Complex Planetary Systems II: Latest Methods for an Interdisciplinary Approach
Proceedings IAU Symposium No. 382, 2024
A. Lemaitre & A.-S. Libert, eds.
doi:10.1017/S1743921323004957

Positive Weathering Feedback Compensates Carbonates at Shallow Ocean Depths

Hakim Kaustubh

KU Leuven, Institute of Astronomy, Celestijnenlaan 200D, 3001 Leuven, Belgium
Royal Observatory of Belgium, Ringlaan 3, 1180 Brussels, Belgium
email: kaustubh.hakim@kuleuven.be

Abstract. Continental silicate weathering and seafloor carbonate precipitation are key steps in the carbonate-silicate cycle to draw down CO_2. Contrary to the classic understanding of negative feedback, silicate weathering can exhibit positive feedback at high temperatures. Taking into account this positive feedback, the compensation depth (CCD) in exoplanet oceans becomes shallower, implying a potential instability in the carbonate-silicate cycle at high temperatures.

Keywords. Carbon Cycle, Carbonate Compensation Depth, Positive Weathering Feedback

---

1. Introduction

The carbonate-silicate cycle is a geochemical cycle that is thought to have enabled temperate climates during the history of Earth by recycling CO_2 through planetary carbon reservoirs (Walker et al. 1981; Berner et al. 1983; Krissansen-Totton et al. 2018). The regulation of atmospheric CO_2 ensures that the greenhouse warming effect of CO_2 is sufficient to maintain a clement surface temperature T and a liquid water reservoir on the surface, which are vital for long-term habitability Catling & Zahnle (2020). During the Archean, when the sun was only 70% as bright as today (Sagan & Mullen 1972), a warmer climate was ensured by a higher CO_2 partial pressure $P_{\mathrm{CO_2}}$ and a lower intensity of silicate weathering (Kasting et al. 1993). Walker et al. (1981) discovered that the weathering of continental silicate rocks provides negative feedback to create a thermostat-like effect. If outgassing increases, $P_{\mathrm{CO_2}}$ rises and consequently weathering intensifies to increase the CO_2 drawdown. Alternatively, if outgassing decreases, weathering diminishes until $P_{\mathrm{CO_2}}$ is high enough to attain a new balance between weathering and outgassing. Once the silicate weathering products are transported to oceans by rivers, the precipitation of carbonates occurs on the seafloor for eventual subduction of carbonates into the mantle (Sleep & Zahnle 2001). The carbonate compensation depth (CCD) is a critical ocean depth below which carbonates are unstable and dissolve into the ocean (Broecker & Peng 1987; Zeebe & Westbroek 2003). If the ocean depth exceeds the CCD, the carbonates cannot be removed from the ocean-atmosphere system and the carbonate-silicate cycle halts.

2. Positive weathering feedback

With the application of a multi-regime silicate weathering model ($W = f(P_{\mathrm{CO_2}}, T)$) of (Maher & Chamberlain 2014), Hakim et al. (2021) find that weathering exhibits negative feedback at low temperatures ($W \propto T$), but positive feedback at high temperatures ($W \propto 1/T$, Fig. 1a). There is a transition from the classic kinetic limit (Walker et al. 1981) to the thermodynamic limit. The transition temperature is sensitive to rock composition

