bag. A quiet ka-thump, ka-thump, ka-thump. The inner tube of my tire, I figured, must have become twisted after I patched a flat tire. I thought about stopping to straighten out the twist, but instead decided to carry on because the new noise was interesting. It me a an audible signal of my speed, which was entertaining.

I was on the return leg of an overnight bicycle camping trip to Big Falls, Minnesota in the state's north woods. There, the iron-stained Pigeon River, flows with bog-stained water no older than the last rain to cascade over some of the oldest rock in North America -- the granites and gneisses of the Archaean Eon more than 2.5 billion years old. Both the ***water*** and the ***rock*** had risen up from below, the water having been condensed from steam after the Big Melt, and the granite having been crystallized as silicate slag from the geothermal furnace running hotter then than it does now.

Miles ahead of me on the mainly flat pavement was my home in Bemidji, Minnesota, a small lakeside of about 10,000 souls located on glacial sand plains of the Pleistocene Epoch, which formed only about 15 thousand years ago. The time gap between the solid rock at Big Falls and the loose sand at Bemidji spanned more than half of Earth history.

Bicycle trips give you lots of time to think. As I traveled, I unpacked four different types of time. Most familiar is the ***arrow*** time of history, a narrative that flows relentlessly from past to present, in my case a six hour bike trip. Also familiar is the ***cycle*** time of repetition, each of the one-second-long revolutions of the wheel. Less familiar is the ***one*** time of a discrete event, in my case the singularity of a flat tire that divided my return trip into two segments, one with a thump, and one without. Least familiar, because we take it for granted, is the ***all*** time of universal constants, in this case the strength of my bike's steel frame, which experienced no change whatsoever.

All Time

Some things never change. I refer to the universal constants and universal laws on which the entire edifice of physical reality is built. The freezing point of pure water at standard atmospheric pressure is 0 °C or 32 °F. This has ***never*** changed because it ***cannot*** change because it's ***baked*** into the laws of physical chemistry. Carbon will always have six protons, and oxygen eight. The force of gravity will always be controlled by the same universal constant, at any time and any place: $6.674 \times 10^{11}\ \mathrm{m}^3\ \mathrm{kg}^{-1}\ \mathrm{s}^{-2}$. Both *Newtown's* law of gravity and *Einstein's* theory of general relativity depend on that never changing. The solubility of a quartz grain from the Archaean Rocks of Big Falls is the same as that from the Pleistocene sands of Bemidji.

These universal constants are present ***all*** the time, which is why I refer to their role in history as ***all*** time.

Arrow Tiime

Next easiest to fathom are the unidirectional changes of ***arrow*** time that have been playing themselves out slowly and surely ever since its birth. There are ***five*** basic narratives.

The ***first*** and most compelling is the slow cooling of the entire planet since its origin during the Big Melt. Some of the original heat remains with us today, though the overall temperature has fallen steadily. Some day, Earth will be a cold stone in space.   Though new sources of heat are being added, they sum up to less than that lost. These include: The release of latent heat during crystallizations. Heat from the kinetic energy of meteorite impacts. Radioactive heat from nuclear decay. Frictional heat from interior circulations and tidal stretchings.

This gradual cooling down has worked out really well for us. During the Hadean Eon, Earth was too hot to hold surface water and therefore too hot for life. During the early Archean Eon, it was too hot for plate tectonics to work as we know it, meaning the continents on which climates arise couldn't happen. Today, it means that geothermal energy still available everywhere, not just in volcanic places.

The word "geotherm" is a fun one to learn. It's the rate of change of temperature with depth below Earth's surface. Below the effects of weather and climate Earth averages about 57ºF (**13.9 ºC**). In the outer crust the temperature increases fast at the rate of about **25º C** per kilometer (35*F/mile). The deepest mine, 2.4 miles (**3.9 km**) down, has a temperature of about 140ºF (**60 ºC**). Deeper in the crust, the geotherm diminishes, being about **12 ºC** per kilometer.

Heading down to Earth's deeper concentric layers, there are no reversals. Heat is always moving outward from its super-hot interior toward the coldness and emptiness of space. The temperature reaches about 500-600*C at the base of the crust, which is close to the melting temperature of granite. It reaches about 1200ºC at the base of the hot, but still rigid tectonic plates.... about 4000º C at the base of the mantle... and about 5,000ºC at the center of our molten core.

The ***second*** arrow time narrative is the gradual slow-down of Earth's rate of spin. Were Earth completely solid and gravitationally separate from its moon and other planets, it would spin friction-free against the vacuum of empty space. Instead, it has orbital mechanics involving the moon and tides that rise and fall against the land. In the Early Archean about 3.5 billion years ago, an Earth Day was only about 14 hours long. One billion years later, it was about 21 hours long. At that point, the day length changed little until about half a billion years ago until it began to slow down again to the present 24 hours per day.

This slowing of the spin has worked out well for us. Meteorological storms whirl and twirl as a function of how fast the Earth spins. Imagine the power of storms today being tripled because everything was spinning three times faster. The original proximity of a close-in moon created oceanic tides a thousand feet high. Imagine how our coastal communities would have responded to that. Stresses flexing in the solid brittle crust would likely have set up huge daily earthquakes.

Running opposite to earth's cool-down is a ***third*** narrative, the warm-up of the sun. On Earth's birthday, the sun was a much fainter star, giving off about 30 percent less radiation than today. Yet we know that liquid water was present, with life originating by about 4 billion years ago. To account for this "faint young sun paradox," the early Earth must have had a thicker greenhouse blanket. As the sun slowly brightened over geological time, the equilibrium concentration of carbon dioxide in its atmosphere fell in response.

The sun will continue to brighten in luminosity into the future. Earth will receive more solar energy, To compensate for this increased solar heating, the strength of earth's greenhouse will continue to fall. Carbon will slowly be transferred from sky to underground reservoirs. At some point, perhaps half a billion years from now, the concentration of atmospheric carbon will drop below the level required for photosynthesis. Life as we know it will end. At some further point, perhaps 2 billion years from now, the sun's stellar fuel will begin to run out and its corona will extend outward to gradually vaporize our atmosphere.

A ***fourth*** narrative involves ocean chemistry. The decrease in CO_2 associated with solar brightening, and a decrease in volcanic hydrothermal exchanges associated with earth's cool-down, have caused the pH, or acid-base balance of the global ocean, to rise steadily.[60] About 4 billion years ago, the ocean of the early Archean was slightly acidic ~6.5. During the last half billion years of the Phanerozoic the ocean has become alkaline, with values of ~7.5 to 9.0. Today the average is about 8.1. The earlier, lower, more acidic pH values undoubtedly affected chemical reactions during the origin of life and early metabolisms, and the regulation of the climate via the partitioning of CO_2. Modern acidification of the ocean is pushing us back in the direction from whence we originally came.

A ***fifth*** unidirectional change in arrow time has been the progressive diversification of life through natural selection. The pressure of natural selection to create new life forms adapted to current conditions is as relentless and ubiquitous as that of the sun heating up, the Earth cooling down, the Earth's spin slowing down, and the ocean pH increasing. Every opportunity at every time in every place was exploited. The result was, is, and will be, organic evolution.

Arrow time need not be steady, or controlled by enormous geophysical and geochemical gradients. It can also be the accumulation of purely random events, at all scales of time and space -- a chain of links that can be told as a story. A narrative of ... "this happened, and then that happened, and then that, and so forth." Just as does every person's story is unique, so too with every place. For example, I offer a simple story of climate change for our farm in central North Dakota, where I climbed the windmill as a child to grasp concept of climate for the first time.

Had the drillhole beneath our windmill been drilled more deeply, it might have encountered a layer-cake sequence of floodplain silt, sand, and swamp deposits called the Fort Union Formation. Its strata date to an interval about 55 to 65 million years ago when our earliest mammal ancestors were rapidly diversifying in a much warmer, less-continental subtropical climate. Lazy rivers meandered westward toward a nearby sea. In Center, North Dakota, a town less than a hundred miles away vast quantities of its low-grade, high-sulfur, lignite coal are being mined and burned to power electric grids far away.

Cut down into the Fort Union formation were gullies from the 5-million-year-old Pliocene Epoch that left behind ribbons of streambed gravel. Between the channels were rich organic soils. These are clues to a younger, more temperate forested ecosystem above a gently sloping landscape in the process of being slowly eroded. The Arctic Ocean was ice free.

Filling those gullies and burying those soils is an unusual sediment called glacial till: a densely packed and sheared deposit of silt and clay containing scratched and broken stones. These are all clues to the last of many glacial expansions of the Pleistocene Epoch with the last 2 million years. Each was a slow binge of ice followed by a rapid purge. Though these expansions were triggered by regular

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[60] Halevy, 2017, The geologic history of seawater pH

variations in the shape of Earth's orbit around the sun, their presence at this low latitude was controlled from below by subglacial friction and geothermal heat.

About 20 thousand years ago, a slight change in sunlight triggered a release of CO_2 from the deep ocean, warming the Earth and forcing the ice sheet to retreat northward. Left in its wake were large erratic boulders and sheets of meltwater sand and gravel that buried remnant blocks of ice. These later melted to form small lakes called locally known as potholes, but called kettles elsewhere. The shoreline sediments of these potholes contain the bones of shaggy ice-age megafauna who came to drink in a tundra landscape.

The deepest potholes contain a sedimentary paleoclimate archive for the present Holocene interglacial epoch. About 8,000 years ago, the summer climate was much drier and hotter than the one I knew as a child. As the water table dropped, hundreds of potholes dried up, forcing migrating waterfowl to congregate densely on nearby Kettle Lake, which was an unusually deep natural well. Within its sediments is a twenty-foot-thick strata of *struivite,* an unusual phosphate mineral that is effectively re-crystallized bird poop.

Within the surface soil we farmed with our plows, cultivators and reapers were the beautifully shaped arrowheads of Lakota Nation, who had been forcibly removed during western expansion of the United States before my ancestors emigrated from Norway. Stone implements littered our fields each spring, having been heaved up from below by winter frost before being washed clean by early rains. These artifacts indicate that the windswept short-grass prairie of indigenous peoples had been livable for millennia. Crusts of lime on the undersides of some reveal strong evaporation during the prairie summers, rather than moister forested conditions.

When the Lewis and Clark expedition passed nearby in 1803-1805, they described a strongly continental climate, with dry brutal winters, humid hot summers, and barely enough precipitation for rainfall agriculture. That's the one I remember as a child. The modern climate is already warmer and drier than that.

Cycle Time

Having covered All Time and Arrow Time, I now turn to ***Cycle Time***, the temporal, quasi-periodic cycles of Earth history that occur over many magnitudes of time. The shortest, like the Earth's spin, are familiar to everyone. Like clockwork, Earth rotates once each day, the moon orbits the earth every 28 days, and our planet revolves the sun in 365 days. Unlike clockwork, the frequencies of these cycles have been changing since the birth of our planet.

Earth's longest temporal cycle is the supercontinent cycle, which spans hundreds of millions of years. Driven by almost unthinkable mechanistic forces, the continents gather like rafts of flotsam into supercontinents like Pangea, then break up and disperse back into different continental fragments. Today, continents are scattered all over the globe with a lopsided concentration in the northern hemisphere. Scarcely 200 million years ago, most of the continents were clustered in the southern hemisphere. Before Pangea about 200-300 million years ago, there was Pannoitia about 500-600 million years ago, and before that Rodinia about 1000 million (1 billion) years ago, and before that, anywhere from 3 to 6 earlier supercontinents dating back to about 3 billion years ago, depending on how you define a supercontinent.

This is a pretty cool idea for a book about climate change because all climates present and past are fundamentally controlled by the distribution or clustering of continents, which, in turn, is driven by geothermal whole mantle convection. So, in the simplest sense, one's climate changes as one moves about. A car trip from Florida to Maine to experience a different climate could also be achieved by a tectonic trip.

Less familiar and shorter-term examples of Earth's temporal cycles include the changing eccentricity of its orbit every 100,000 years, the regular changes in tilt every 41,000 years, and the orbitally driven wobble of earth's axis of rotation every ~21,000 years. Quasi-periodic cycles at much shorter time scales include glacial Heinrich events at the scale of millennia, and the multi-year Southern Oscillation giving us El Nino and La Nina years.

The sun also behaves cyclically, with an 11-year sunspot cycle with slightly more and slightly less luminosity, though not enough to appreciably change the climate directly. There is, however, an indirect climate connection through the influence of sunspot cycles, which modulate flux of cosmic rays, which influences the amount of stratospheric ozone, which has a limited effect on our meteorological climate.

Physical, rather than ***temporal***, cycles, include the familiar movements of materials within earth system, for example the well-known water cycle. Falling as precipitation, it flows back toward the sea in rivers, aquifers, and glaciers... where it evaporates or sublimates back to the sky...from which it falls again as precipitation to start the cycle anew. The carbon cycle begins with volcanic gases of carbon dioxide, methane, and carbon monoxide dissolved in magma. These exsolve to the atmosphere during eruptions before being removed back to solid and liquid forms as soil carbon, peat, coal, limestone, petroleum and pitch. These liquid and solid forms of carbon eventually return back to the air via volcanoes, combustion, weathering, and metabolism. Sulfur, nitrogen, and phosphorous have related cycles as well.

Cycles are nested within cycles. A good example comes from the meaning of the concept "last ice age" which I treat here in powers of ten during the last billion years.

At the scale of ***one*** *[1]* millennia, glaciers were growing and shrinking throughout the globe during the last thousand years. This oscillatory pattern ended about 1950 with the rapid onset of human carbon emissions during the Great Acceleration. Half century earlier, the northern hemisphere was beginning to warm itself out of the so-called *Little Ice Age*, during which mountain glaciers in the Alps and Scandinavia expanded, beginning in the 14th century. The Greenland Ice Sheet also experienced Little Ice Age growth, reaching its maximum interglacial extent in the four centuries between 1450 and 1850.[61] Summit ice caps near the equator, for example [Quel-**kay**-uh] ~~Quelccaya~~ in Peru, also reached peak cold conditions during the late Little Ice Age between 1750 and 1850 CE. [62]

At the scale of ***10*** millennia, The Little Ice Age expansion and contraction was one of several advances and retreats during the present interglacial epoch called the Holocene, the 11,7000 years of

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[61] A particularly good record is from the Quelccaya ice cap in Peru. Annually Resolved Ice Core Records of Tropical Climate Variability over the Past ~1800 Years, by Thompson et al, Science 340:6135, 945-950, DOI: 10.1126/science.1234210

[62] Thompson et al., 2013, Annually resolved....

general warmth and stability in which civilization emerged. The most punctuated Holocene retraction of glaciers was during the mid-Holocene climatic optimum about 6000 years ago, a time when the Greenland Ice Sheet was smaller.

At the scale of ***100 millennia***, the Holocene interglacial was merely the latest in a series of ten interglaciations occurring within the last million years that came and went on a time-scale of a 100,000 years. During each, Earth experienced a period of about a 90,000 years of progressively colder and more glacial conditions that was followed much briefer warm intervals about 10,000 years long called interglacials. During each glacial advance, an ice sheet named after the Laurentian Mountains in Canada, expanded southward from source areas in the subarctic to expand as far south as Kentucky. During interglacials, it retreated back to Baffin Island, where a small residual remains today. These oscillations were in phase with other large ice sheets in the northern hemisphere, notably Scandinavia, the British Isles, Russia, and mountain ice sheets in western North America. Ice sheets and caps in the southern hemisphere expanded in parallel as well, but were much smaller.

At the scale of ***1,000 millennia***, or ***1 million*** years or longer, the main mechanisms shift from internal and orbital controls to irregular ones governed by tectonism. The Pleistocene Ice Age began with an abrupt cooling and the growth of temperate-latitude sheets about 2.6 million years ago. This is when the Greenland Ice Sheet assumed its present configuration, and when Iceland was first heavily covered by its namesake ice. This epoch-scale event was brought on, in part, by the tectonic emergence of the Isthmus of Panama, which forced warm, moist water northward on the Gulf Stream to precipitate as snow.

At the scale of ***10 million*** years, this epoch-scale ice age was the culmination of progressively colder conditions and expanding glaciers during the Cenozoic Ice Age. It's onset was about 40 million years of earth history when the Himalayan mountains began to rise to create what is sometimes called the Third Pole. An ice-free continent called Antarctica broke away from Australia to begin migrating toward the south pole, creating the circum-Antarctic oceanic current that locked Earth into the ice age it remains in today.

At the scale between *a **100 million** years*, our icy Cenozoic Ice Age, defined by the persistence of ice sheets at high latitudes, is merely the last of six or seven major intervals of ice-sheet glaciation during the whole of Earth history. These intervals, known as known as global *ice-house* climates, were separated by much longer intervals called *greenhouse* climates, the most recent of which a whopping 250 million years earlier during the Permo-Carboniferous glaciation. The ice-free Mesozoic Era is much more representative of the breadth of geological history than is our unusually cold modern world.

We will remain within what geologists call an ice-house climate state until the last polar ice has melted away, which will take quite a while. The last vestiges of that ice will likely be the most polar, shaded, and windswept portions of the East Antarctic Ice Sheet.

One time Singularities

The most challenging kind of time to understand in Earth history are its ***one-time*** events, those that are never repeated, but change the story forever. These are Earth's singularities. Its defining moments. Its dramatic scenes. Examples include: first drop of water in the ocean; the origin of life; the rapid oxygenation of the planet; the meteorite impact that took out the dinosaurs; the origin of

Homo sapiens; or the invention of the internal combustion engine. Each was a turning point in Earth history, never to be experienced again, but setting the stage for everything thereafter.

Earth's current climates cannot be understood without reference to geological time. This deep narrative is ***so*** more than a long, slow, straight arrow. It's a container for its cycles-within-cycles, and a scaffold for the great singularities Earth history, on of which was the emergence of human consciousness.

