GEOCHEMICAL CLIMATE REGULATION BEYOND EARTH

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INTRODUCTION

The last two decades have seen major advances in climate science in the Solar System and a great leap forward in our knowledge of planets around other stars—exoplanets. We now know of a large and increasing number of exoplanets with masses and equilibrium temperatures that suggest they could be Earth-like. But what does this really mean? Will they have liquid water oceans? Plate tectonics and carbonate-silicate cycles? Biospheres?

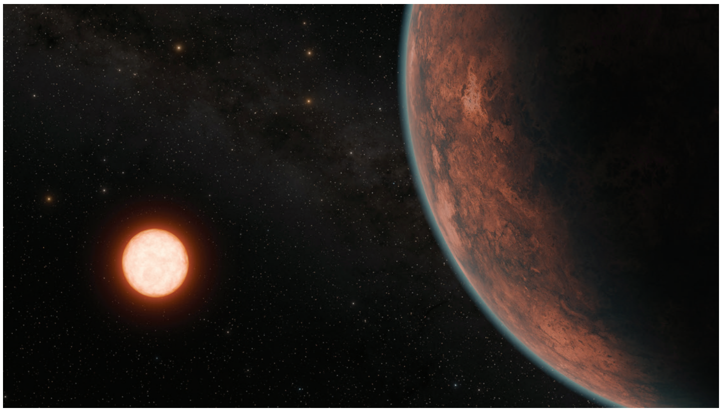
This issue focuses on the complex array of processes that influence Earth's carbon cycle. Once we move beyond Earth, we are forced to confront the question of how common these processes are elsewhere. Our close neighbors in the Solar System provide insights into what happens when climate regulation breaks down, but also into how entirely different climate regulation systems can operate. Outside the Solar System, the observational challenges remain daunting, but some clues have emerged, and more are set to follow. Furthermore, exoplanet theory provides a wide perspective that is yielding new ways of thinking about climate closer to home.

Lessons from the Solar System

Our Solar System is the natural place to start when thinking about extraterrestrial climate feedbacks. Venus has a similar mass to Earth and absorbs less solar radiation overall*, but it has a 92-bar CO_2-dominated atmosphere and a much hotter surface (741 K on average). Carbonate minerals aren't stable on Venus's surface today due to the high temperature and presence of sulfur-bearing gases (Zolotov 2018), and without surface liquid water there is no possibility of a carbonate-silicate cycle. However, there may be other climate feedbacks due to variations in albedo or the total greenhouse effect. It's also possible that Venus passed into its current state from an early Earth-like phase via a runaway greenhouse transition, but hard evidence for this scenario is still lacking.

Mars's atmosphere—also CO_2-dominated—is much thinner, just 0.006 bar on average. Carbonate mineral formation, the main long-term sink of carbon on Earth, is inhibited on modern Mars because liquid water is almost never stable. Some carbonates are visible on Mars's surface, but we see less than expected given its watery history (Ehlmann and Edwards 2014). This may partly be due to observational bias, but it is clear that Mars's habitability sputtered and then failed a long time ago, between 3 and 4 Ga, during Earth's Archean period. While Venus's inhospitable climate appears to be an outcome of its orbital distance, Mars's lack of a carbonate-silicate cycle has more to do with its low mass, which inhibited the onset of plate tectonics and led to rapid escape of the atmosphere to space followed by early shutdown of the hydrological cycle.

For the closest analog to Earth in the modern Solar System, we have to look beyond planets altogether. Saturn's moon Titan is far too cold for surface liquid water, with a surface temperature of 94 K. Nonetheless, it has a 'hydrological' cycle driven by hydrocarbons that creates rain, lakes, and river networks eerily similar to those on Earth. As a condensable species that also has a greenhouse effect, CH_4 on Titan plays a similar role to H_2O on Earth. Interestingly, it has been postulated that Titan's H_2 is also analogous to Earth's CO_2, due to its long residence time and collision-induced greenhouse effect (McKay et al. 1991). Understanding the drivers of Titan's climate is a key objective of NASA's *Dragonfly* mission, which is due to launch in 2028.



Artist's impression of Gliese 12 b, a rocky world orbiting a red dwarf star. Such planets help researchers assess whether close-in exoplanets can retain atmospheres—a central question in understanding geochemical climate regulation beyond Earth. CREDIT: NASA/JPL-CALTECH/R. HURT (CALTECH-IPAC).

Exoplanet carbon cycles

Beyond the Solar System, exoplanets have the potential to yield sweeping new insights into climate feedbacks. Observations have established the existence of a large population of small, gas-rich planets—sub-Neptunes—that have no direct analogue in the Solar System. Rocky planets also appear common, although we still know little about them. Many rocky planets have now been observed in the 'habitable zone', defined as the region where received stellar flux is consistent with surface liquid water, given the existence of plate tectonics and a carbonate-silicate cycle broadly like Earth's. Most of these planets orbit red dwarf stars, because our current observational techniques work much better on small stars with close-orbiting planets than on stars like the Sun (Wordsworth and Kreidberg 2022).