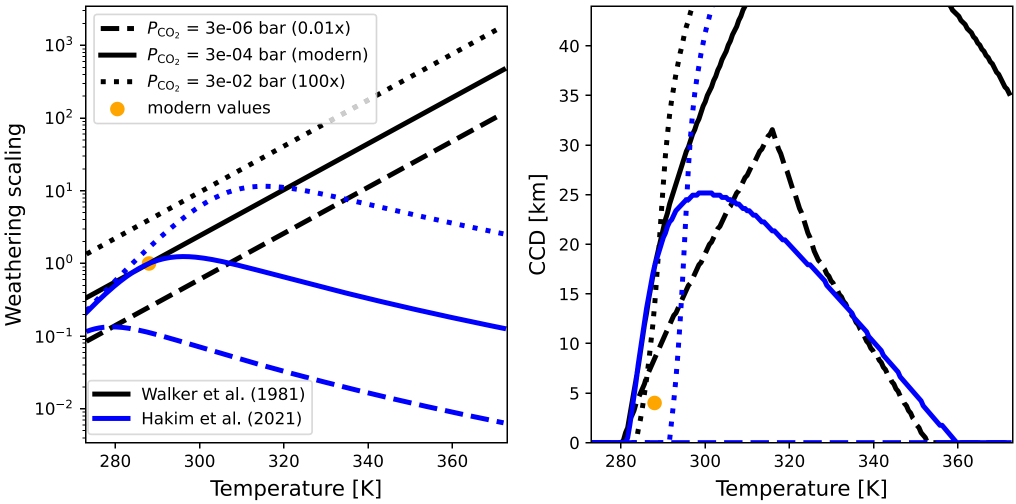

Figure 1. (a) Continental weathering scaling relations of Walker et al. (1981) and Hakim et al. (2021) for three P_{CO_2} values. (b) Carbonate compensation depth (CCD) in exoplanet oceans for the two weathering models is based on the OCRA ocean chemistry model (Hakim et al. 2023).

(e.g., kinetic and thermodynamic properties of granite, basalt or peridotite) and soil transport properties (e.g., flowpath length, soil age) (Hakim et al. 2021). The transition temperature also increases with P_{CO_2} (Fig. 1a calculations for 3 constant values of P_{CO_2}). It is important to note that P_{CO_2} should be coupled to T via a climate model (Krissansen-Totton et al. 2018), but it is kept constant here to isolate the effect of temperature.

3. Shallow Carbonate Compensation Depths

Fig. 1b shows that the CCD first increases and then decreases with T (ocean temperature = surface temperature). For the modern model (black solid line, Fig. 1b), the CCD sharply increases from about 0 km at 288 K to >45 km at 310 K. Beyond 360 K, the CCD decreases due to silicates becoming more stable than carbonates (Hakim et al. 2023). The CCD becomes deeper at 100× modern P_{CO_2} and shallower at 0.01× modern P_{CO_2}. When the multi-regime weathering model from Hakim et al. (2021) is used (blue lines, Fig. 1b), the CCD becomes shallower at high T than that in classic kinetic weathering cases. This is a result of the transition from the negative weathering feedback at low T to the positive weathering feedback at high T (Fig. 1a). This effect is strong enough to ensure that no carbonates are stable in oceans when P_{CO_2} is 0.01× of the modern value. Shallower CCDs at higher T imply a potential instability in the carbonate-silicate cycle. Future studies need to evaluate the effect of the coupled climate and multi-regime weathering models on the CCD.

References

Berner, R. A., Lasaga, A. C., & Garrels, R. M. 1983, American Journal of Science, 283, 641. doi:10.2475/ajs.283.7.641

Broecker, W. S. & Peng, T.-H. 1987, Global Biogeochemical Cycles, 1, 15. doi:10.1029/GB001i001p00015

Catling, D. C. & Zahnle, K. J. 2020, Science Advances, 6, eaax1420. doi:10.1126/sciadv.aax1420

Hakim, K., Bower, D. J., Tian, M., et al. 2021, Planetary Science Journal, 2, 49. doi:10.3847/PSJ/abe1b8

Hakim, K., Tian, M., Bower, D. J., et al. 2023, Astrophysical Journal Letters, 942, L20. doi:10.3847/2041-8213/aca90c

Kasting, J. F., Whitmire, D. P., & Reynolds, R. T. 1993, Icarus, 101, 108. doi:10.1006/icar.1993.1010

Krissansen-Totton, J., Arney, G. N., & Catling, D. C. 2018, Proceedings of the National Academy of Science, 115, 4105. doi:10.1073/pnas.1721296115

Maher, K. & Chamberlain, C. P. 2014, Science, 343, 1502. doi:10.1126/science.1250770

Sagan, C. & Mullen, G. 1972, Science, 177, 52. doi:10.1126/science.177.4043.52

Sleep, N. H. & Zahnle, K. 2001, Journal of Geophysical Research, 106, 1373. doi:10.1029/2000JE001247

Walker, J. C. G., Hays, P. B., & Kasting, J. F. 1981, Journal of Geophysical Research, 86, 9776. doi:10.1029/JC086iC10p09776

Zeebe, R. E. & Westbroek, P. 2003, Geochemistry, Geophysics, Geosystems, 4, 1104. doi:10.1029/2003GC000538

https://doi.org/10.1017/S1743921323004957 Published online by Cambridge University Press