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TAKEAWAY

When defined more broadly, Earth's climate also includes changes in radiation from the sun and beyond, changes in the magnetic field, and changes in the flux of extraterrestrial dust and asteroids coming our way.

KEY POINTS

At the millennial time scale, the radiant energy streaming at us from the sun is nearly constant, varying by about 0.1 percent, enough to cause very small and very predictable climate effects. At the billion year time scale, the irradiance has increased from a much dimmer early sun and will continue to increase until earth is blown away.

The annual light shows known as meteor showers and the dramatically explosive meteors and shock waves of history are part of Earth's broader sense of climate. Based on NASA's inventory of Near Earth Objects, nearly a thousand asteroids 1 kilometer in size or larger have potential global impacts.

Magnetic weather manifests visibly as the aurora, most famously as the Aurora Borealis, or Northern Lights. The intensity, direction, and inclination of the field changes with every second.

Powerful gamma-ray bursts from beyond the solar system may influence earth's climate through a cascade of chemical effects involving nitrogen and oxygen including the ozone layer and stratospheric smog.

The dinosaur-ending asteroid creating Chicxulub Crater created the most dramatic episode of climatic change known to Earth. The atmosphere was roasted with molten blobs of rock that circled the earth, falling to light countless fires that darkened the skies for years, chilling the planet.

SCRIPT AND TEXT

Pause ......

Episode 18 - Cosmic Climates

Pause

Welcome to Climate Underground

I'm your host, Robert Thorson

Thanks for joining us.

Pause.....

The definition of climate is straightforward -- the *prevailing atmospheric conditions* of a given region. For the gaseous troposphere, these conditions involve meteorological phenomena like average temperatures, precipitation, and wind direction. Regional classification grouping these phenomena gives rise to our familiar named climates, such as hot-wet *tropical* and cold-dry *polar*.

But what about *prevailing atmospheric conditions* having ***little to do with*** the troposphere and its air masses? Think magnetism. Though it takes place within the atmosphere, it's neither a gas nor a substance. Instead, it's an electromagnetic field, one experiencing constant change or weather, and prevailing conditions or climate. Birds and butterflies flying in the troposphere depend on magnetism when they migrate, as do sea turtles and many other creatures. Simultaneously, they are in magnetic and tropospheric prevailing conditions.

Humans traveling over Earth's surface with a magnetic compass would find that the magnetic climate is changeable as with meteorological climate. But instead of temperature, rainfall, and wind, it's three main components are***: intensity***, a measure of strength; ***declination,*** the compass direction the needle is pointing; , and ***inclination***, the vertical component. As with tropospheric weather, these components experience constant change for the same fundamental reason: fluid motion. Just as there is a climate history, so too is there a magnetic history with direct, quantitative measurements dating back to 1590 C.E.

Below Earth's surface the prevailing magnetic intensity increases dramatically, reaching 25 units of Gauss at the core-mantle boundary. At Earth's surface, the strength of the magnetic field is about two orders of magnitude lower, ranging from 0.25 to 0.65 Gauss. Above the Earth's surface, the magnetic field weakens outward, even as it extends a great distance. In the direction facing the sun it extends to about ***65,000*** kilometers (40,000 miles) into the outer atmosphere. In the opposite direction in the magnetic shadow of the Earth, it extends over ***6 million*** kilometers (4 million miles). This zone is called the ionosphere. Being a EM field rather than a substance, magnetism overlaps with the temperature-defined units of the atmosphere into the Exosphere, which fades gradually away into space. At a distance of about 100,000 km (62,000 miles), roughly half way to the moon, the exosphere as we know it ends when we can no longer detect the faint glow of ultraviolet radiation being given off by rare hydrogen atoms excited by the solar wind.

In 1600, Sir William Gilbert, royal physician to Queen Elizabeth I of England, was the first to show convincingly that Earth's magnetic field resembles that of bar magnet with north and south poles, a dipole. A strong magnetic field has been present for at least 3.5 billion years, based on the magnetism of ancient rocks. And based on continuous measurements spanning centuries, we know that the field experiences continuous change. This requires the continuing presence of an electric dynamo.

This is where the similarity between meteorologic and magnetic climates gets really interesting. Except for the materials involved, they are both fundamentally created by the same mechanism, thermal convection followed by spin.

Earth's fluid troposphere is physically unstable because it's hotter at the bottom than at the top, having been warmed by the absorption of solar radiation. That heat rises by convection, creating cells of moving air that circulate up as they lose their heat, circulate down as they lose even more heat, and then are then re-heated to keep the process going. Earth's most familiar circulation of this type is the Hadley Cell, which moves up at the equator, down in the subtropics, and back to the equator. These cells are converted into helical rolls by the Coriolus force that manifest at the surface as the familiar trade winds. The troposphere is never at rest.

Earth's fluid outer core is also physically unstable because, like the troposphere, it's hotter at the bottom than at the top. The source of that heat is controversial. Nobody can go there to investigate, but geophysicists are pretty sure what's going on. Certainly, the liquid outer core is slowly crystallizing to solid mineral particles. These sink to accrete the growing inner core, releasing both the latent heat of crystallization, the heat created by friction, and the loss of potential energy. Additional heat is also being generated by the nuclear fission of heavier uranium isotopes located deeper in the solid core. Convective rise is aided by lighter elements exuded during crystallization.

Regardless of cause, the temperature difference driving convection in the liquid outer core is very high, being approximately **~5700 ºC** (10,340ºF) at the bottom and **~3500 ºC** (6380ºF) at the top. The viscosity of this hot iron is unknown, but may approximate that of liquid water. As a rule of thumb, geophysicist Bruce Buffet suggests that the distance of day's motion in the atmosphere is equivalent to about 100 years of motion in the core. Because we have only about 400 years of observational evidence, this is equivalent to having only four days' worth of data to characterize the meteorological climate.

As with the Hadley Cells rising above the surface of the crust, the unnamed cells rising above the inner core are elongated by the Coriolis force into helical rolls aligned parallel to the axis of rotation. Because these swirling rolls take place within an electrical conductor, they set up a dipole magnetic field. This process is thought to have been broadly stable for the last billion years, a time when we know the inner core was accreting. The geologic record suggests nearly 4 billion years of strong magnetism, without which life could not exist.

Magnetic weather manifests visibly as the aurora, most famously the Aurora Borealis, or Northern Lights. These are rapidly moving curtains and ribbons of shimmering light with colors somewhere between phosphor green and glowing red, and patterns that spiral, jet, or flicker. The light is produced when Sun's solar wind --a stream of charged particles, mainly electrons and photons-- collide with and ionize molecules of gasses in the atmosphere. The swirling and dancing lights reflect variations in the solar wind and Earth's magnetic field, and they are especially strong during solar storms. Seen from space, the auroral lights circle the poles like fuzzy green donuts.

Invisible magnetic weather is easily measured and tracked with instruments. The current location of the ***geomagnetic north*** pole is near Nunavut on Ellsemere Island in the Canadian Arctic. This is about 11 angular degrees away from the ***celestial north*** pole. The location of the magnetic pole is migrating toward Siberia at a velocity of about 40 km per year, and seems to be speeding up. Historic records show that this migration, has been continuous since first measured. In New England, stone walls from the 18th and 19th century were built on property lines laid out with magnetic surveying instruments. These no longer align with magnetic north because the ***declination*** has changed. The ***intensity*** of the magnetic field is currently diminishing, down about 10 percent from a century ago. The ***inclination*** varies continuously as well.

Earth's meteorological and magnetic climates are both fundamentally organized by latitude between equator and pole. Contour lines of equal magnetic force parallel lines of latitude. Perpendicular to these are enveloping lines of variable force that parallel lines of longitude. At the south magnetic pole, the lines of force emerge vertically, and curve gracefully at lower angles northward toward the equator where they flatten to horizontal. Moving to the northern hemisphere, they gracefully curve to steeper angles until they plunge vertically straight toward the dipole field at the core. Thus every line of latitude, north and south, has its own characteristic angle of inclination, a property very useful for assigning a paleo-latitudes to chart the ancient drifting of our continents.

Just as there are paleoclimates of the atmosphere, so, too, there are paleoclimates of the magnetosphere. Looking back through deep time with the broadest brush, the troposphere has two fundamental states: *ice-house* when it has polar ice caps, and *green-house* when we do not. Similarly, Earth's magnetic climate has two main states*, normal* and *reversed* polarity, between which the field flip-flops from one extreme to the other. The names normal and reversed are as arbitrary and inconsequential as the designation of north and south poles. Transition times between these states range from about 4 to 10 thousand years -- mere moments on the geological calendar.

For the last 780,000 years ago, earth's magnetic pole has been in the same state, the so-called normal state. But before that, the magnetic field lines were reversed. These reversals occur on average of about three times per million years.

The longest interval of magnetic stability known was during the Cretaceous Period when no reversals happened for a staggering 40 million years. This interval coincided with massive volcanism and tectonism. The best explanation for this anomalous magnetic stability is that something dramatic happened at the core mantle boundary, sending up an unusually strong and long-lasting pulse of heat strong enough to stabilize the magnetic moment in one direction only. There is nothing remotely comparable to this in the 160-million-year-long record of paleomagnetism.

The physical mechanism for magnetic reversals begins with ambient conditions. This involves a long-term deterministic term driven by convection and diffusion, and a short-term stochastic term driven by random noise. Flips are caused when times of diminished intensity from the deterministic term coincide with spikes of randomness from the stochastic term. This happens on average about once every 3 million years.

The more frequent events, those that show up in the record as diminished intensity and inclination, but which do not cause outright reversals, are called excursions. They happen much more frequently, roughly about 8 times per million years, and can occur within either polarity.

Though there is a link between Earth's magnetic climate and its tropospheric climate, they are usually temporary and limited. One example is the Lechamps magnetic Excursion about 42,000 years ago, which weakend the field, increasing the flux of cosmic radiation, thinning the ozone layer and briefly cooling the climate.

Indirectly, the magnetic field provides us with an opportunity to reconstruct the climatic force of the sun. Locked within the ice sheets is a continuous record of ^{14}C, a cosmogenic isotope created when the solar wind reacts with nitrogen in the upper atmosphere. The abundance of this isotope through time is preserved in the bubbles of the ice archive, preserving a history of the solar wind, the strength of which is controlled by Earth's magnetic field. The long-term record confirms two things, the regularity of sunspot cycles, and the remarkable consistently of solar luminosity. Changes in the strength of the sun at the century or longer time scales are small potatoes compared to other changes within the Earth System. One notable exception to this generality is the Maunders Minimum, a time of very low sunspot numbers between 1650 and 1715. This occurred within the prolonged Little Ice Age, and was not a cause of it.

The great value in discussing magnetic climates is not in the detailed physics, but in the broader mechanisms and chronologies. Both are created by the same cascade of three fundamental processes: heating from below, fluid convection, and Coriolus deflection. Both have two dominant and opposite states at long time scales: normal vs. reversed for magnetism, and ice-house vs. hot-house for meteorology. Both have additional modes at shorter time scales: events and excursions for magnetism, and millennial and century changes for climate.

Cosmic material

Our cities a bubbles of scattered light that diffusely brighten the night sky. Seeing more than a few stars is often challenging, and the Milky Way is invisible. Away from such light pollution, however, the night sky can be so dark that the Milky Way casts a shadow on the ground. The rural North Dakota I remember as a child from the mid 1950s and as a teenager from the mid 1960s was one such place. I developed a yearly habit of watching the Perseid Meteor Shower in mid-August. Like fireworks, it radiates outward from the constellation of Perseus, named for the son of Zeus.

These showers are bright streaks of light that fade as quickly as they appear, usually lasting no more than a half-second. Each of these showers is essentially the re-lighting of the tail of a comet from ages past.

Comets are primordial chunks of frozen ***gas,*** mainly water, methane, and ammonia, mixed with stony interstellar ***debris***--mainly dust-- that follow long orbits around the sun. When near the sun, the ices vaporize to create the visible tail. In the process, small pieces of grit, sand, and larger materials are ablated, or removed. These spread out in orbit as invisible elliptical rings. When Earth's orbit intersects these rings, the tiny particles are re-illuminated as streaks of light on parallel trajectories as they are burned up in Earth's high atmosphere. The fine residue eventually falls as dust. Coarser residues fall as small meteorites.

Annual meteor showers are well known and clearly named. Because they are prevailing atmospheric phenomenon, they broadly qualify as climatic, even though they are of cosmic origins.

The comet dust that falls on earth after meteorite showers is part of a much larger pattern of continuous fall. Each year more than 4000 tons of extraterrestrial materials settle on Earth's surface as dust from above. This steady fall can be likened to the steady fall of pollen on a piece of lawn furniture in spring. If you know the rate at which it accumulates, the mass of dust can give you a estimate of how much time has elapsed since you last wiped the surface clean.

Most of this dust comes from stuff that burns up or blows up in the atmosphere. According to NASA, any space rock smaller than the size of a school bus --about 82 feet (25 m)-- won't make it to the surface. For example, the 56-foot-diameter (17 m) rock that that lit up the sky over [Chill-**Yaa**-Binsk]

~~Chelyabinsk~~, Russia in 2013 exploded before it could make a crater, leaving only fragments.

But about 190 asteroids that fell in Earth's past were large enough to punch all the way down to its surface to leave visible scars called impact craters. The best preserved and most visited is the stunningly well-preserved Barringer Crater in the Arizona desert, also called Meteor Crater. It's 1.9 km (0.74 mile) across. The nickel-iron asteroid that made it is calculated to have been 50 meters in diameter, and traveling at the whizzing speed of about 12.8 kilometers per second (30,000 mph). When it fell about 50 thousand years ago the climate was wetter and fully vegetated, and surface erosion was beginning to blur it. Mammoths and ground sloths likely visited a watering hole at its base. Luckily, the Holocene climate became arid, slowing its rate of erasure, and preventing it from being cloaked by thick vegetation like one of those Mayan ruins in the jungle.

Earth's three largest impact craters, all more than fifty times larger than Barringer Crater, were created by chondrite meteorites ten kilometers across or more. These are: [**Vred**-duh-vert] ~~Vredefort~~ in South Africa with a rim-to-rim diameter of 160 km across and dating 2.00 billion years old; [**Chix** - ahh - lube] ~~Chicxulub~~ in Mexico at 150 km and dating to 66 million years old; and Sudbury in Ontario, Canada at 130 km and dating 1.85 billion years old. Each is special in its own way. All were discovered and initially studied for the associated mineral and energy resources.

Of these, the most famous is the Chicxulub Crater, the impact site of the dinosaur-ending meteorite about. Discovery of the crater is now one of the most fascinating stories of scientific discovery because it was predicted to exist long before it was found. Geologist Walter Alvarez was trying to come up with a way to determine the timing of the great extinction at the end of the Cretaceous about 66 million years ago. With the help of his father, Luis Alvarez, they decided to use the steady background sedimentation rate of cosmic dust as an indicator of elapsed time. Their tracer, or proxy for cosmic dust, was the heavy metal element iridium, which is very rare in earthly dust because most of it sunk downward into the growing core.

Working on lab analysis with Frank Asaro and Helen Michael, the amount of iridium dust they found was far too high to have come from the steady background dusting by tiny cosmic particles. It could only have come from a colossal meteorite impact. Their 1980 write-up, *Extraterrestrial cause for the Cretaceous-Tertiary extinction,* has since been one of the most widely cited scientific articles ever published.

The climate impacts went beyond extraordinary. This was the most abrupt climate change known since the final bombardment of Earth by meteorites at end of the Hadean Eon, the same one that pockmarked the Moon with craters. The impactor was about 10 kilometers (6.2 miles) in diameter. After striking Earth 66 million years ago, the atmosphere was instantly roasted with molten blobs of rock that circled the earth. Upon falling they lit countless fires, that released staggering quantities (~15,000 teragrams) of soot that blackened the skies for years, blocked much of the sunlight, chilled land and sea, and wiped out the base of the global food chain. It was an utter disaster.

With the climatic and ecological impacts worked out, the Alvarez team went looking for the smoking gun of an impact crater. None were found because the impact took place in a shallow sea, and the site was later blanketed by marine limestone, making it barely visible at the surface. Beneath that cover, the impact site extends to a depth of 20 km into the crust.

Since publication of the KT impact theory, there's been a heightened sense of alarm about game-changing meteorite impacts. Hollywood responded with the movie Armageddon. NASA responded with a robust program of inventory and prediction for Near Earth Asteroids, or NEAs. In late 2021, the current inventory was 28,000 NEAs, and about 3000 are added each year. As of January 2022, nearly a thousand are 1 km or larger, and have the potential for global impact. Nearly ten thousand are 140 m or larger, a size capable of randomly destroying a small city.

Counter-intuitively, the rate of asteroid impacts on planet Earth has not diminished since its birth by the same process. Instead, the last 290 million years, the last six percent of earth history, has been a time of unusually intense bombardment. [63] The rate of "incoming" asteroids during the Paleozoic was 2.6 times lower.

The topic of geo-engineering the atmosphere is being widely considered to help ameliorate the worst consequences of climate warming to come. One emerging idea is to deliberately spread a veil of dust in Earth's stratosphere that would reflect sunlight, and cool the planet. Another is to fertilize the ocean with iron to stimulate marine biological productivity and sequester carbon from the air. Setting aside the global political challenges, geological support for both of these ideas comes from a natural experiment done long ago. A team led by Birgir Schmitz reports in *Science* that, 466 million years ago, an asteroid exploded into iron-rich dust that blocked sunlight in the stratosphere and spiked the ocean with nutrient, causing an abrupt cooling into an age.[64] The good news is that this was quickly followed by an explosion of biodiversity known as the Great Ordovician Biodiversification Event, the most sustained and important enrichment of marine biodiversity ever, at least partially the courtesy of an asteroid explosion.