Red dwarf stars have a few quirky features. Most significantly for planetary climate, they spew out atmosphere-stripping extreme ultraviolet radiation at orders of magnitude greater relative intensity than the Sun. Some early studies suggested this would not be too much of a problem for atmospheric retention, but the most recent *James Webb Space Telescope* data are revealing that many rocky planets around M-dwarfs may in fact be airless. This trend needs to be confirmed by follow-up observations, but if it holds, it limits the prospects for conventionally habitable Earth-like planets around red dwarf stars.

For rocky exoplanets that do retain their atmospheres, theory has already yielded some insights. The amount of water a planet possesses is probably critical—at about 230 to 690 ppmw, Earth's surface and mantle water inventory is small compared to what we expect for many exoplanets (Dong et al. 2021). At a few times Earth's surface water inventory, sub-aerial land would be absent altogether, resulting in a waterworld. Lacking continental erosion and weathering, waterworlds will have carbon cycles dominated by seafloor weathering and potentially limited seafloor volcanic outgassing due to overburden pressure (see Li and Li 2026 this issue and Bach and Diehl 2026 this issue). They will also lack a supply of nutrients to the surface ocean from continental weathering, which could limit biospheric productivity, depending on the rate of supply from hydrothermal alteration and other seafloor processes.

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* Venus receives 1.9 times more solar radiation than Earth, but reflects about 75% of it to space versus Earth's 30%, so the total amount absorbed is around 30% less.

Other carbon cycle effects may emerge due to the planet's external forcing. The spectra of red dwarf stars contain less light at blue wavelengths and more in the near-infrared, which reduces the ice-albedo feedback (Joshi et al. 2012). Because many temperate rocky planets around red dwarf stars will be tidally locked, with permanent day and night sides, changes in continental distributions could affect weathering rates particularly strongly. Finally, for Earth-like exoplanets around any star type, higher received insolation should lead to lower atmospheric CO_2 if a carbonate-silicate cycle is active, making climate more unstable to transient carbon cycle perturbations. The same phenomenon has probably affected Earth through geologic time, making it broadly more susceptible to glaciation, including Snowball events, in the second half of its history (Minsky et al. 2025).

The redox chemistry of rocky exoplanets likely varies significantly. Varying rates of escape to space of hydrogen relative to heavier elements in models of exoplanet atmospheric escape lead to predictions of near-surface atmospheric oxygen fugacity that range between −8 and +8 $\log_{10}$ units away from the iron–wüstite buffer. This implies correspondingly huge variations in atmospheric composition, from primordial H_2-dominated envelopes to CO_2- and even O_2-dominated atmospheres in the most extreme fractionation cases (Cherubim et al. 2025). Atmospheric redox has a profound effect on the carbon cycle, as on highly reducing planets carbon takes the form of CO, refractory C or CH_4, rather than CO_2. On such planets, carbonate-silicate weathering will be unlikely to dominate climate, and other effects, such as photochemical conversion of CH_4 to long-chain hydrocarbon hazes, may be more important instead.

Despite theoretical progress, direct observational constraints on exoplanet carbon cycles and geochemical climate regulation are still scarce. Transit spectroscopy presents new opportunities through near-infrared observations of rocky surfaces, although it is still early days for this approach (Paragas et al. 2025). We can also get indirect geochemical information on the compositions of rocky exoplanets from the dying remnants of stars—white dwarfs. White dwarfs are so small and dense that any heavy atoms in their atmospheres rapidly sink downwards. If their spectra exhibit lines of elements such as Fe, Mg, or Si, it is therefore a clear sign that rocky material has recently fallen in. Careful analysis of these spectral lines can constrain critical aspects of the material's chemical evolution, including redox state (Doyle et al. 2019).

The ultimate challenge for exoplanet research is searching for signs of life. It is a hard problem, and we still have much to learn. Recent attempts to observe biosignatures remotely have already generated intense interest, but robust searches for life will require a strong understanding of how planets behave when life is absent. The problem is multifaceted, but exoplanet carbon cycles and climate regulation are critical, because they determine the variation of key gases such as CO_2 and O_2 through time. The topics covered in this issue are Earth-specific, but they will be important to exoplanet biosignature definitions in the future.

The roots of geology date back to an era when many believed life could routinely emerge from dead matter. It is poetic that such a venerable discipline will remain essential to progress as we begin to search for life among the stars.

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Robin Wordsworth is a professor of planetary science at Harvard University, USA. He is an NSF CAREER award recipient and served on the 2022 NAS Planetary Decadal Survey. Robin's research focuses on the physical and chemical evolution of terrestrial-type planets. Current interests include the past climates of Mars and Venus, the nature of the transition from sub-Neptune to rocky exoplanets, the coupling between climate and the biosphere on Earth, and the quantum nature of CO_2 radiative forcing. Robin is originally from the Scottish Highlands and grew up close to the shores of Loch Ness.

Charlotte Minsky is a PhD candidate studying planetary science at Harvard University, USA. Her work focuses on modeling long-term climate change and biogeochemical cycles in Earth's deep history, and she is interested in how planets we know can help us think about planets we don't know yet. Prior to her PhD, Charlotte studied the history and philosophy of science as a Gates Cambridge Scholar at the University of Cambridge (UK), and hunted for exoplanets as an undergraduate on the MIT Transiting Exoplanet Survey Satellite (TESS) team. She hails from a series of basalt ridges in western Massachusetts, USA, emplaced during the breakup of supercontinent Pangaea.