A holistic look at Earth's chemical cycling sheds light on how the planet stays habitable

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We all know Earth is special, but we may not fully appreciate how good we have it on this planet. Unlike its planetary neighbors, Earth has remained habitable for billions of years thanks to a complicated, everchanging dance of elements.

A study by researchers at the University of Chicago, Rice University, and the California Institute of Technology sheds new light on the delicate balance of biogeochemical cycles that keep Earth temperate, hydrated and thriving.

The cycling of elements between the oceans, atmosphere, and land plays a role in keeping the climate stable, but it is so complex that scientists typically isolate pieces of the whole to try to get a better grasp on how they work. However, a new study, published in the *Proceedings of the National Academy of Sciences* on March 13, offers a different approach.

The researchers instead offer a broad, simplified point of view, using a new set of mathematical tools to illuminate relationships among the different chemical cycles that were previously hard to spot.

"Our approach provides a new way to identify the fundamental building blocks of stability in the chemical components of Earth's climate—the underlying ways in which the climate can be stabilized over geological time due to the movement of elements across the ocean, atmosphere, and rock reservoirs," said Preston Cosslett Kemeny, a UChicago TC Chamberlain postdoctoral fellow and first author on the paper.

"This is an elegant, simplified way to think about an enormous problem, which organizes a lot of previous research on elemental cycles into packages of chemical reactions that can be balanced and understood," said UChicago Asst. Prof. Clara Blättler, senior author on the paper.

Cycles and climate

We often take for granted that the planet Earth has supported complex life for hundreds of millions of years. But this stability was certainly not guaranteed—one need only look next door at Mars and Venus, which formed from roughly the same materials as Earth, but do not even currently support liquid water. What's Earth's secret?

A key aspect is chemical cycling. Elements like carbon, sulfur, and calcium move between the land, ocean and atmosphere in ways that have kept the conditions at Earth's surface relatively stable over hundreds of millions of years.

For example, scientists think the planet's temperatures are partly maintained by carbon shifting gradually back and forth between the ocean, atmosphere, and land. When carbon dioxide builds up in the atmosphere and heats the surface, it causes rocks to break down faster—moving carbon into the ocean and subsequently into rocks at the seafloor. Over millions of years, the planet gradually cools back down as the carbon is sucked out of the atmosphere.

Untangling these cycles has been the work of decades. It's challenging because the cycles last for millions of years, are endlessly changing, take place over the entire globe and interact with each other constantly. It's so complex that scientists often only examine pieces of the entire picture—typically considering a limited number of element cycles or a small subset of their interactions. But when pieces of the puzzle are missing, researchers have to make assumptions to fill in the gaps.

Kemeny wondered if working this way might tend to cloud the overall picture of how biogeochemical interactions give rise to planetary stability.

He, along with Blättler, Mark Torres of Rice University, and Woodward Fischer of Caltech, took a step back. They ran a mathematical analysis in which they considered a wide range of chemical reactions comprising major chemical cycles, but did not specify how or how much the cycles interacted with each other.

The result is a framework that identifies all of the major and minor combinations of reactions that balance Earth's carbon cycle and their relations to one another—something that had been missing from the field. Viewed this way, the Earth's climate can be represented by a set of interconnected chemical equations that must balance over certain time periods.

The authors said their work is useful as scientists continue to study the history of Earth and how the climate has changed over time.

"For example, say that you are considering a hypothesis for why the climate changed in the past—such as the major cooling of the last 65 million years," Kemeny said. "You can take this framework and use it to say, well if X process increased or decreased, then it should have also caused Y to happen, or would have needed to be balanced by Z, and that you have to account for those outcomes—so with that prediction we can look for evidence for the joint operation of the whole geochemical system."

Other relationships between chemical cycles can become visible when looked at in the bird's-eye view. "For example, this analysis identified a new way to balance carbon fluxes in the ocean-atmosphere system while accumulating atmosphere oxygen," Kemeny said.

Taken as a whole, "We hope it's a beautiful way to help understand all the chemistries that are involved in making Earth a safe place for life to evolve," Blättler said.

More information: Preston Cosslett Kemeny et al, Balance and

imbalance in biogeochemical cycles reflect the operation of closed, exchange, and open sets, *Proceedings of the National Academy of Sciences* (2024). DOI: 10.1073/pnas.2316535121

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