A final topic of philosophical note involves what are called "secondary craters." These are the results of primary impact craters so enormous that they splashed large rocky fragments high into Earth's atmosphere that then fell back down to the surface with enough force to create smaller craters. In Wyoming, 31 secondary craters the size of buildings or larger came from a primary crater whose location remains a mystery, likely because its buried by sediment.[65]

Broadly speaking, the steady rain of cosmic dust and the repeated fall of meteorites is part of our prevailing atmospheric conditions, and is thus an aspect of Earth's climate. This aspect of the problem is of the rare exceptions for which climate change comes at us from above, rather than from below. The best we can do to ameliorate this external threat is to nudge small asteroids away so they don't hit us. One experiment of this kind is underway as I write.

Radiation

A third and final aspect of cosmic climates involves the radiation received by Earth from anywhere in the universe, mainly the sun. Regional differences that might be considered climatic, are due mainly to Earth's magnetic field which steers, shields, and focuses incoming radiation and the solar wind, and Earth's ozone layer, which selectively blocks incoming radiation, especially harmful

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[63] Mazrouei, 2019, Earth and Moon impact flux

[64] Sokol, 2019, Dust from Asteroid breakup...

[65] Science Staff, 2022, News at a Glance

ultraviolet radiation. Changes in either the magnetic field or the ozone layer change our cosmic climates.

The most pervasive radiation is the faint cosmic background radiation filling the entire universe as a consequence of the Big Bang 13.8 billion years ago. Earth receives its tiny portion uniformly and without change, mainly in the microwave portion of spectrum.

Most local and predictable is our daily dose of radiation from the sun, called irradiance. When I was learning science in grade school, the sun's output was treated as an invariant constant: roughly 1.36 kilowatts per square meter on a plane held perpendicular to the sun at one astronomical distance, meaning the distance between Earth and the sun. The so-called constant is actually a current average value that varies up to 0.1 percent higher during a solar maximum, when sunspots are more common, a pattern that follows the familiar 11 year solar cycle. The maximum range within the last 400 years of measurement has been about 0.2 percent. It's nice to have such a steady friend in El Sol.

This irradiance is equivalent to about 2 calories of heat energy added each minute for each square centimeter. This is the heat you feel when you stand in the sun. That heat is the power that drives the weather.

The most variable aspect of radiation climate are gamma ray bursts -- intensely energetic explosions that are thought to occur during supernova eruptions during the birth of black holes or neutron stars. The energy released in a few seconds is equivalent to the total that will be released by our sun in its expected ten-billion-year lifetime. The good news is that they are very rare, and the radiation is focused in a narrow jet perpendicular to stellar rotation.

The main effects on earth would arise from changes in atmospheric chemistry involving nitrogen and oxygen, which may lead to destruction of the ozone layer and a cascade of other effects involving: a sun-blocking photochemical smog from nitrous oxides, and potent acid rains from nitric acid. The role of such gamma ray bursts in Earth's past climate changes and extinctions are largely unknown.

In summary, climate defined narrowly, is average weather. Climate defined more broadly includes other prevailing atmospheric phenomena such as magnetism, incoming cosmic debris, and changes in radiation.

Part 3 - Past and Future

19 - ENERGY TURNING POINTS - 3343

TAKEAWAY

The great singularities of organic evolution reveals that life has always been in search of more concentrated forms of energy. Humanity's current obsession with fossil fuels follows a trend dating back to the origin of life.

KEY POINTS

Life came from nonlife when it captured tiny zaps of external abiotic energy to grow and reproduce in some scalding, anoxic, volcanic setting where nucleic acids, amino acids and lipids came together.

Photosynthesis captured the energy of the sun that streamed down from above, changing Earth forever by exhausting oxygen to the hazy skies of the Archaean Eon.

The supernova of biology, the Cambrian explosion occurred when animals emerged to eat other living things for the first time, including each other. Trophic cascades came on the scene as the slow fire of digestion.

Humans captured the fast fire of combustion to make a hearth a home, and to use as a versatile tool. Cooked food led to bigger brains and a more cohesive social group, fostering language.

Finally, humans captured the even faster fire of combustion within a chamber that converted thermal to mechanical energy, igniting the industrial revolution in the mid 18th century.

Each energy singularity changed Earth's climate forever.

SCRIPT AND TEXT

Pause ......

Episode 19 - Energy Turning Points

Pause...

Welcome to Climate Underground

I'm your host, Robert Thorson

Thanks for joining us.

Pause.....

SETI

NASA's search for life on Mars is an unrequited obsession. The precursors for life were definitely there 3 billion years ago at a time when microbial life was thriving on Earth. Mars had an abundance of organic molecules from which life could be assembled. It had a cool moist atmosphere with water flowing in streams and building deltas in seas. Those seas left behind is an archive of sedimentary rocks that have recently been explored for signs of life. Alas, after five rover missions --Sojourner, Opportunity, Spirit, Curiosity, and Perseverance-- that cruised, drilled, sampled, and analyzed surface materials, researchers have found no evidence for life on Mars, present or past, other than the robotic geologists we sent there.

The apparent absence of life on Mars has not silenced interest in the *panspermia* hypothesis that life on Earth originated elsewhere in the solar system before being splashed here as passengers within asteroids from Mars or beyond. The few meteorites we have from Mars have been intensively scrutinized, but reveal no sign of life.

The apparent absence of life elsewhere in our solar system is somewhat surprising because the molecular building blocks of life are abundant throughout it, and presumably elsewhere in the universe. In fact, they're so abundant in carbonaceous chondrite meteorites that some smell like tar when freshly broken. The most carefully studied of these, the stinky Murchinson meteorite, was witnessed to fall on Australia in 1969. It contains up to 12 percent water by weight, and had more than 70 amino acids. But there is no sign of life. "So far as we know," writes cosmochemist Tim Gregory, "the Earth is the only place in the Universe where molecules evolved into minds and can question their own origins." [66]

The most tantalizing possibility that life may exist elsewhere in our solar system is the presence of a gas called *phosphene* in the acidic upper atmosphere of Venus. As originally reported, this gas is present in quantities great enough to suggest the likelihood of microbial metabolism. Recent studies, however, have downgraded this interpretation back to the mere suggestion of life. If Vesuvian microbes are present, they must be airborne because the surface of Venus is far too hot to support them; Mariner 2 measured that temperature at 932 degrees Fahrenheit before it was fried to a crisp.

Origin

In a previous episode we explored three types of geological time: the *all-time* of universal constants, the *arrow-time* of familiar history, and the *cycle-time* of repeated events, and only mentioned a fourth kind of time: the *one-time* events of game-changing singularities. In this episode, we continue the narrative of Earth history by examining key turning points from which there was no turning back.

Because the story is so huge, and because this is a podcast about climate change, I narrowed that story for singularities down to a single theme: the *energy transitions* associated with the history of life, beginning with its origin.

The origin of life is the ultimate singularity for climate change because, without it, there would be no knowledge that life exists at all. Since its creation, life has played a huge role in Earth's carbon and

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[66] Gregory 63

oxygen carbon cycles, and therefore its climate. And, of course, there would be no fossil fuel because there could be no fossils, and nobody to burn it.

For starters, we don't yet know whether the origin of life is singular or plural. There may have been several origins prior to about 4 billion years ago, each rebooting from scratch following a colossal meteorite bombardment and wholescale melting of the surface.

The last, and perhaps only, origin of life occurred between 4.0 and 3.8 billion years ago in some scalding, anoxic, volcanic setting where: -- nucleic acids, amino acids and lipids came together in one place and figured out a way to use tiny zaps of external chemical reactions to grow and reproduce. Those reactions with mainly carbon compounds may also have involved hydrogen cyanide (HCN), hydrogen sulfide (H_2S), various metal brines, and perhaps the surfaces of clays or other minerals.

But what, exactly, is life? Presently, there's no standard universal definition.

I like paleontologist Andrew Knoll's progressively less succinct definitions, beginning with: "chemistry with a history," and followed by "organisms are chemical machines that evolve through time." The latter combines the two key points: metabolism and genetics. His slightly less parsimonious definition is anything characterized by "growth and reproduction, metabolism and evolution." In other words, life is a "self-sustaining chemical system capable of incorporating novelty, a replicator capable of being selected."[67]

Science writer Carl Zimmer devotes a whole book to the subject: *Life's Edge: The Search for What it Means to Be Alive."* His short list of life traits includes: "metabolism, information gathering, homeostasis, reproduction, and evolution." An even shorter list distilled by experts is "self-reproduction with variations." Some philosophers argue there's no point in having a definition at all because it narrows our thinking. Others opt for an empirical definition, deciding that life is anything that couldn't have arisen by chance, which, statistically, is any cascade requiring more than 15 chemical steps.

Regardless of your definition of life, there's no question that it sprung from non-life as an emergent phenomena: a thermodynamic island of local order feeding off the growing disorder of a larger system. At this conceptual level, an eddy emerging from a stream and a living cell emerging from a briny geothermal soup are separate manifestations of the same thing. A whirlpool, can't replicate itself. A more fit whirlpool can't be selected over a less fit one. There's no direct selection for better landforms, oceans, mountains, and so forth, meaning they cannot evolve as isolated components of the Earth system. But it is quite fair to say that they evolve indirectly because they are always responding to the evolution of life.

The oldest evidence of life is a speck of carbon inside an igneous zircon grain found at Jack Hills Australia dating to 4.1 billion years. It's depleted in the isotope carbon 13 relative to inorganic carbon, suggesting it came from a living thing. The oldest compelling biomarker or chemical signal for ancient life dates to 3.8 billion years from volcanic rocks of Earth's oldest proto-continent, the Isua Supracrustal Belt in west Greenland. The oldest bona fide physical *fossils* are tube-like structures in rims of volcanic pillow lavas that are 3.5 billion years old.

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[67] Knoll, 66-67. Check out Hazen 127 for paraphrase.

Genetically, the oldest living thing on Earth that could have given rise to everything else --our LUCA or Last Universal Common Ancestor-- is a sulfur reducing (uses sulfur to release energy), autotrophic (creates their own food, like plants), prokaryotic (lack a nucleus), hyper-thermophile (loves scalding water) that can tolerate ambient water temperature up to 140^{o} C (280^{o}F), which is well above the boiling point of water. A volcanic source seems assured, but whether this was a deep sea vent or a shallow pool remains unresolved. A deep source is suggested by the fact that the early Earth lacked significant ozone to protect cells from being destroyed by ultraviolet radiation before they could spread.

Many other arguments support a volcanic origin of life circumstantially: the ubiquity of marine spreading centers, the solubility of needed metals in hot acidic water, the abundance of phosphorous and nitrogen, and an abundance of crystals and clays that could have lent a substrate for assembly. [68]

Since its origin, the dominant forms of life on earth has remained close to the original, likely a microbial slime or film, or mat growing in the absence of oxygen. Genetically, these anoxic hydrogen oxidizers, sulfur reducers, and methane producers are the bottom rung in the chain of life. None of the six five Phanerozoic mass extinctions ever come close to wiping out Earth's microbes, because they are capable of living in the deepest, darkest environments.

In one recent and spectacular study, eight bacterial groups similar to those living on Earth's surface, have been found in sediments buried 101 million years ago. Apparently, they have been existing in isolation since then, perhaps in some sort of hibernation.[69]

Some bacteria, it turns out, are technically too big to be considered microbes. Recently discovered in the roots of mangrove trees by microbiologist Verena Carvalho is a new bacterium that is 2 cm long and has a giant genome. The provisional name is *Thiomargarita magnifica*. It's 500 times larger than anything else known.[70] You can see them wiggle with your naked eye. What on earth will we find next?

Singularities

The second great energy singularity was to shift to solar and away from geothermal. In a word, a shift to photosynthesis, the ability to synthesize organic compounds by using the energy of photons to strip hydrogen from water, combine it with carbon from the air, and make sugar. The first organisms to do were cyanobacteria, formerly called blue-green algae. And they're still around.

Tapping the sun's power greatly revved up the energetics of Earth's surface. But the spread of microbial life was held in check by the concentration of nutrients in the chemical broth from which the molecules of life were extracted. The critical ingredients in that broth were the elements carbon, hydrogen, nitrogen, oxygen, phosphorous, and sulfur, CHNOPS for short.

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[68] STANLEY 2015 *Hydrogen oxidation* $2H_2 + O_2$ à $2H_2O$ + energy *Sulfur reduction* $S + H_2$ à H_2S + energy *Methane production.* $CO_2 + 4H_2$ à $CH_4 + 2H_2O$ + energy

[69] News at a glance, 2020, Oldest microbes found?

[70] Pennisi, 2022, Gian Microbe...

Today, the total energy captured by photosynthesis is a mind-boggling 130 Terawatts, which is six times more than all humanity uses in a single day. Still, this is only a small portion of the total illumination by the sun. One salient result of photosynthesis is the release of its exhaust gas oxygen. Prior to about 2.4 billion years ago, evidence for only faint, dilute, and rare puffs of free oxygen have been found. Thanks to photosynthesis, it now consitutes about 18% of our atmosphere by mass.[71] From the point of view of Earth's early microbes, oxygen was a toxic pollutant. It's also hard on animal bodies, which is why we need "anti-oxidants" to remain healthy.

Bounding the halves of earth history without and then with oxygen is the Great Oxidation Event, or GOE, which took place roughly midway through Earth history. Before then, in that chemically reducing world, ancient beaches were golden with pyrite, an iron sulfide known as fool's gold. Ancient streams were full of pitchblende, the ore of uranium. The oceans were tinged dark with dissolved iron, masking the familiar blue of today. The geological record suggests earlier traces of oxygen, but these were quickly gobbled up by the chemical hunger of so many molecules for available oxygen.

All of this changed rapidly at the time of the GOE when the concentration of gaseous oxygen rose to about 1 percent volume in the atmosphere. The smoggy orange haze of reduced organic compounds in the air disappeared. After that, there was enough free oxygen left to dissolve into the ocean and precipitate its iron into beds of metal oxide and red chert. This oxidation did not occur in one fell swoop. Rather it flickered back and forth until the transition was complete.

Was the climate changed? That depends on how you define climate. The prevailing physical meteorology was much the same before and after the transition. But the chemistry and clarity of the atmosphere were very different. That qualifies as climate change to me.

The ***third*** great energy singularity for life was the ability to absorb food directly from the sea, rather than make it by photosynthesis. This was first accomplished --we believe-- by the odd entities known as [Edd-ee-**ack**-run] ~~Ediacaran~~ fossils. Evolving from sponge-like predecessors, this biota constitute the oldest well-organized form of multicellular life. These soft fossils showed up abruptly in the geological record about 600 million years ago as the Earth was warming out of its Cryogenian ice house state at the end of the Proterozoic.

In form, they take a variety of shapes resembling tubes, disks, air mattresses, fronds, and cones. None are thicker than a few millimeters, giving them large surface areas relative to volume. In habit, they lacked hard parts and moving parts, suggesting they apparently lay like immobile amoeba on the sea floor beyond the reach of ultraviolet light, or were attached to the bottom, obtaining their energy by directly absorbing dissolved organic matter through their outer membranes and growing to the size of frisbees. In taxonomy, for many years it was not clear whether these were animals, colonies of protists, or symbionts, as with lichens.

This changed In 2018, when a team of chemical paleontologists learned that most iconic Ediacaran fossil of all, [Dick-En-Sone-ia] Dickinsonia, a bilaterally symmetrical oval-shaped form, contained cholesteroids, a biomarker "found only in animals." [72]They conclude that the limbless, soft

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[71] Drewney, 19

[72] Bobrovskiu, 2018, Ancient steroids...

Ediacaran creatures were animals, precursors to the explosion of biodiversity and complexity at the base of the Cambrian.

By the aftermath of the Cryogenian ice age, there was apparently enough organic matter dissolved in the sea, and enough oxygen available to metabolize it. A comfortable living could be had by soaking up the tea, the dilute organic broth of sea water. There was no significant climate impact that we know of associated with this fauna.

The ***fourth*** big singularity of life with respect to energy, known as the Cambrian explosion, happened 542 million years ago. This supernova of biology, marked the onset of most of the major animal groups we have today, and the complete replacement of the Ediacaran fauna. This marks the base of the Cambrian Period, which marks the base of the Paleozoic Era, which marks the base of the Phanerozoic Eon. That's how marked this singularity was.

Organisms became mobile for the first time in the fossil record. Stated another way, evidence for true animals emerged. In fact, the Cambrian is officially defined not by a body fossil, but by the trace fossils of a burrowing worm (*Treptichnus pedum*) in marine muds of Newfoundland.

The explosion was not of life, but of life on the move, and of hard parts that could preserve in the fossil record. Hard parts like teeth strong enough to tear some hapless creature apart. Hard parts like shells to armor one's self from those predatory teeth. Limbs to move, to chase whether something to eat or to escape to safety from being eaten. Sensory organs like eyes and ears, electric fields, and pressure transducers to seek food and to avoid becoming food.

This kind of Nature, this last ninth of Earth history, is the part giving rise to the phrases "eat or be eaten," and "Nature, red in tooth and claw." Charles Robert Darwin, who agonized at the abruptness of the Cambrian transition, remarked on this new type of natural selection: "What a book a devil's chaplain might write on the clumsy, wasteful, blundering, low, and horribly cruel works of nature!" This burst of biodiversity was less about filling abiotic niches than filling niches created by the game of consuming one another.

Rather than drawing energy from the sulfur chemistry of volcanic vents as did the first bacterial extremophiles, or by using sunlight to bind carbon and oxygen, as did photosynthesizers, or by soaking up an organic broth through cell membranes as did the Ediacarans -- for the first time in Earth history, natural selection rewarded organisms for eating other organisms, dead or alive. In a single virtual geological instant, herbivory, carnivory, and omnivory flashed onto the scene.

Trophic cascades came into being. The higher up the food chain you ate, the more concentrated the energy was in your meal. This was a very successful invention because the same basic cascades emerged independently after each mass extinction. The marine apex predators of today, killer whales of the Cenozoic, occupy the same trophic level held by the mosasaurs of the Mesozoic, and the armored placoderms of the Paleozoic. The terrestrial apex predators of today, the wolves of the Cenozoic occupy the level held by velociraptors of the Cretaceous and the therapsids of the late Paleozoic. The airborne apex predators of today, the birds of the Cenozoic occupy the level held by pterosaurs of the early Mesozoic and the giant dragonflies in the late Paleozoic. All of these forms come from lineages created during the Cambrian explosion.

The implications for climate change are enormous, because the hard parts are made almost exclusively of the bio-mineralized calcite that became the limestone that soaked up the carbon dioxide that cooled earth down from the scalding bath temperatures of the Cambrian ocean before the explosion, estimated to be about 34ºC or 95ºF, more than twice those of today.

Terrestrial animals would later become key players in Earth's climate story, most notably grazers, who played a key role in building carbon up in the soil.

Humans are the only group of animals in the history of life that ramped up energy use up to the ***fifth*** level. The controlled use of fire. This level went beyond the ***slow*** oxidation of organic matter via digestion to its ***rapid*** oxidation via combustion -- of grass, wood, and coal for a variety of reasons. Just as photosynthesis was a precursor of animal existence, so, too, was fire a precursor of humans existence. All thirteen species of our genus Homo used fire. No other great ape does. This seems to have made the difference.

As with the nucleus of an atom or the star of a solar system, a central hearth of fire in the dark brought early hominins together in a circle of safety from wannabe carnivores. It illuminated them in a circle of warmth and light, fostering social interaction and facilitating social and language development. At the center of those circles was roasting food rendered more palatable and nutritious for having been cooked, allowing for smaller stomachs and larger brains. The quest for fire was effectively the quest for humanity.

The controlled use of fire was put to many uses. It was a versatile tool for frightening predators away, communicating with other humans at a distance, driving herbivores together for an easy kill, burning off surface vegetation to create wood-free clearings, destroying the homes of enemies, and bringing light into underground caves so that they might be transformed by art.

On the ground surface everywhere --except for ice sheets and deserts of sand-- was an ubiquitous supply of fuel, whether grass, brush, dung, shrubs, or wood. Natural fires set by lightning or by molten rock would have been common enough to observe and learn from. Burning beds of peat with leaves and logs may have aided the transition burning beds of lignite coal. Given the power of combustion, anything that *would* burn *was* burned when it could be put to human advantage.

At some point, some campfire smothered in ash created the improved fuel known as charcoal, which concentrated the heat of carbon even more because the volatiles that burn at a lower temperature had been driven out. Though harder to ignite, both charcoal and its namesake coal burned longer than wood and were denser with energy. Additionally, they could be transported easier.

The climatic implications are clear, especially for local climates. The albedo changes when forests are burned. Soot has a local cooling effect.

The final singularity

The final and ***sixth*** energy transition was to control the use of fire ***inside*** a combustion chamber. This allowed the conversion of heat energy ***into*** mechanical energy. The initial success was the steam engine invented in England in 1712 by Thomas Newcomen, and greatly improved in the 1770s by Scotsman James Watt. Fire was used to boil water and a strong chamber was built to control the powerful *phase transition* from liquid to vapor. The explosive expansion drove a piston, which rotated a shaft, which was put to any number of uses: driving a pump, moving looms, sawing wood, pounding iron into shape, and so forth. The industrial revolution was born. A turning point in human history.

Transportation was revolutionized as well. Railroad locomotives were steam engines on wheels that moved themselves forward on parallel tracks. Steamships were steam engines that turned underwater er propellors, moving the vehicle forward. The first automobiles were steam engines too, moving themselves forward on roads. By carrying or hauling combustible fuel, power could be made available anywhere at any time. The positive feedback was astonishing. Coal burned in a steam shovel could be used to mine coal that could be hauled by steam locomotive could to places that burned coal to make more steam shovels.

The steam engine was succeeded in the late 19th century by the improved technology of the internal combustion engine. They are to internal combustion engines what typewriters were to word-processors.

For mechanical engines, the main technological impovement was skipping the step of boiling of water. Steam no longer dove the pistons. Instead it was the even more powerful explosion of a vaporized mist of liquid petrochemicals mixed with oxygen and ignited by a spark.

The stepwise success of engines set up a positive feedback between energy use, power, and wealth. Wood gave way to coal, coal gave way to oil, oil is giving way to gas, and soon this will all be abandoned ... I hope.

We now stand at another critical energy singularity. The phasing out of these fossil fuels, hopefully by 2050. Despite decades of warnings about climate change, however, the global human society remains stubbornly addicted to fossil fuels. Why? The simple answer is that each of life's energy singularities involved finding a more concentrated forms of energy, and that fossil fuels are no different. They're the most concentrated form of energy we've found that is currently deemed safe enough and cheap enough by global culture. Fossil fuels currently contribute nearly 70 percent of all global energy demand.

Perhaps the transition away from fossil fuels will be accelerated by the arrival of nuclear fusion. That could revolutionize nearly everything. That might be the seventh great energy transition of life history.

20 - POLYCHROME EARTH - 2453

TAKEAWAY

Going green has become a cultural meme that preferences one color of nature over another, terrestrial ecologists above other natural scientists, and that misrepresents the bulk Earth history.

KEY POINTS

Green is the general color direction we're heading in this warmer, wetter more carbon-rich atmosphere of our own making, with lusher forests over higher mid-latitudes and no permanent ice sheets at all.

Earth is a polychrome planet dominated by blue that has changed its default terrestrial color many times from a global red-hot magma, to a black basalt crust, to a blue universal sea. The creation of terrestrial landscapes gave us the earth tones of gray-brown rock and dry soil.

The strong oxidation of the atmosphere 2.4 billion years ago cleared an organic haze of orange into blue skies and painted the unvegetated terrestrial earth in rusty yellows, oranges, and reds.

The greening of terrestrial continents in the mid-Paleozoic and the consequent great increase in weathering sequestered so much carbon that it plunged us into an icehouse conditions.

SCRIPT AND TEXT

Pause ......

Episode 20 - Chameleon Earth

Pause

Welcome to Climate Underground

I'm your host, Robert Thorson

Thanks for joining us.

Pause.....

Returning to Green

When training to become an exploration geologist, I attended a boot-camp summer field school in the Bighorn Basin of Wyoming. It was my first experience of visiting and working under desert conditions. I recall a baking-hot summer landscape colored by the dusty browns and grays of rock and rubble, with rattlesnakes common. Returning to the Midwest in late August, we crossed over brown sea of short-grass prairie on the high plains of South Dakota before reaching the cultivated patchwork of settled agriculture -- with dull green pastures, tawny fields of harvested grain, and some gray-brown fallow fields. The final leg of my journey was northward into the cooler, northern forests of pine, birch, maple, and aspen. I'll never forget how wonderful it felt like to be surrounded, once again, by lush, moist, green woods after spending a summer in earth tones. This memory comes to mind whenever I hear the phrase "going green."

Four years earlier, on December 24, 1968, the crew of the Apollo 8 spacecraft was orbiting the moon with Earth hidden from view. Curving over the moon's surface, William Anders glanced out the window and said: "Oh my God! Look at that picture over there! There's the Earth coming up. Wow, that's pretty." That's when he snapped *Earthrise*, my favorite photo of home. Above the bleak, dusty gray of the pock-marked lunar surface, our planet was a brightly lit blue marble. White bands and circles of clouds signifying atmospheric circulation swirled over a background of ocean blue. There's only one patch of tawny brown and another of dark olive green.

Seeing the blue marble raises the question: Why is "going green" such a big deal in environmental culture and politics when it's such a small part of the actual earth? Why is the minority color of green singled out and prioritized over the majority of other, equally natural colors: the blues of water, whites of clouds and snow, the pastels of beaches, and the many hues of painted deserts. Could our bias toward green be an atavistic wish for the forest canopy of our primate ancestry before we left the trees for the savannah? Was it this instinct that kicked in when I returned home to forest after my first extended sojourn away?

When Lake Erie goes green with algal blooms, the default *blue* color of the clearwater lake is painted over.... fish die for lack of oxygen... neurotoxins taint the water... and the landscape stinks of sulfurous rot. This kind of going green is not a good thing. As I write, the Himalayan Mountains are going green in our warming world because the glaciers are melting back, and a carpet of green tundra is expanding in their wake. This kind of going green is not a good thing.

Happily the Grand Canyon of the Colorado Plateau is heading in the opposite direction towards browner, hotter and drier conditions during the region's worst megadrought in a thousand years. If, the canyon country *were* to go green, we would lose the very features that makes it so attractive, the polychrome rock and the steep, sharp angles of its slopes. Within the blink of a geological eye, it would begin to resemble the curved highlands of West Virginia where the elevated Appalachian Plateau is underlain by flat-lying Paleozoic rocks. The differences in landscape shape, from angular in Colorado to curved in Appalachia, is mainly a consequence of a moist soils and an interwoven fabric of roots in humid regions.

The color branding of environmental politics may be instinctive, but it sends the message that green environments are better than non-greens. They are not. A green polar bear would be a dead polar bear because the loss of white camouflage would be fatal. Green colors are no better and no worse than the yellow-reds of the painted desert, the gray-browns of exposed rock, the blues of the sea, and the whites of ice sheets. Going green is a form of color chauvinism that reinforces the implicit bias that terrestrial biomes are better than aqueous others, and that moist biomes are better than dry or snowy ones. Within the natural sciences, the phrase going green prioritizes botany over zoology, forest ecology over dune ecology, and terrestrial ecology over oceanography, glaciology, and outcrop geology.

Earth is a polychrome planet that has changed its default colors many times. Each of these color changes involved a climate change of one form or another.

Early Colors

When Earth was an infant planet, there was no hint of green anywhere. At the surface was an orange-yellow glow the magma ocean in the process of cooling down to basalt. Above the surface, the early sun was too feeble to penetrate a dense blanket of stratus clouds holding ocean's worth of water. Straight streaks of light from meteors, and jagged streaks from lightning, struck the earth frequently. Seen from the moon, there was only one earth tone, a diffuse, off-white veneer of water clouds tinged brown with methane and other organic compounds. At this hot stage, and without land, Earth had only a single enveloping climate.

Earth's second surface color was mostly black. The magma ocean had crystallized into a thickening basaltic crust, except where red-hot lava was flowing. The only green to be seen was the apple-green color of olivine mineral crystals tinging the otherwise black and dark gray of basalt.

At some threshold level of cooling, freshly distilled water precipitated from the thick stratus to submerge the thin black crust with a universal ocean deeper than that of today. From above, it was blue, though not as azure blue as today, given the dissolved iron and organics. Above the water was a hazy brown sky like that of serious air pollution today.

Earth's first terrestrial landscapes were broad shield volcanoes dotting the surface like a global archipelago. Over time, the partial melting of basalt created clots of silica-rich crust that hardened into rocks like granite and gneiss that floated higher than the darker more primitive rocks. These clots merged to form terranes that merged to form the nuclei of continents called cratons. Though too buoyant to be subducted back down into the mantle, they were constantly in the process of being recycled, amalgamated, and broken. By the end of the Archaean about 2.5 billion years ago, much of today's continental crust had been created. A pallet of terrestrial earthtones became possible, dominated by the dull grays and browns of rock, the color of sun-blasted and etched concrete. The bulk of the sea kept its off-blue color.

This would change during the Great Oxidation Event about 2.4 billion years ago. The chloroplast green of photosynthesis began coloring shallow waters near the beginning of the Proterozoic about 2.4 billion years ago. Microbes known as cyanobacteria rimmed the otherwise largely lifeless planet as biofilms, and as strange mounds called stromatolites composed mainly of limestone. Their waste gas was oxygen, an element that merges with metal ions like iron and manganese to create countless shades of rust, giving soils, for the first time, their characteristic yellow, brown, and red colors, dominated by the *terra cotta* of fired pottery and deep tropical soils.

The sea, clarified of iron, turned bright blue. The air, clarified of its photochemical haze, turned brilliant blue. As with Mars today, the land surface was stony, dry, rusted yellow-red to orange, jagged badlands, and decorated with lacy braided streams. On Mars, this 3 billion year-old color is frozen in time. On Earth, similar colors were painted over.

The next important color was white. Near the end of Earth's Proterozoic Eon, during the Cryogenian Period, 720 to 735 million years ago, Earth experienced the coldest condition of its entire history. With its carbon cycle temporarily out of whack, glaciers grew to engulf the entire terrestrial planet. Pack ice and ice shelves like those of the Arctic today covered the equatorial oceans. Such intervals of intense glaciation are nicknamed *snowball earth*. On four separate occasions during the period, the whole Earth became white before it reverted back to clear blue oceans and Mars-colored landcapes.

Terrestrial Green

The earliest true plants clung to the marine shore because they, like amphibians, relied on standing water to reproduce. So, initially, only a narrow fringe of green separated yellow-red land and blue sea.

Beginning about 475 million years ago ground-hugging, rootless, spore-bearing plants like liverworts began to move inland. By 430 million years ago, there were brushy club mosses and towering tree-like fungi that more closely resembled single-stemmed saguaro cacti. By 420 million years ago, during the mid- to late Silurian Period, plants had evolved *pores* called stomata that could open and close to take in carbon and exhaust oxygen without desiccating. They also developed the vascular tissue to support those exchanges,[73] a plumbing system of cells that allows them to pump water up from root tips to the air, and to pump dissolved nutrients wherever they were needed.

The first true forests of mid-Devonian age, 395-385 million years ago, were dominated by [Gill-**bo**-ah] ~~*Gilboa*,~~ enormous plant with trunks resembling those of palm trees and a canopy of fronds resembling those of ferns and horsetails. Following it were trees that look familiar, the Late Devonian [ar-ee-**op**-ter-is [~~*Archaeopteris*~~ forests, which resembled slender cedars or junipers a hundred feet tall. The biomass of new forests sopped up carbon from the air, reducing its concentration, and cooling the climate.

The spread of forest created abundant food and habitats in a setting where previously, only the most pioneering animals like spiders had existed. This food was out of reach for the lobe-finned fish of the shore, and the ponderous amphibians of the nearshore. The evolutionary voltage to claim the food of the forested interior was enormous, giving rise to another new invention about 340 million years ago, the animal amniote egg. This was a water-tight package that could resist desiccation and feed growing embryos. With that invention, animals dispersed over the continents.

A Devonian forest ecosystem was thus born, not as a single package, but as a series of breakthrough inventions that accumulated one at a time: chloroplasts, vascular tissue, roots, stomates, seeds, animals, and others.

What had previously been exposed rock and rocky sediment became a shaded carpet of roots within a fluffy soil that covered the land with organic fiber. Rains that formerly washed away in flash floods to leave dry braided channels could now soak in to the surface to feed aquifers below, and to be

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[73] Gensel, 2021, When did terrestrial plants arise?

sponged up by fiber. Deserts became non-deserts, not because more or less rain fell, but because the rain that did fall could –for the first time—be held in place. The flow of streams lasted longer when fed by these aquifers, than by the formerly quick gully-washers.

The growth of forest also changed the hydrology of continental interiors. Much of the rain that formerly ran off to the sea could now be stored in interior aquifers where it could be sucked up by plant roots and transpired back into the air through leaf stomata to raise the humidity. Much of the rain that fell in such continental forests had been recycled into and out of the ground several times.

That carpet of plants needed mineral nutrients in order to grow. In the sea, those nutrients could be absorbed from liquid water. On land, they must be taken from the rock by bacteria, strands of fungi, and plant roots working together symbiotically. Such a network of roots is much more effective at weathering crustal rock than merely being washed by the rain. As a consequence, the spread of land plants led to an order-of-magnitude increase in the rate of chemical weathering and mineral nutrient flux.

Under this scenario, rocks turned into silts and clays instead of merely sands, giving rise to broad alluvial lowlands with perennial meandering streams, rather than vast alluvial fans with ephemeral braided channels. Flowing in the meandering streams was a steady flux of suspended mud, which tinted our rivers gray brown at times of flood, and delivered umpteen gigatons of mud to our continental shelves, much of which contained organic matter.

All this led to another major drawdown in the concentration of atmospheric carbon. The enhanced weathering sent surges of the nutrients downstream to lakes and seas, especially the critical micronutrient phosphorous. The result was blooms of photosynthetic algae that sunk to the bottom of seas as muck that was left undecomposed for lack of oxygen. The enhanced downstream flux of weathered mud into swamps and continental shelves also pulled carbon from the air.

In a spectacular case of positive feedback, greening of the land led to gradual carbon sequestration, which led to cooling, which led to polar glaciation. Once glaciers formed, their growth and decay in response to Earth's orbital influences caused sea level to rise and fall, which allowed those swamps and shallow marine settings to be preserved in subsiding sedimentary basins. The locking up of that carbon up into the coal cooled the planet even further.

In short, the green new deal of the late Devonian was a dominant factor in driving the the planet into a long-lasting ice age. High latitudes became white with snow and ice. Dark rock edged the ice sheets, especially during temporary retreats. Light browns and grays indicated places too steep or dry for vegetation. Glaciers expanded and contracted like window shades being pulled down-and-up over temperate forests, tundra, and steppes. Earth became a polychrome planet.

Eventually Earth's continents shifted, the Devonian glaciers receded, and Earth toggled back into its default greenhouse state. This ended with a return to icehouse conditions during the late Carboniferous and Permian for similar reasons. Locking up that much carbon caused the concentration of oxygen to rise in the air to nearly double what it is today. In response, dragonflies became the size of newspapers, and millipedes the size of hogs.

With so much oxygen in the air, spontaneous wild fires became relentless. Some beds of coal called ***fusain*** consist mainly of burned black carbon or soot that fell as dust from smoky skies. It seems that the air was seldom clear... because fires were so easily lit... because the oxygen was so concentrated. In a fascinating set of nested feedback loops, the abundance of green caused a rise in atmospheric oxygen, which reduced the abundance of green by enhanced burning.

Greenhouse conditions returned to Earth at the end of the Permian and lasted for about 250 million years. At times, nearly every terrestrial square inch was forest green. At other times, the grays and browns of megadrought were dominant. Not until about 34 million years ago did Earth begin to seriously return to its present icehouse condition.

The Anthropocene, our current geological epoch, has a color pallet all its own. When seen from space, patches of color with unique shapes ---rectangles, circles, ribbons--are appearing and disappearing. As the climate changes --generally wetter where it was previously wet, and generally drier where it was previously dry-- the pattern of Earth's polychrome colors are shifting. There is less glacier white, more ocean blue, more desert brown, and more tundra and forest green.

21 - END OF ICE - 3048

TAKEAWAY

Owing to a campaign of denial and misinformation by fossil fuel companies, procrastination by the developed nations, and economic catch-up by developing nations, we have baked into the climate system enough carbon to drive Earth out of its current icehouse state.

KEY POINTS

In August 2019, the nation of Iceland held a national funeral for one of its glaciers, Okjokull, that had been killed by human-caused global warming.

Climate change was an emergent subdiscipline of geology when it was rapidly accelerated by the 1840 publication of Louis Agassiz's catastrophic glacial theory of a global deep freeze and the extinction of all life. For several decades, that fear engulfed the educated elite.

Independent of the emerging ice age theory, the history of the global warming via an enhanced greenhouse effect began in 1827 with Jean Baptiste Joseph Fourier, was firmly established in 1859 by John Tyndall, and globally computed by Svante Arrhenius in 1896.

The recognition that CO_2 loading was a "large scale geophysics experiment" requiring immediate attention was irreversibly launched in 1857 during the first International Geophysical Year.

The subsequent history of climate change has been dominated more by domestic and international politics than by the settled science.

SCRIPT AND TEXT

Pause ......

Episode 21 - End of Ice

Pause

Welcome to Climate Underground

I'm your host, Robert Thorson

Thanks for joining us.

Pause.....

In August 2019, Iceland's Prime Minister Katrin Jakobsdottir and a hundred supporters attended a funeral for glacier named [**Oh**-Kjo-kull] ~~Okjokull,~~ nicknamed "Ok." They hiked up a mountain, held the ceremony, and left behind a bronze plaque on a boulder titled "A Letter to the Future." The plaque reads: "In the next 200 years all our glaciers are expected to follow the same path." In place of a signature is the date "August 2019" and the carbon dioxide concentration from the Keeling curve of "415 ppm."

When first mapped accurately in 1890, Okjokull covered 16 square kilometers (6.2 square miles) and the carbon dioxide content of earth's atmosphere was about 280 ppm. By 2014 it had shrunk to less than 0.7 square kilometers and the ice was longer thick enough to move, meaning it could no longer be considered an true glacier. When the funeral was held in 2019 the CO_2 content was 415. Since then, it's risen beyond 421. The trend seems unstoppable.

This sets up the question: If Iceland loses its ice, what will the country be called?

In terms of global glacial volume, Iceland only the tip of the iceberg, so to speak. It holds **3.6** cubic kilometers of ice relative to Antarctica's **30 million**. The tip is one eight millionth of the whole.

Historical Concerns

The modern climate catastrophe of rapid glacier loss is the opposite of the initial climate catastrophe envisioned in the 19th century, when rapid ***glaci***ation, rather than rapid ***deglac***iation was the concern.

In 1840, Swiss geologist Louis Agassiz's published his paradigm-breaking book *Etudes sur les Glaciers* (Studies of Glaciers). Within it was the first scientific description of a former extensive “ice age” in Earth History. Without credit, he appropriated this idea of [Dee **Eye**-Ziet] "~~Die Eiseit"~~ or "The Ice Age" from his friend, the German naturalist Karl Friedrich Schimper.

Agassiz, a charismatic paleontologist, was an old-school catastrophist, believing that his Ice Age was an instantaneous global refrigeration so ***potent*** that the whole planet was covered by ice, extinguishing all life, including microbial life. Some thought it so ***abrupt*** that it froze mammoths in their tracks as they grazed on flowers. In Agassiz's view, the Ice Age was the ***most recent*** of a series of blank-slate ***re-***creations of life on Earth by an omnipotent creator.

Agassiz was definitely right that the last ice sheets had formerly spread over large portions of the northern hemisphere and had shaped its landscape in unusual ways. He was dead wrong about the ice-ages global extent, cause, and rate. We now know that protracted episodes of more extensive glaciation is a completely natural phenomenon that takes tens of thousands of years to culminate, and left much of the globe uncovered by ice.

Within decades, evidence was soon discovered in northern Europe and the Great Lakes region of North America that glaciation wasn't a one-off, but had happened multiple times. Logically, fears for the next episode of glacial return gripped the imaginations of naturalists throughout the mid and late 19th century.

Having read Agassiz's *Etudes sur les Glaciers* in the original French and Elisha Kent Kane's *Personal Narrative* of Arctic exploration, one of America's most astute 19th-century naturalists, Henry D. Thoreau, became particularly worried about climate change as an existential threat. When looking out over an unusually thick snowfall in Concord, Massachusetts near the end of a climate episode known as the Little Ice Age, he asked himself in 1853: "Who can believe that this is the habitable globe? The scenery is wholly arctic.... It looks as if the snow and ice of the arctic world, traveling like a glacier, had crept down southward and overwhelmed and buried New England."

After nearly freezing to death while returning at night to his small house above Walden Pond in Concord, Massachusetts, one of the "rudest blasts" of winter sent him to thinking about human extinction by ice catastrophe. In his account of that experience in *Walden* (1854), America's original environmental manifesto, he asked that we not "trouble ourselves to speculate how the human race may be at last destroyed,... It would be easy to cut the threads [of human existence] any time with a little sharper blast from the north. We go on dating from Cold Fridays and Great Snows; but a little colder Friday, or greater snow would put a period to man's existence on the globe." Here, he's referring to a well-documented but extreme meteorological events such as a cold snap of protracted subzero temperatures and snowfalls deep enough to bury houses.

Acting in the opposite direction, climate warming as a consequence of coal-fired industrialization was recognized before Agassiz published his ice-age theory,. The fundamental physics of Earth's greenhouse effect had been described in 1827 by Jean Baptiste Joseph Fourier, a precocious mathematician from Napoleon Bonaparte's Egyptian army.[74] Though Fourier never used the term "greenhouse effect," and though he never specified which gasses might be involved, he argued that Earth's atmosphere insulated its surface from heat loss.

Three decades later in 1857, a French intellectual named Eugene Huzar speculated that carbon emissions and deforestation would likely offset the almost certain return of another ice age. "In one or two hundred years," he predicted, and when "criss-crossed by railways and steamship, covered with factories and workshops, the world will emit billions of cubic meters of carbonic acid and carbon oxide, and, since the forests will have been destroyed [by the axe and saw], these hundreds of billions of [tons of] carbonic acid and carbon oxide may indeed disturb the harmony of the world." [75] Wow! That was 165 years ago at the time of this writing.

Huzar was the first to comprehensively link our fossil-fueled industrialization, expanded transportation, climate change, atmospheric acidification, biotic extinctions. That same year, Eunice Foote, an private American scientist, independently published and confirmed that carbon dioxide absorbed heat radiation and would raise Earth's temperature.

Two years later in 1859, John Tyndall, an Irish physicist, worked out the chemistry of Fourier's greenhouse effect through a series of challenging laboratory experiments. Tyndall established that the sun's rays easily penetrate dominant gasses in our atmosphere (nitrogen and oxygen) to warm

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[74] …(Archer, 15)

[75] (L'Arbre del science, Paris: Dentu, 1857, 106.]

earth's surface, but that the outgoing longer wavelengths of heat radiation were absorbed by CO_2, thereby creating a thermal blanket. It was this mechanism, he concluded, that allowed Earth to warm itself above the colder baseline conditions indicated by blackbody radiation.

Tyndall was also interested in how his greenhouse state could accomodate greatly expanded continental glaciation. Following pioneering geologist, Charles Lyell, he argued that the continents had been lifted upward to the threshold altitude of the snowline. Believing this uplift to be erroneous, Scotsman James Croll suggested a radically different theory for global glaciation in 1864, that major expansions were instead due to slight differences in the heat balance cause by orbital variations subsequently amplified by earthly feedback mechanisms. His astronomical theory was later verified, upgraded, and strengthened by the Serbian mathematician Milutin Milankovich in the early 20th century.

In 1896, the Swedish chemist Svante August Arrhenius, a future Nobel prizewinner in chemistry, actually ran the numbers for climate change via the greenhouse effect. Following two years of pencil and paper arithmetic, his calculations turned out to be astonishingly accurate. He predicted that if CO_2 were to fall by half, earth's mean temperature would drop by 5 ºC, prompting ***glaciation***. Likewise, a doubling would lead to a rise of 5-6 ºC, prompting ***deglaciation***. His results are consistent with modern modeling predictions. In what may be the first widely known hypothesis for climate engineering, he urged humanity to burn coal profligately to stall the imminent arrival of the next ice age.

The 20th Century

Meanwhile, back in the United States, the heat and drought of the 1930s turned the High Plains into a dust bowl. Seeking to understand its cause, the atmospheric scientist Gilbert Plass extended the work of Gilbert Stewart Callendar, who had had extended the work of Arrhenius, who had built on the work of Tyndall, Foote, and Fourier. In 1956, Plass formulated a full theory for global climate change linked to CO_2 feedbacks and orbital forcing. When presented at a 1957 conference for the International Geophysical Year, His theory gave a lasting and permanent boost to the idea that climate change comes from the underground. In this same year, the year of the Russian satellite Sputnik, pioneering climate scientists Roger Revelle and Hans Seuss described the rapid industrial CO_2 loading of Earth's atmosphere as a "large scale geophysics experiment." One response to this work was Charles Keeling's now famous decision to monitor the atmospheric concentration of CO_2 above Mauna Loa.

That same year in 1957, the American Petroleum Institute became publicly worried about what would come to be known as global warming. Their centennial celebration of U.S. petroleum production featured a symposium called "Energy and Man" that was clouded by fears of global warming. Physicist Edward Teller told the assembled oil company executives that they were threatening the climate, and that "there is a possibility that the icecaps will start melting and the level of the oceans will begin to rise…" [76] That symposium 65 years ago laid out what is happening today.

In 1965, President Lyndon Johnson asked the National Academy of Sciences for synthetic assessment on air pollution with a special report on the "invisible pollutant" of atmospheric carbon dioxide. Roger Revelle convened and chaired a committee of five. By that time, the Keeling curve

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[76] (McKibben, 73).

had five years of data, during which the CO_2 content of the air had risen by 1.36 percent. Using this linear trend, they predicted that, by the year 2000, the CO2 content would be about 20 percent above the pre-industrial level, and that the average surface temperature would be between 0.6ºC warmer. They were very close to being correct.

Though the greenhouse theory suggested that the average temperature should be warming, the actual meteorological data for the 1940s to 1960s showed that that slight global cooling was taking place, especially in the United States. This cooling, it turned out later, was due to the aerosol pollution created by the exhausts of burning fossil fuels. Misled by inadequate data, scientists were unaware that the heat-*reflecting* aerosol pollution from fossil fuel emissions was counteracting its heat-*absorbing* greenhouse consequences. Only after the environmental regulations of the 1970s cleaned up the sooty skies did greenhouse heating return with a vengeance, beginning about 1980.

During the decade of confusion, J. Murry Mitchell of U.S. Weather Bureau and many climatologists became concerned that we were already cooling toward the next ice age. He knew that the average climate of the last two million years was far more likely to be glacial than interglacial. The present interglacial epoch, they thought, had already lasted too long relative to preceding ones.

In 1972, a group of leading paleoclimate scientists met at Brown University to discuss the possibility of an oncoming ice age. By then it was widely known that peak sunlight from orbital influences had occrrued thousands of years earlier, and that mountain glaciers had already re-expanded from those minimum limits. Though the attendees at the meeting agreed that the natural trend was definitely toward more ice, they could not agree whether this was being offset by human greenhouse emissions.

Concerns for global cooling were part of 1974 treaty talks between U.S. President Ford and Soviet President Brezhenv. Several ideas that seem crazy today were discussed to keep the global climate warm, including: building a dam across the Bering Strait to bottle up the Arctic Ocean, covering portions of the polar caps with black foil to lower the albedo and melt them; increase CO_2 production as a means to warm the planet; or to melt portions of the polar ice with nuclear bombs.

The 1978, a bipartisan United States Congress overwhelmingly passed the National Climate Program Act, which greatly increased research funding in climate science, and laid out plans for international research on earth's climate future. In that same year, climatologist Stephen H. Schneider founded a new scholarly journal *Climate Change.*

The following year, 1979, was a tipping point for understanding climate change. Geologist Frank Press, a high-level science advisor to President Jimmy Carter, asked that the National Academy of Sciences look into the matter of fossil fuel combustion and climate change. As a result, the world's leading climate scientists sequestered themselves at Woods Hole, Massachusetts to produce what is now known as the Charney Report, named after its lead author, Jule Charney. They predicted that CO2 would double from pre-industrial levels by the mid 21st century. Using numerical models that seem clunky relative to those of today, the Charney group predicted that Earth would warm somewhere between a troubling 1.5 ºC and a catastrophic at 4.5 ºC.[77] A massive re-analysis in 2020 by 25 scientists from the World Climate Research Program verified that this 40-year-old prediction

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[77] Voosen, 2020, Global warming forecasts sharpen. See also McNutt, 2019. Time's up, CO2

was stunningly accurate. They narrowed the range for Earth's climate sensitivity to a doubling of CO2 by 2.6 ºC and 3.9 ºC with a best estimate of 3 +/- 1.5 ºC. This eliminated the best and worst case scenarios of the Charney Report, but underscored its accuracy.

After that prediction, the world mostly watched and waited. By 1988, climate scientist James Hansen was testifying to Congress that a definite anthropogenic warming signal had finally emerged from the statistical noise of natural climate change. This is when, wrote climate activist Bill McKibben, that energy companies began a disinformation campaign through The Global Climate Coalition, set up to "'to coordinate business participation in the international policy debate' on climate change," and to "'emphasize the uncertainty' in the scientific data about climate change. Thus began the most consequential lie in human history." [78]

Attorney Gustave Speth, in a legal brief for a lawsuit on behalf of Our Children's Trust, wrote that "under every US president since Carter, fossil fuel extraction and use have continued to grow,". *They Knew*, is the title of his book. Its subtitle "The US Federal Government's Fifty-year role in Causing the Climate Crisis." In short, this cause-effect has been bipartisan policy. The central problem has not been the energy industry or our politicians, but the majority of consumers and voters who support them, respectively.

Speth concludes: "Federal "actions on the national energy system over the past several decades are, in my view, the greatest dereliction of civic responsibility in the history of the Republic." [79]

The First IPCC report arrived in 1990. One of its most important outcomes, the United Nations Framework Convention on Climate Change, launched in 1992, marks a turning point in global climate policy. The 1997 Kyoto Protocol was the first truly global effort to actually mitigate climate change. Its key provision was that the nations that profited from polluting the most would make deeper cuts that those who polluted the least. The U.S, then the world's largest carbon polluter, did not sign on to the agreement. The next major step was the 2015 Paris Accord. Having been informed by multiple IPCC assessments, it was able to make projections for what was needed to keep Earth from warming beyond a safe 1.5ºC threshold, or beyond a dangerous higher threshold of 2oC. Each nation was given a chance to determine how they would meet emissions reductions, and make pledges to meet them. The U.S. signed on, signed off, and then signed back again.

At this point, we know that the glaciers will not be returning any time soon. Preserved in annual layers of ice at Vostok Station Antarctica is an archive of earth's atmospheric chemistry spanning the last 420,000 years, which is long enough to capture four full climate cycles swinging from full glacial to full interglacial. Following the solar insolation peak of each interglacial, it declined gradually to some threshold, whereupon there was an abrupt change to cooler conditions, sea ice, and glacial growth. [80]

All of the inceptions of new ice ages in the last million years began with an atmospheric CO_2 concentration in the vicinity of 260-280 parts per million. We've already greatly surpassed that concentration. Currently at 420 parts per million, the carbon content of Earth's atmosphere is rising to levels that have not been matched since the Miocene Epoch 10 million years ago.

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[78] McKibben, Falter

[79] Gerrard, 2021, The Children's Climate....

[80] Yin, et al, 2021, Insolation triggered abrupt weakening....

Without our anthropogenic carbon emissions, glaciers would be returning. Sea levels would be falling. Areas experiencing increasing drought and wildfire would be facing moister and greener conditions. What we've done is break the toggle switch of Earth's glacial-interglacial pendulum. The old rules no longer apply.

The most rapid and well-documented natural temperature rise in Earth history occurred at the boundary between the Paleocene and Eocene Epochs of the Cenozoic Era about 56 million years ago. This pulse of heat is known as the PETM, the Paleocene-Eocene Thermal Maximum. Natural releases of CO_2 and methane rose to a level 10-20 times that of today. With all the positive feedbacks combined, this release caused an abrupt 10ºC rise in average global temperatures, acidification of the oceans, a dramatic rise in sea level up to 70 m higher than present, and expansion of tropical and temperate ecosystems toward both poles. Is this where we're heading?

The consequences of the PETM are the same ones we're concerned about today. But the biggest difference between then and now is the *rate* of carbon transfers. Current rates of human transfer, up to ~40 gigatons of carbon per year, are unmatched in the fossil record. It took 1000 years to accomplish during the PETM what we've accomplished in a single century.

A rapid reversal to natural drawdown in carbon dioxide took place about 49 million years ago at the end of the Eocene climatic optimum. Called the azolla event, it's named after a tiny freshwater fern called azolla that flourished during the Arctic summer to form thick floating mats of carbon-sucking plant tissue.

Then, the Arctic Ocean was warm like tepid bathtub in summer, with turtles and palm trees common, and had little to no ice in the winter. Because of the tectonic arrangement, the ocean was largely landlocked and dominated by freshwater. Each summer the azolla flourished and grew in the upper layers of the lake. Each winter they died and sank into deeper anoxic water, transferring CO_2 from the air to underground, or in this case underwater sediment. Within a million years, CO2 levels had dropped from about 3500 to about 650 parts per million. Earth's Eocene greenhouse state was left behind. Earth's present ice-house state lay directly ahead. For the first time since the Paleozoic, we would have ice sheets at both poles.

We don't have a million year to draw down our surfeit of carbon. The dates we talk about are the years 2030 and 2100, time spans less than a century.

Was the PETM abrupt temperature rise a good or bad thing? A value-neutral Earthly frame of reference cannot say. As primates, we were beneficiaries. The rapid spread of warm, wet forested conditions greatly increased plant diversity, creating ecological niches more favorable to the first *euprimates,* or true primates, which are first found at the base of the Eocene. Under continued warm-humid conditions, this radiation quickly gave rise under to our taxonomic order, the anthropoids. Though our species of *Homo sapiens* was a child of the Pleistocene ice age, our major clade of apes and monkeys (infraorder *Similiformes*, formerly known as *anthropoids*), was a child of that greenhouse warming.

Was the Azolla event a good or bad thing? Again, a value-neutral Earthly frame cannot say. All we know is that this seems to have tipped the balance toward the current ice-house state our species is part of.

From the modern human frame of reference, the answer is clear. The rapid change back toward a greenhouse state is a disruption to the current world order. That we don't need.

We're still in it.

Since the Archaen Eon, only about a ninth of earth history is spanned by icehouse states, making the greenhouse state the default condition for earth history.

Two widely known Paleozoic ice house conditions are the Permian-Carboniferous (326-267 Ma) and the late Devonian to early Carboniferous (361-349 Ma). Both were associated with polar settings for the great southern continent of Gondwana. Two earlier and more severe icehouses occurred in the Proterozoic: the Neoproterozoic (0.74-0.63 Ga) and the much older Paleoproterozoic (2.3-2.2 Ga).

Our current state of icehouse conditions began with the decline from the Eocene greenhouse optimum about 50 million years ago. The Azolla event at about 49 million years ago may have been a tipping point. It marks the beginning of a falling trend line with ups and downs that has continued to the near present. Highlights include the slow onset of the rise of the Himalayas, the abrupt chilling of Antarctica about 34 million years, the onset of Pleistocene ice ages about 2.6 million years ago and the last glacial maximum about 20,000 years ago.

The toggle between ice-house and greenhouse states has multiple causes. But they are dominated by two main factors: the configurations and elevations of continents relative to the poles; and the carbon/oxygen content of the atmosphere as a consequence of organic and inorganic sequestration of carbon into solids. Supercontinents are linked to times of slow plate spreading and therefore low volcanic CO_2 emissions, and therefore and colder climates, for example the late Neoproterozoic scenario of snowball earth. Conversely, times or rapid plate spreading are associated with high CO_2 an order of magnitude higher than those of today and much warmer climates, for example the Cenomanian hothouse conditions of the mid Cretaceous.

Earth, by definition, is still in an icehouse state. We are now leaving that state, owing to the surge in carbon emissions from our engines and furnaces, factories, and land use practices. We will remain in that icehouse state until the last of the ice sheets are gone. Melting everything will take some time. If current trends continue, it will be the end of ice as we know it.

22 - EDGE OF THE SEA - 2785

TAKEAWAY

The apparently stability of the edge of the sea is an illusion created by the human propensity for short-term thinking. Within the Cenozoic Era, mean global sea level has continuously risen and fallen between +70 and -130 meters.

KEY POINTS

Since the 1960s, global sea level rise has been accelerating, and is now is now 4.8 millimeters per year, owing to rapid Greenland melt.

Sea level rises and falls against a local shore at many time scales ranging from the daily tides to prolonged intervals of fast plate spreading over tens of millions of years. Net local rise or fall of the land subtracts from or adds to the global rate. Transient rises of local sea level are due to many factors, most notably the way each unique coastal settings amplifies unique meteorological factors such as storm surges and wave setups.

The causes of sea level rise on any shore are the sum of global factors, mainly the amount of land ice, water temperature, volume of ocean basins, and local factors, mainly uplift or subsidence due to tectonism, isostasy, compaction, fluid withdrawals, and lateral gravitational factors.

Evidence for a sea-level 6-9 meters above the present shore is an ubiquitous, though discontinuous, feature across the planet. Formed during the last interglacial about 125 thousand years ago, it indicates where we are heading as glacial melt continues.

Though compelling to geologists, the last interglacial shoreline is considered a "low likelihood, high-impact storyline," which means only that the processes leading to it are not yet included in the numerical models.

SCRIPT AND TEXT

Pause ......

Episode 22 - Edge of the Sea

Pause

Welcome to Climate Underground

I'm your host, Robert Thorson

Thanks for joining us.

Pause.....

Pattern of Rise

Years ago, I took a week-long reading vacation on an isolated beach between rock headlands in Downeast Maine. My beach book that year was an unusually fat one, a large-format version of the King James Bible, which I read from start to finish in four days. I wasn't seeking spiritual guidance. But I thought that reading the world's most bestselling book would be a good idea for someone who writes books.

Each day was the same. If the tide was rising, I'd plant my beach chair about 20 feet above the water, reading until my feet started to get wet. I'd then pick up, move back about 20 feet back, replant my chair, and read until my feet got wet again. When the tide reversed, I reversed my movements in similar increments. Never have I been more intimate with the rise and fall of the sea.

On that beach, the time scale between low tide at ebb, and high tide at flood, is measured in hours. Geologists have reconstructed a similar ebb and flood at the timescale of 100,000 years as global glaciers expanded and contracted during the last million years. On ten occasions, the edge of the sea ebbed slowly during what's called a ***regression***, reaching a low point of about 130 meters or 425 feet below present sea level. This drop in sea level was due mainly to the slow removal of water needed to build ice sheets on the land, but also to the the contraction of water as it got colder. After a stillstand of thousand years or so, the lowered edge of the sea reversed itself and began to rise against the land in what's called a ***transgression***. During this warming half of the glacial hemicycle, the sea reached an upper stillstand somewhere between 6 and 9 meters above the present shore, or 20-30 feet. The rise and fall within these limits was quasi-regular and quite predictable.

The ***last*** time this natural warming and rising hemicycle occurred was during the present interglacial. It was responsible for the postglacial rise of sea level to its early 20th century position, which was a less than a foot below present. The penultimate, or ***next-to-last*** time this happened was during the peak of the last interglacial about 125,000 years ago when the average annual temperature was similar to what we have today, and when sea level was 6-9 meters higher. Evidence for this higher shoreline is found throughout the world like a discontinuous bathtub ring. In some settings there's an abandoned sand beach. In others there's a wave-cut terrace. In still others, like the Florida Keys, there's the flat top of an old coral reef that's now exposed as an archipelago of low islands. What are now the flat-tops of these islands were formerly the wave-flattened flat tops of a then-submerged reef. The same is true for the island nations on coral atolls, the Marshall islands, Maldives, and others. All are fated to be submerged.

Locating our global coastal cities below this globally recognized interglacial shoreline is my candidate for the dumbest mistake ever made by civilization. "What the ocean does in geological time," writes geologist David Archer, mocks "the putative permanence of our coastal settlements."

The long-term rate of sea level rise for the last several thousand years has been about 1 millimeter per year, the thickness of a well-rubbed dime. Excellent global tide-gage evidence for the early 20th century overlaps and matches late Holocene geological evidence for this rise in the same way that the Keeling curve for atmospheric CO_2 matched the archive from ice sheets. Based on the IPCC's

AR6 report, sea level rose 0.2 meters (from 0.15 to 0.25) for the interval 1901-2018 with an average and accelerating 20th century and early 21st century rate approaching 1.8 millimeters per year. For the last dozen years of this record, 2006-2018, this rate nearly doubled to 3.7 millimeters per year (3.2 to 4.2). For the interval 2010-2020, NASA ascertained an average rate of 4.8 millimeters per year, owing to unprecedented melting of Greenland ice. [81] This accelerating trend seems likely to continue. If and when the rate reaches 6.1 mm/yr, coastal mangrove forests will be unable to keep pace.[82]

The IPCC predicts that, by 2100, global mean sea level will rise in the range of 0.28-0.55 meters for a low emissions scenario (SSP1-1.9), and 0.63–1.02 meters for the high emissions scenario (SSP5-8.5) relative to the 1995–2014 average.

But here's the rub. Neither of these scenarios take into account what has been obvious to glaciologists for nearly a century. That the Greenland and Antarctic ice sheets have ***already*** crossed tipping points and are now disintegrating by glaciological mechanisms that do not scale with emissions. More bluntly, they are undergoing irreversible collapse. As the AR6 report gently puts it: "Under the higher CO_2 emissions scenarios, there is deep uncertainty in sea level projections for 2100 and beyond associated with the ice-sheet responses to warming. In a low-likelihood, high-impact storyline and a high CO_2 emissions scenario, ice-sheet processes characterized by deep uncertainty could drive GMSL rise up to about **5 m** by 2150." Five meters.

The gentle phrasing of the AR6 "low-likelihood, high-impact storyline" requires some translation. By ***storyline,*** they mean a narrative cascade of events. By ***low-likelihood***, they mean they can't be certain enough about rates because these mechanisms are not incorporated into the global models because not everyone agrees. By ***high-impact***, they mean that coastal cities and lowlands will be drowned, a conclusion reached by geologists nearly two centuries ago when nobody was listening. Indeed, the frontispiece of Charles Lyell's *Principles of Geology,* published in 1830, shows a coastal submergence and re-emergence of this magnitude.

Where could 6-9 meters of sea level rise come from? Details of this budget problem are still being worked out. But the best current guess at present is that the Antarctic and Greenland Ice Sheets will each kick in about 4 meters of rise with an additional meter coming from the loss of mountain glaciers and the expansion of the ocean by warming. This total of about 9 meters or 30 feet will bring the sea back up to where it was during the last interglacial, and previous interglacials. Geologically, this is the normal expectation.

Consider the record heat of July 2019 in Greenland. In that single month, 197 billion tons of water poured into the Atlantic from an ice sheet being roasted under bright sunlight, raising sea level 0.02 inches (0.5 mm). Consider a recent news story in late February 2022 revealing that the Antarctic shelf ice has reached its lowest extent ever. Both of these news flashes bode poorly for the coasts of the Earth.

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[81] Voosen, 2020, Seas are rising faster than ever.

[82] Kelleway et al, 2020, Thresholds of mangrove survival....

Ice sheets disintegrate by three well-known and distinct positive feedback mechanisms. The oldest and best known is *marine ice* ***sheet*** *instability*. When I was a graduate student in the late 1970s, we were already thinking this situation was imminent. As ice sheets grow, they depress the crust below sea level like a dimple on a rigid sheet, even though the outer edges remain stabilized on bedrock shallows or sills. When ice sheets pull back, the water deepens and the edge widens in the direction toward the center of the ice sheet. This means that it will disintegrate at an accelerating rate.

Already, the enormous Thwaites glacier in West Antarctica has pulled back from its sill and is now in irreversible retreat. It's undersea shelf and bedrock constriction have been buttressing much of the West Antarctic ice sheet behind its grounding line. No longer. The weakening has been due principally to marine melting on the underside of its shelf. These warmer waters are the result of heat transfer from the atmosphere to the oceans, where 90 percent of global warming has gone. And that atmospheric warming was and is due to our carbon emissions.

Quoting the AR6 report: "It is likely that the Antarctic Ice Sheet... dominated by the West Antarctic Ice Sheet... has lost 2670 ± 530 Gt, contributing 7.4 ± 1.5 mm to global mean sea level rise over 1992–2020... Mass losses from West Antarctic outlet glaciers, ... outpace mass gain from increased snow accumulation on the continent."

A second positive feedback mechanism is called *marine ice* ***cliff*** *instability*. In this case a calving bay of an ice sheet migrates back into the main mass. The cliff faces then detach along crevasses and crumple as they fall downward into the sea. This is the main mechanism of failure for the fjords of West Greenland today. The feedback for loss is positive. The taller the ice cliff the faster it retreats. And the faster it retreats, the taller the ice cliff.

The third main feedback mechanism is ***surface melting***, the main issue for Greenland at present. Surface melting finds its way down to the glacier bed via holes or moulins, which are essentially crevasses pried open by the greater pressure of liquid water relative to that of ice. The more surface water there is, the faster it's conveyed to the bottom. And the faster it's conveyed, the faster the flow by sliding to coastal fjords. Another positive feedback. Additionally, the greater the loss by surface melt, the lower the surface of the ice sheet. A lower surface is a warmer surface, increasing the melt even more. Another positive feedback. This lowering is what's happening to Greenland today. Quoting AR6: "Over the period 1992–2020, Greenland likely lost 4890 ± 460 Gt of ice, contributing 13.5 ± 1.3 mm to global mean sea level rise. There is high confidence that Greenland ice mass losses are increasingly dominated by surface melting and runoff, with large interannual variability arising from changes in surface mass balance."

The rapid response of sea level to ice sheet disintegration during the demise of the great Laurentide Ice Sheet suggests an analog that offers little comfort. During the 400-500 years interval between ~14.7 and ~13.5 thousand years ago, global sea level rose by 16-25 meters with mean rates of ~40-60 millimeters per year. This is more than an order of magnitude faster than today's fast rates. This average rise of 18 m or 60 feet, an event known as Meltwater Pulse 1a, occurred in a matter of centuries,. To put this rate into a human perspective, I've known six generations of family: my great grandmother, born is 1875, my grandmother, my mother, my daughter, and my grand-daughter, born in 2020. That's 145 years and rising. In that duration during Meltwater Pulse 1a, sea level would have risen 7-12 meters or 22-42 feet. If my granddaughter has a normal life expectancy, she will live to see the IPCC projections for the year 2100, and likely witness the high-impact storyline of a steady great coastal flood.

At longer time scales, the link between global temperature and sea level rise is linear "Past sea level varied by 10-20 meters (30-60 feet) for each 1°C change in the global average temperature," writes David Archer in *The Long Thaw*. Though we've already reached a change of 1 °C, we haven't yet reached the predicted 10-to-20-meters of rise because there's a lag time built into the process, the time it takes to melt that much ice. The Paris Climate Accord of 2015 asked that we hold the rise to 1.5°C. Unfortunately, the less sanguine geologists I discussed this with think we'll blow past 2 °C on our way to 3 or 4 °C. This would translate to a rise between 20-80 meters of submergence.

Submergence seems to be where we're headed during the time frame of the next million years. The carbon content of our current atmosphere already exceeds that of the mid Pliocene thermal maximum about 3 million years ago, when global marine temperatures averaged 2-3 ° C higher than present, and sea levels were about +20-30 meters higher than present. Return to the full greenhouse state of the Cenozoic Era would bring global to +70 meters. This makes the last interglacial shoreline of 6-9 meters look like small potatoes.

And if we go further back we reach a time when we had no ice sheets at all, and the tectonic geographies were can no longer be useful. During the mid-Cretaceous sea levels were a whopping 250 meters above the present shore. Beyond that is the Paleozoic, when comparably high sea levels flooded much of the ancient continents. The midwestern cities of Chicago, Saint Louis, Detroit, and Cleveland all lie on the floors of former oceans. Beyond these Paleozoic extremes is the nearly universal ocean of the early Archaeon Eon, where there was hardly any land at all. Theoretically, Earth's first ocean might have been three times deeper than today, drowning everything on today's Earth but the highest peaks.

Cause of Rise

A change in sea level is not the same thing as a change in climate. Sea level responds to many factors at many time scales, only some of which are driven by climate. At the shortest time scales there are tsunamis, seiches, wave setups, and storms. At longest time scales, there are major tectonic, mineralogical, and thermal conditions transitions in the mantle that release more or less water. Over the full range of rises and falls, climate and sea level interact.

With respect to the ***current*** climate warming, there are two main components to sea level rise: long-term and transient.

The first involves a ***long-term*** net rise of global sea level. Solid water stored on the land as glacier ice is melting to create liquid water that flows to the sea, adding to its volume, which requires a rise. This involve a transfer **between** climates, because the losses take place mainly in the polar latitudes, and the gains take place mainly in tropical/subtropical latitudes distant from the ice where the water expands by heating. This component is ***earthly,*** because it involves the whole system.

The second main component involves a ***transient*** rise of local sea level above or below the net global rise. This is taking place because the strength of storms is increasing owing to the warmer temperatures and higher moisture content of the atmosphere. Stronger storms mean more flood rainfall added to higher waves superimposed on higher wave setups, superimposed on a higher mean sea surface. Human engineering has both increased and decreased these transient levels. This component is mainly ***meteorological***.

Humans live in specific places, each with its own sea level story of the past, each with its own present circumstances, and each with its own future story. To understand sea level in a particular place, we must first isolate those factors that are truly ***global*** from those that ***regional***, and from those that are ***local***, and know how these scales interact.

For **global** factors, we must ***start*** with the abundance of water on earth's surface in any form. During the early Hadean Eon it was zero because all the water was held in stratus clouds. During the birth of the universal ocean it was higher because the mantle was too hot to hold as much water as it does today. A ***second*** factor is how much of that water mass is held as liquid in the ocean basins versus solid water stored as land-based ice. A ***third*** factor is the temperature of that water because warmer water occupies more space for the same mass. ***Finally*** we must consider the volume of the global ocean basins, which changes through time as they are enlarged and shrunk tectonically, and as they fill with sediment.

Considering only the last three variables of liquid mass, liquid temperature, and basin size leads to a budget equation with nine possible outcomes. Maximum sea level occurs when basin size is smallest, no water is stored on land as ice, and the water is warm. Minimum sea level involves large basins, lots of land ice, and cold temperatures. All of this varies continuously.

Next there are **local** factors that either add to or subtract from the global factors. Each shoreline is different. The land may be rising or falling due to active tectonics or isostatic effects. The land may be subsiding owing to natural sediment compaction and dewatering, the extraction of fluids, or the dissolving of materials at depth. And then there are local changes in the height of the sea caused by changes in the configuration of channels that influence local tides, currents, and storm setups.

Finally, there are differences in the height of the sea due to differences in earthly gravity. Differences in the local strength of gravity due to the differences in mass within the crust and mantle result in a whopping 190 meters of vertical relief on the surface of the sea. It turns out that the direct gravitational influence of the underground is even larger than that of the water buget toggle between ice ages. As the distribution of mass changes within the earth due to convection, so too, does the level of the sea above it change. To this downward vertical pull we must add the horizontal pull of gravity caused by adjacent ice sheets and land masses.

In short, the rising sea level we're worried about today is not level. The physical rise is not uniform. And the economic and cultural costs are even less uniform. Steep rocky coasts near melting ice sheets will do quite well as a consequence of this mass transfer. Gentle soft coasts far from melting ice will suffer the most.

23 - CLIMATE FUTURES - 2848

TAKEAWAY

Though rigorously scientific climate models can help us predict the climate future, they cannot take into account the unpredictability of human beings.

KEY POINTS

Climate models are amazingly sophisticated mathematical representations of Earth's past, present, and future behavior for different conditions based on scientific laws are applied to grid cells of latitude, longitude, and elevation.

Despite their scientific rigor, future predictions of Earth's climates are based on guesses about the global sum total of human behaviors, which is notoriously unpredictable. The near future may bring either thermonuclear war or nuclear fusion, the holy grail of carbon-free energy.

Given uncertainties about the future, geological evidence provides the only means of calibrating climate models for conditions significantly different from those of recent history. Once calibrated, the retrodictions of the past can be confidently flipped to predictions of the future.

To find past paleoclimatic analogs for future conditions, we have stepped further and further back in time to progressively warmer conditions: from the mid Holocene optimum to the last interglacial, the mid Pliocene thermal maximum, and the Early Eocene Climate Optimum.

Earth's climate future will be governed by three great uncertainties: the behavior of humans; the rate of ice sheet loss by irreversible mechanisms already underway; and the release of methane from seafloor sediments and permafrost. None of these are yet nailed down.

SCRIPT AND TEXT

Pause ......

Episode 23 - Climate Futures

Pause ......

Welcome to Climate Underground

I'm your host, Robert Thorson

Thanks for joining us.

Pause.....

The most critical moment of my graduate education at the University of Washington is seared into my memory. I was making a desperate pitch to convince my graduate committee that the Seattle area had indeed been deeply depressed by the weight of an ice sheet before rising back up again at a rate consistent with the known sea level history. My secret weapon? Sheets of paper computer printout taped like wallpaper over nearly every square inch of the library conference room. They contained the output of a mathematical model I created using a now-nearly-extinct computer language called FORTRAN entered vis punch cards, and with the output being black and white text characters.

Forty years later, computer models are so sophisticated and easy to use that we forget they are models, rather than virtual reality. Inputs are lines of code keyed into the cloud. Outputs are full-color realistic animations on high resolution digital screens.

Models predicting climate change are the most complex ever built because climate is the aggregated outcome of thousands of earthly processes linked together. Each is a giant piece of intellectual infrastructure built and tested and calibrated by huge teams of scientists and engineers, and designed to be used by whomever is interested. In terms of teamwork, each is analogous to a physical city, with millions of players in billions of places. Once built, vetted and shared, users can ask the model questions such as: "What will happen to this if we do that?" .

The IPCC uses what's called a Global Earth System Model (GESM) coupled with regional and local models of varying scales. Each of the two acronyms reveal something important about how they work together. The CC in IPCC comes from the ES in GESM. More simply, climate change comes from the Earth system. The I in IPCC for intergovernmental is the human stand-in for the natural G in GESM indicating global. The M in Model informs the P for Panel.

The GESM isn't a physical model, like a mechanical globe, but an enormous bundle of mathematical expressions describing the scientific laws that govern how components of the Earth system interact. Examples include the conversion of solar radiation to heat, or the dissolving of carbon dioxide into the ocean. The engine of the ESM or Earth System Model is a GCM or general circulation model for the atmosphere and oceans.

Such a model would be complex even if we restricted it to a single concentric layer or a single geographic place. More realistically, Earth is mosaic of geographic grid cells tiled in three dimensions against one another in vertical layers. The model equations must therefore be applied to every layer of every grid cell. Based on the equations, each grid cell receives input from, and sends output to its six neighboring cells --to the right and left, to forward and backward, and to up and down. All these calculations are done, over and over in whatever time increments are specified. A typical grid cell is 100-150 kilometers on a side, with up to 50 vertical layers and the time frame may be minutes to millions of years.

This Global Earth System Model used by the IPCC is called CMIP6, the sixth version of the Coupled Model Intercomparison Project of the World Climate Research Programme. The basic idea is that different models, each with strengths and weaknesses, are compared with one another in a sort of meta-analysis. Understanding CMIP6 lies far beyond the scope of this podcast episode.

Fundamentals

Knowing what climate models are, it's now time to think more fundamentally. Let's think about yesterday. You can recall a series of activities and events, some more memorable or significant than others. It's easy to create a storyline to explain them. Novelists do it all the time using the procedure: this happened because this happened, and so forth.

Now flip the storyline into tomorrow. What will happen? It's fairly easy for those who are living a life of routine, for example that of an incarcerated person, or that of a worker's daily commute or that of a day care drop-off and pickup. But we can never be sure of anything. And we can never predict the details that will emerge, even important ones. The world is far more uncertain that we suppose.

In short, we can explain *yesterday* far more accurately than we can predict *tomorrow*. That's the fundamental problem with climate prediction. As famed physicist Neils Bohr quipped. "Prediction is very difficult, especially if it's about the future!" More parsimoniously, nobody can really know for sure what will happen or how a system will behave.

Weather forecasting or prediction has gotten very good. Ten-day forecasts are more often right than wrong. The physical data on which predictions are based is excellent: for example air pressure, temperature, and humidity. And the physics within the models is firmly established in atmosphere-ocean general circulation models. Having studied meteorology in college in the early 1970s, I'm stunned by how the addition of new technologies are mainly responsible. Two book titles -- *Sudden Sea* and *The Children's Blizzard,* explain the surprise of the 1938 Hurricane in the Eastern U.S. and the surprise of the High Plains blizzard in 1888 depend on the uncertainty of our forecasts because the data wasn't good enough.

Weather prediction is easy compared with climate forecasting. Weather doesn't involve human behavior in the 10-day interval. Climate does, and that's the tricky part. The physics of our climate models are very robust and well calibrated. The human behaviors are much more challenging to predict because they involve multiple cultures within 195 sovereign nations composed of millions of individuals. Wild cards are everywhere. Whether we keep the temperature rise to 1.5 ºC is a question of social psychology, not Earth physiology. Will we reach zero carbon emissions by 2050? Or will we just make hollow pledges? Nobody knows because nobody can know for certain. The mutually assured destruction of global thermonuclear war might intervene at any moment.

When I first became concerned about climate change in the mid 1970s, and read the Charney report in 1979, it would never have occurred to me that global culture couldn't get its act together to halt or slow down carbon emissions within the next decade. The informal projections and extrapolations I made about human society turned out to be dead wrong.

More broadly, using science to predict the future is, technically, a form of science fiction because no one can really know what will happen. This doesn't stop me from being a firm believer in climate models. Some of my colleagues are experts, using the Community Earth System Model (CESM) created by the U.S. National Center for Atmospheric Research to run their experiments for days of computer time.

Prediction is what I call *forward thinking*. It answers the question: "Given this, what will happen?" Forward thinking is applied to predict the value of a stock, a gallon of gas, he number of people infected by latest variant of the Covid epidemic, or the global consequences of one country's unprovoked invasion of another. The further out in the future the prediction is, the less likely it is to be true.

When geology was founded two centuries ago, its goal and central practice was *inverse thinking,* to answer the question: "Given this, what happened?" This is what detectives do at crime scene investigation -- us tangible clues to constrain and explain what happened, thereby ruling certain interpretations in or out. The early clues in geology were compositions, textures, and fossils within rock strata. Today, these are supplemented by more sophisticated laboratory analysis and dating methods.

To make this work, geologists adopted a fundamental principles called *uniformitarianism*. Roughly stated: "the present is the key to the past." The basic assumption is that the processes operating today also operated in the past. For example, if we see a sand ripple forming in a tidal current today, we can assume that an identical ripple in sedimentary rocks of the past, was also created by a similar tidal current.

Let's extend this principle to the study of past climates. Arid sand dunes contain within them diagnostic grain sizes, surface textures, and sedimentary details that are unique to this climatic setting, and do not occur in any other. Finding these same features in a fossilized sand dune proves that those same climatic conditions were present at that past place at that time. In another example, dried up lake beds leave distinctive polygonal cracks found throughout the globe. Seeing an ancient one proves that an ancient lake dried up. Raindrop impressions in a rock billions of years old prove that it rained billions of years ago. A sheet of sand in a sediment core taken from a coastal lagoon behind a barrier island proves a past hurricane. A layer of floodplain mud proves a flood event.

Though reconstructing the past is still the dominant goal of geology, the climate crisis has steered much of the recent effort toward predicting the future.

Using the geologic record to make future predictions is a reverse form of uniformitarianism. This principle reads: the past is the key to the present. If something happened once, it can happen again. A good example comes from the recent expansion of beavers in northern Alaska northward as taiga forest replaces tundra. Though this was surprising to wildlife ecologists, it was no surprise to geologists who, more than half a century ago, discovered strata in the high arctic containing beaver-chewed wood that was 8000 years ago, indicating a warmer than present interval at that time.

Climate modelers can predict our climate futures. But there's no actual way they can test whether those predictions are true or not, especially for situations different from the historic present. The best alternative is to test these same models against very different past climates to see how their predictions square with actual evidence. The good news is that paleoclimate data sets are abundant, thanks to the hard work of geologists and others in the last half century.

Consider this. We've nearly doubled pre-industrial CO_2 levels to reach ~420 ppm. This is higher than at any time in the past 10 million years. How can we know what Earth will be like? Though we can extrapolate our models forward, we have no way to verify the predictions. The anituniformitarian alternative is to go back in Earth history to times when the CO_2 levels and continental configurations were similar to our model scenarios. If our models do a good job explaining the past, then we can be confident they will also do a good job explaining the future. These geological times in the past are referred to climate analogs.

Stepping backward.

The first year of the Keeling Curve in 1958 recorded an average CO_2 concentration of **316** parts per million. I was seven years old at the time. This was a world without concern for climate change, so no warmer analog from the past was needed. Since then, there have been two narratives. One moving forward as an increase in CO2 concentration. The other moving backward to find times in the past with that same concentration that might serve as an analog.

When I got started in climate science in the late 1970s, the concentration had risen to about **330** parts per million. Seeing only a moderate change, the climate analog we began to use was the ***Medieval Climate Optimum*** dating from about 950 to 1250 C.E., a warmer period in northern Europe associated with improved agriculture and general well-being. Though many of the constraining records were historical, many others were geological.

As global warming continued, however, we abandoned the Medieval analog as not being extreme enough, moving back to the ***mid-Holocene*** climate optimum or "Hypsithermal," or "Altithermal," centered about 6,000 years ago. Tree-lines were at higher elevations and further north in the Arctic. The Greenland Ice Sheet was slightly smaller, mountain glaciers had retreated to their inner Holocene limits, and Kettle Lake North Dakota was one of the few local waterfowl resting places that had not dried up. Though global CO_2 was not elevated significantly above its average of about 270 ppm, regional climates were behaving differently.

As the Keeling Curve kept rising during the 1980s through the 2000s, we gradually abandoned the mid-Holocene analog as not being extreme enough. So we looked farther back to the peak of the ***last interglacial*** about 125,000 years ago when the global temperature was about 1°C warmer than pre-industrial temperatures, roughly where we are at today, though at a lower CO_2 concentration. The most gripping prediction here involved a sea level 6-9 m above present.

Since the 2010s, we've pretty much given up on using the warm peak of the last interglacial as a useful analog because the CO_2 concentration today of **420** ppm far exceeds that of any interglacial of the Pleistocene, and we've baked lots of carbon warming into the future. So we stepped even further back in time to an even warmer interval within the ***Pliocene Epoch*** about 3 million years ago that preceded the ice expansions of the following Quaternary Epoch. Being only a few million years old, its tectonic paleogeography was similar to the present and its plants and animals were broadly similar to those of the Holocene Epoch, greatly simplifying the use of the analog relative to earlier times.

The specific interval of interest is the middle Pliocene warm period between 3.15 and 3.85 million years before present. Happily a plethora of data from land, sea, and shore is present to establish the boundary conditions for model forecasts. Using this data, the Pliocene Research Interpretation and Synoptic Mapping project, PRISM for short, has created a sophisticated portrayal of this past analog, with some parts of the Earth actually cooler relative to today.

The overall summary description doesn't sound bad at all for the temperate latitudes: "the hydrological cycle was enhanced, ice sheets were smaller, sea level was higher, forest cover was expanded and arid deserts contracted." Surface air temperatures over land and sea were highly variable. Sea surface temperatures were typically 4-8 degrees higher in the Arctic, though not changing at all in places in the equatorial Atlantic and Pacific. Land temperatures were up to 12 degrees warmer over Greenland and the West Antarctic, and in high alpine settings. Land temperatures cooler than present occurred at high elevation in continental interiors. Sea levels were as much as 25 m above present, indicating significantly reduced ice sheet volume.

Having reconstructed the past based on paleo conditions from the fossil record, the goal now is to apply reverse uniformitarianism. To flip the PRISM model calibration forward into the future using the IPCC's intermediate emissions scenario for the year 2100 and beyond. Quoting the IPCC AR6, "by 2300, an intermediate scenario used in the report leads to global surface temperatures of 2.3°C–4.6°C higher than 1850–1900, similar to the mid Pliocene Warm Period (2.5 °C–4°C) about 3.2 million years ago.

Within the past few years, emissions-control skeptics like me are beginning to abandon even the Pliocene analog. The next one we can step back to is the ***Early Eocene Climate Optimum***, an exceptionally warm interval about 50 million years ago during Earth's most recent greenhouse state, before its current icehouse state. At that time temperatures were 10-18ºC higher than pre-industrial. The IPCC's high emission scenario (SSP5-8.5) suggests that we may experience "temperatures of 6.6°C–14.1°C by 2300," well within the range of the Eocene climatic optimum. Beyond that analog is the mid-Cretaceous analog, which might come in useful for our worst case scenarios for beyond the 21st century. [83]

Were we to continue to keep stepping back, we would eventually reach the molten birth of the planet.

Modeling Challenges

There's an old saying in computer modeling. Garbage in, garbage out. This is too harsh, for no ethical scientist knowingly puts trash in their models expecting to get treasure back out. Being less harsh, the output of any model always depends on the assumptions that went into making it, the biases that led to those assumptions, and the factors nobody thought of.

With respect to modeling our climate futures, there are two great uncertainties that are not included in our emission scenarios because the problems are not yet sufficiently well constrained.

The first is involves methane, Earth's most important cumulative greenhouse gas. At the century scale, methane has about 34 times the greenhouse warming potential than carbon dioxide, but disappears rapidly, with half gone in the first decade and most gone by 20. When methane disappears from the atmosphere, the carbon does not. Instead, it's converted to carbon dioxide, which lasts much longer.

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[83] Tierney et al, 2020, Past Climates...

We know from geological evidence that the release of large quantities of carbon into the atmosphere via methane releases has spiked rapid heating events in the past, particularly the PETM, or Paleocene-Eocene Thermal Maximum. The main concern today is the unknown amount of methane that might be released as a positive feedback from greenhouse warming. Methane trapped within or released by melting permafrost, and methane trapped within ices or clathrates in ocean muds.

Climate scientist David Archer notes that if just 10% of the methane in hydrates were to reach the atmosphere within a few years it would be the equivalent of increasing CO_2 concentration of the atmosphere by a factor of 10, an unimaginable climate shock. The methane hydrate reservoir has the potential to warm Earth's climate to hothouse conditions, within a century. [84] Looking for past analogs for methane release during interglaciations, however, one team showed that deglacial emissions of methane were smaller than expected. [85]

The second great uncertainty involves the rate at which our ice sheets will disappear. Quoting AR6: " Higher amounts of global mean sea level (GMSL) rise before 2100 could be caused by earlier-than-projected disintegration of marine ice shelves, the abrupt, widespread onset of Marine Ice Sheet Instability (MISI) and Marine Ice Cliff Instability (MICI) around Antarctica, and faster than-projected changes in the surface mass balance and dynamical ice loss from Greenland."

The IPCC should be praised for its caution. Modeling doesn't work when you don't have enough certainty to run the numbers. What you do instead is to call attention to "high-impact, low certainty" conditions in storylines. These are the ones geologists know have happened in the past, and are looking at most closely for future scenarios.

Finally, there's a silver lining to the dark cloud of denialism and inactivism of the past half-century. Global society has done so little for so long that we now have a statistically reliable linear relationship between the passage of time since the Great Acceleration beginning in 1950 on the X axis and observed climate changes on the Y axis, whether for the global thermal state or for regional climates.T he IPCC, writes Paul Voosen, can now use "the actual warming over the past few decades to constrain the [model] ~~CMIP~~ projections," which will "reduce the uncertainty of the model projections by half." [86]

No longer are we entirely dependent on **models** based on physical principles or **reconstructions** of paleoclimates to predict the future. We can use historic reality, correlations from the last 70 years projected ahead another 78 to the year 2100. Quoting climate scientist Robert Kopp: "We now have enough independent lines of evidence, that we don't need to use the climate models as their own line" of reasoning. We can extrapolate.

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[84] archer, 168?

[85] Dynonisius et al, 2021, Old carbon reservoirs.

[86] Voosen, 2020, Earth's climate destiny... Voosen, 2021, U.N. climate panel confronts...

24 - COMMON LANGUAGE - 3253

TAKEAWAY

Miscommunication occurs when the words World, Planet, Globe, Earth, and Nature are used interchangeably as synonyms. To effectively deal with the climate crisis, we must speak the same language.

KEY POINTS

World is the human component of the Earth, including the things we've engineered and domesticated. The context is humanity.

Nature means two things. Most often, it's the counterpoint to world with strong emphasis on living things. More broadly it's all living things, a usage that avoids the false dichotomy separating humans from other living things. The context is living things.

Planet is the totality of the oblate spheroid that spins and revolves the sun along with its moon and sibling planets. The context is the solar system.

Globe is the spherical surface of our planet, or, less commonly, a physical scale model of it. The context is spherical geometry. Modern usage is most often adjectival, as with global.

Earth is the entire material system of solids, liquids, and gasses between the sweet spot of its iron core and the outer edge of the atmosphere. The context is a holistic dynamical system.

SCRIPT AND TEXT

Pause ......

Episode 24 - Common Language

Pause...

Welcome to Climate Underground

I'm your host, Robert Thorson

Thanks for joining us.

Pause.....

For the last twenty years I've kept three small objects on my writing table to help guide my thoughts when writing. One is tiny **globe** with a map of the ancient **world** mounted on a stand with a tilted axis. Another is magnetic compass mounted in a brass case smelted from **earthen** materials whose needle jiggles with every stoke of my keyboard, and is naturally aligned by the **planet's** magnetic field. The last one I added was a **natural,** beach-smoothed pebble of white milky quartz.

These objects communicate with me visually, like icons, with no need for words or definitions. The study of such visual, non-verbal messaging is called ***semiotics.*** But when I apply words or definitions to them, I leave the study of *semiotics* to enter the territory of ***semantics,*** a branch of linguistics that studies word meanings. Thanks to semantics, what I say and what you hear are not in perfect alignment. Herein lies the tap root of miscommunication.

In my opening paragraph, I deliberately used the word Globe, World, Earth, Planet, and Nature in that order. I know what ***I*** mean by each. But as you listened, the subconscious meanings ***you*** attach to each of those words influenced how you received my message. Enough common information gets through to allow us to keep communicating. But some information blocked or filtered out, and some is skewed. That's when we begin talking past one another.

Mathematics, engineering, science, and law have very specific and rigid nomenclatures -- not because they like words better than other disciplines, but because precision words streamline communication and prevent miscommunication. But when the whole world must have a common conversation, as with the climate crisis, our definitions must be general enough for transmission and reception, yet specific enough to prevent serious miscommunication. Finding the balance is hard..

The words World, Planet, Globe, Earth, and Nature stream relentlessly from our media, even though they are seldom defined. Though often used as synonyms, this is a mistake because their meanings overlap only at the fringes. Comingling these words impairs our response to the climate crisis. The result is a deluge of miscommunication, most of which is unintentional, but some of which is deliberate and manipulative.

In this last episode of my original podcast, I share with you how I use these words, so that you can help share the ideas with others.

Let's start with definitions. The first four are clear.

- ***World*** is the human component of the Earth, including the things we've engineered and domesticated. The context is humanity.
- ***Planet*** is the totality of the oblate spheroid that spins and revolves the sun in the company of its moon. The context is the solar system.
- ***Globe*** is the spherical surface of our planet, or, less commonly, a physical scale model of it. Given that the world has gone digital, modern usage is usually adjectival, as with global. The context is spherical geometry.
- ***Earth*** is the entire energized material system of solids, liquids, and gasses between the sweet spot of the planet's iron core and the stratosphere. The context is the dynamical system.

- ***Nature*** is a muddle because it's used inconsistently in four different ways. Most commonly, nature the ***non-human*** part of biology, or the ***non-human*** part of all material reality, thereby setting sets humans apart. Far less commonly, nature is the sum of ***all*** living things or ***all*** of material reality making it synonymous with Earth. The context is human vs. non-human.

With reference to my three objects above, the white pebble is a *natural* object created by *earthly* processes --the hydrothermal steam that deposited the quartz vein, the glacial erosion that tumbled it in a meltwater stream, and the shoaling surf that rounded it with *planetary* tides. The compass is *worldly,* having been created for human benefit, and *earthly*, having been smelted from ore. The alignment of its needle arises from *planetary* spin, which, at this scale, is also earthly spin. The *globe* is a spherical miniature map of the Earth's surface.

Now let's apply these definitions to the climate crisis. The *world* is tweaking the chemistry of the atmospheric component of *Earth* at the *global* scale, causing its surface temperature to rise. *Nature* and the world are being affected. The *planet* remains largely unaffected.

In terms of value judgments based on human morality, climate changes is irrelevant to the *globe* and *planet,* neutral from *Earth's* point of view, somewhat negative for the integrated sum total of *world* and *nature*, and either positive or negative for specific elements of *world* and *nature.*

In the previous episodes, I tried to use these words consistently. But to when using quotes, and to prevent boredom, I sometimes used them as synonyms.

And now, I zoom into each of the five words, with a review of some of the more important point regarding them.

Planet

A *planet* is any large celestial object that orbits a star. The name we've given to our planet is Earth. The main connotation is being a member of the solar system. It's orbit around the sun is close to two-dimensional, tracing the shape of an ellipse on a plane called the ecliptic. When I use the word planet, my connotation is of one object circling a star. To say "Earth orbits the sun" is shorthand for "the planet we've named Earth orbits the sun."

All eight planets are spherical, or nearly so, the gas giants of Jupiter, Saturn, Uranus and Neptune because they're dominated by fluids, and the rocky planets of Mercury, Venus, Earth, and Mars because they were molten when shaped. Earth remain soft enough to deform into a spheroid that becomes more like a sphere the colder it gets and slower it spins.

Between the inner and outer planets is the asteroid belt, an estimated 2 million orbiting rocky, misshapen, and broken fragments that never quite congealed into a planet, thanks to gravitational issues involving nearby Jupiter. Largest of these asteroids is Pallas Ceres at nearly 1000 km across. Beyond all eight planets are distant clouds of icy dust where comets dwell, for example the Oort Cloud and the Kuiper Belt.

When you hear Earth used as the name of our planet, think of it as one in a family of siblings that revolve around a much more massive star, and share a broadly similar story. Earth seems to be the odd one out, the only one known to possess a veil of liquid water from which life arose, and the long-duration plate tectonics to keep that life going.

Our local family of the sun and its planets links upward to the grander, but still local story of the Milky Way galaxy, which links upward to the grander story of the entire universe.

All of the planets came together about 4.6 billion years ago when a continuum of matter gathered into concentrations at random distances from the sun. Each concentration coalesced through a game of winner take all in which larger objects swept up smaller objects by virtue of their stronger gravity. Molecules of gas, specks of dust, tiny blobs called chondrules, asteroids, planetesimals, and planetary embryos. All came together nearly at once.

Earth's history as a planet continues. Annually, it receives about 40 thousand tons of extraterrestrial material each year, most of which is dust. Larger objects are Earth-crossing asteroids whose orbital paths intersects ours.

Globe

Globe derives from the Latin *globus,* meaning spherical object. Fundamentally, it's a three dimensional shape, a sister to the cube, not to the square, and cousin to the pyramid, not the triangle, and not to be confuses. But as commonly used, is the surface area of the solid and liquid earth below the base of the atmosphere.

Because I'm hard-wired to be literal in my thinking, the phrase global warming grates on me because it's only the surface of the globe that not warming, not the globe itself .

The word globe also refers to a three-dimensional map, usually, but not always, of the Earth, preferably one that spins on its axis and can be tilted away from vertical. The main connotation is spherical geography. Being a hollow sphere, such maps are expensive to make and hard to store and transport, which is why they've largely disappeared in the flat-screen virtual age. But looking back half a millennium to the time of the early explorers, globes were a vast improvement over the distortions of two-dimensional map projections such as the equal-area projections, that makes Greenland larger than the United States, or the Mercator projection that slices high latitudes into segments resembling the sections of an orange.

Because few of us have globes any more, the noun *globe* is taking a back seat to the adjective *global.* As with global warming or global politics, the basic idea is that something is effecting the entire surface, but not its volume or mass. Human politics have always been about the surface or near-surface because our mining and drilling have never gone more than skin deep, or about 10 kilometers, which is less than one 600th of the distance to Earth's central sweet spot. The phrase global warming works when it applies only to the thin outer veil of the Earth's gas, liquid, and outer crust. The inner portions of the 3-D globe have been cooling down since the first day.

World

When my kids were little, all were obsessed with large-format, search-and-find books. Within this genre, their favorite books were titled *Where in the World is Carmen San Diego?* I recall a half-dozen getting worn out. On every set of facing pages was a dense crowd of people standing, sitting, walking and running about. Carmen San Diego, with his red-striped shirt and hat, was the odd one out, cleverly hidden among hundreds.

The title *Where in the Planet is Carmen San Diego?* wouldn't make sense because the activity has nothing to do with the sun. Nor would *Where in the Earth...?* or *Where in the Globe...?* because he's hidden on a flat surface amidst a crowd of humans.

World is a portmanteau, a compound word created by putting two words together whose namesake was an old-fashioned suitcase of two equal halves. Similarly, the word "world" combines "*were*" as in "werewolf, " meaning human wolf, and "*auld*," meaning old, as with the traditional New Year's Eve song "*auld lang syne*." The formula: *were* + *auld* = *wereauld*, when anglicized, becomes world. It refers to the entire human population on our planet dating back to the dawn of our species. The earliest humans living in the middle of the food chain in Africa a hundred thousand years ago are just as much a part of the world as my grand-daughter born during the Covid-19 pandemic.

By definition, the humanities and social sciences study the world. Hence their *worldview* centers on the human mind, whether individual or collective, ancient or modern. Indigenous voices and centuries of anthropological discovery highlight opposing world views, for example the so-called western worldview of human dominance over Nature, versus the more intuitive perspective of humans being partners with plants, animals, rocks and clouds. But both views are human centered.

The dominant modern worldview is that the Earth is here for human benefit, and that our species can do with it whatever they please. This is not the view of everyone, but it's the one that dominates the global economy of the Human Epoch, the Anthropocene. Earth is getting quite a makeover. Nonhuman animals have been generally demoted to being resources, whether for food (meat), power (draft animals), entertainment (zoos), or companionship (pets). Plants, fungi, microbes, minerals, liquids, and gasses are similarly treated. Being so removed from Nature, our awe at the spectacle of the universe is diminished, making us arrogant to the point of irresponsibility. In its most extreme form this worldview is nicely summarized by former U.S. Secretary of State and former ExxonMobil CEO Rex Tillerson, who remarked: "What good is it to save the planet if humanity suffers?" [87]

From my point of view, the climate crisis derives from letting our *worldview* supercede our *earthview,* largely because we have the power to do so, but also because urban populations are largely ignorant of how the Earth actually works. Our recently internalized and self-anointed supremacy over other species and other components of Earth is unnatural, a self-inflicted wound to our psyches. For most our duration as a species, we've been yet another biological species stuck in the middle of the food chain, just as likely to be eaten as to eat.

Earthly

Originally, the word *erth* referred only to the unconsolidated soil beneath of our feet, the stuff from which plants grew, and --in the Christian creation myth of Genesis-- the raw material from which Adam was born. Over time, the meaning of *earth* was extended to include all of earth's solids --soil, sediment, rock, and organics-- making it synonymous with dry land, as opposed to the liquid sea and gaseous sky. This frame of reference is solid habitat, the home for terrestrial primates, complete with air, life, and water.

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[87] Mann 132, footnote 43.

Through the ages, we eventually learned that Earth's broadly curved surface was neither flat, nor was it the center of everything. Instead it was one of seven planets known to the ancient world, the third one out from the sun. Given our terrestrial bias, we named that planet Earth.

When viewed from the moon, Earth is dominated not the gray-brown-green mosaic of the planet's dry land, but a swirl of blue and white from liquid water, clouds, and snow. A blue marble. *Aqua,* rather than *Earth*, would have been a better planetary name, but it's too late to make this correction now.

Earth is the central object of this podcast series. Not as one of many planets, but as a single, energized spherical volume of gas, liquid, and solid with a well-defined outer boundary. A system with mechanical parts and interacting fluids that's analogous to the human body. But instead of skin there is soil. Instead of hair, there is atmosphere. Instead of a throbbing heart, there is an iron core. Instead of muscle and bone, there is silicate rock and plant fiber. Earth is a far more complex system than the human body, if only because human bodies are part of the larger whole. Additionally, it encompasses a much wider range of materials, has a much, much longer history, and depends on four main sources of energy rather than one --solar, orbital, gravitational, and geothermal.

In Earth's concentric system, all components are important. Broadly speaking, there are two liquid layers: a continuous outer core, and a discontinuous water ocean, which was steamed out of the mantle. Both liquids pre-date and continuously support the happy accident called life. There is one gaseous layer, the atmosphere. And there are three main solid layers of the blazing hot core, the ductile mantle, and the rigid crust.

Nature

Merriam Webster defines Nature at "the phenomena of the physical world collectively, including plants, animals, the landscape, and other features and products of the earth, as opposed to humans or human creations." Setting aside the confusion between world and Earth, the key piece of their definition is the dichotomy of humans versus everything else, each in its own conceptual bin.

I reject this definition for three reasons.

First, Bill McKibben got it right and wrong when he published *The End of Nature* decades ago. In our Anthropocene Epoch, nothing on Earth lies outside of human influence, meaning that nature, as defined by Merriam Webster, no longer exists. We've even tweaked the planetary spin by smoothing out earth's mass distribution. Ice sheet melting has made Earth less lopsided, reducing the shimmy of its rotation.

Second, the word nature, used as a cultural meme, is utterly biocentric. If you watch *Nature* documentaries on public television, as I do, they're almost entirely about living things, usually the charismatic animals and the naturalists who film them. Shows about the magnetosphere are far more likely to be found on a different series, the science channel *Nova,* even though the Van Allen belts creating the auroras and penguins are equally natural. The "nature" documentary I recently watched about the Rancho La Brea tar pits in Los Angeles focused almost exclusively on the ice-age fauna that was trapped there 25 to 10 thousand years ago, rather than the equally interesting question of how one might create a liquid lake of viscous petroleum.

Third, the psycho-social-spiritual removal of humanity from nature in so-called western culture lies at the root of the climate crisis. Two important manifestos of the environmental movement are Henry D. Thoreau's 1854 *Walden* and Rachel Carson's 1962 *Silent Spring.* The underlying premise of both is the inseparability of the human ***subsystem*** of the ***Earth system*** from equally important others.

Using the Right Word

The climate crisis is a *worldly* crisis, not an *earthly* one. *Earth* will do fine without us. In fact, Earth doesn't know or care about the climate crisis because it lacks consciousness, and therefore morality.

Yes, the globe *is* being warmed. No, the globe is *not* being warmed. Both statements are true, depending on whether you're referring to a surface or a volume.

The climate crisis is *global* because it's affecting the entire *planetary* surface, the habitat of *nature*, and the arbitrary nations of the *world.* At the same time, the climate crisis is not global because it's different in every place. At the same time, it's not global because the interior of the spheroid is unchanged.

Earth's previous climate crises were created before the World came into existence about 300,000 years ago, when big-brained *sapiens* speciated away from its sister species in the genus *Homo*. The modern climate crisis was created by that *world*, mostly after 1950. Like a toddler with a stick, humanity has "poked the bear" of the Earth system without knowing how the bear thinks, and how it would behave. The bear is now responding in ways beyond our control. Though the worst is yet to come, I doubt our actions will prove fatal. Morally, the biggest issue is that the rest of Nature is experiencing our collateral damage.

More specifically, the Anthropocene w*orld* of accelerating technologies and energy consumption since the Industrial Revolution have given us the power to perform a *global* makeover of the outer components of the *Earth* system, the land surface, oceans, and the atmosphere. The makeover of the land and ocean were and are deliberate, for example converting forest to cropland, building infrastructure, irrigating drylands, overfishing the seas, pouring concrete in cities, and hardening our shorelines. The makeover of the atmosphere was also mainly deliberate, done mostly after our scientists knew what the consequences would be, but we preferred not to listen. Since the early 1960s, we've added nearly four times as much carbon to the air than before that date. [88]

Scientifically, the crux of the problem of anthropogenic climate change comes in two basic steps. The actions of every individual and nation in the *world* aggregates to one grand sum: the *global* thermal state of the atmosphere. That aggregated global thermal state then creates climate changes that are different everywhere on *Earth,* and effect every surface component. Politically, the crux of the problem is that the most powerful and wealthiest nations contributed most to a global change

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[88] Statistica. https://www.statista.com/statistics/264699/worldwide-co2-emissions/ 9.39 metric tons in 1960, 34.81 om 2020, ,3.7 ratio.

that is now impacting the weaker and poorer nations the most. In an earlier *world* of lower populations and without fixed territorial boundaries, this imbalance would have been accommodated by *natural* migrations from one place to another. Unfortunately, the fixed and carefully defended boundaries of modern sovereign nations blocks these migrations, transforming climate change into a political crisis, and transforming climate migrants into climate refugees.

Looking beneath the surface, *world* lacks the power to wreck *Earth* either as a system or a *planet.* But we have tweaked it. Worldly mass transfers --directly by mining and construction, and indirectly by differential glacial melting-- have caused measurable changes associated not only on the surface, but also involving the rate and style of planetary spin.

There will come a time less than a billion years from now when the sun will expand its corona. As Earth warms, the carbon content of its atmosphere will fall below the threshold for photosynthesis. Earth as we know it will disappear. But the planet will remain orbiting the same old sun. To say, as Peter Brannen does, that "Earth has been many different planets in its lifetime" is simply not true.

More true is that the planet has had many different Earths.