Earth as an Integrated System: Coupling Geoscience with Atmospheric and Oceanic Dynamics

Kobayashi Nanami, Sato Kenta

Department of Earth System Science, Hokkaido University, Nishi 5-chome, Kita-ku, Sapporo-shi, Hokkaido, Japan

Abstract

The classical approach in Earth sciences has often involved the compartmentalized study of its constituent spheres: the solid Earth (geosphere), the fluid envelopes (atmosphere and hydrosphere), and the biosphere. However, the past few decades have witnessed a paradigm shift towards a holistic, systems-level understanding of our planet. This review article synthesizes current knowledge on the dynamic couplings between geoscience-encompassing geology, geomorphology, and tectonics-and the fluid dynamics of the atmosphere and oceans. We explore how solid Earth processes, such as mountain building, volcanic activity, and seafloor spreading, fundamentally dictate climatic patterns, ocean circulation, and biogeochemical cycles over geological timescales. Conversely, we examine the powerful feedback mechanisms through which atmospheric and oceanic forces-including weathering, erosion, and ice-sheet dynamics-sculpt the terrestrial and submarine landscape, modulate magmatic processes, and influence the very pace of plate tectonics. Through the lens of integrated Earth system science, we analyze key couplings including the tectonic-climate connection, biogeochemical cycling of carbon and nutrients, and the co-evolution of life and the planet's physical environment. The article highlights the critical role of modern observational technologies, advanced numerical modeling, and paleoclimatological proxies in quantifying these complex interactions. Understanding Earth as a deeply interconnected system is not only fundamental to unraveling its past and predicting its future but is also imperative for addressing the anthropogenic perturbations currently reshaping the planet.

Keywords

Earth System Science, Geosphere-Atmosphere Coupling, Ocean Dynamics, Tectonic-Climate Interactions, Biogeochemical Cycles, Planetary Evolution

1. Introduction

For much of its history, Earth science progressed through the detailed, yet often isolated, investigation of its major components. Geologists mapped mountains and minerals, atmospheric scientists modeled weather patterns, and oceanographers charted currents. While this reductionist approach yielded immense foundational knowledge, it inherently limited our perception of the planet's true nature [1]. Earth does not operate as a collection of independent parts; it functions as a single, complex, and integrated system where energy and matter are continuously exchanged across the boundaries of the geosphere, atmosphere, hydrosphere, and biosphere.

The concept of Earth as a system gained prominence with the advent of plate tectonic theory, which provided a unifying framework for geology, and was later crystallized by James Lovelock's Gaia hypothesis and the pioneering work of the climate science community. Today, the interdisciplinary field of Earth System Science (ESS) seeks to understand the physical, chemical, biological, and human interactions that determine the past, present, and future states of our planet. At the heart of ESS lies the recognition that the solid Earth is not a passive stage upon which climate and life act, but an active, dynamic driver of global change [2].

This article aims to provide a comprehensive review of the couplings between the geoscience domains-tectonics, volcanism, geomorphology-and the fluid dynamical systems of the atmosphere and oceans. We will delve into the mechanisms through which the Earth's interior engine, manifested as plate tectonics, sets the boundary conditions for climate. Mountain ranges act as elevated heat sources that perturb atmospheric circulation, the opening and closing of oceanic gateways reconfigures global heat transport, and volcanic outgassing regulates atmospheric CO_2 levels over millions of years [3].

Simultaneously, we will explore the powerful top-down influences. The atmosphere and oceans, through weathering and erosion, are the primary agents that dismantle mountain belts, deliver sediments to basins, and control the composition of the crust and mantle. The growth and decay of ice sheets not only change sea level but also deform the solid Earth through isostatic adjustment, potentially influencing magma generation and even plate motions [4]. The hydrological cycle is, therefore, a central thread linking the deep Earth to its surface environment.

This review is structured to first establish the primary drivers from the solid Earth (Section 2), then detail the feedbacks from the fluid envelopes (Section 3), followed by an in-depth analysis of the carbon cycle as a quintessential example of this coupling (Section 4). We will then discuss the role of the biosphere as both a mediator and a product of these interactions (Section 5), the tools and methodologies used to study them (Section 6), and conclude with implications for anthropogenic change and future research directions (Section 7). By weaving together evidence from geology, climatology, and oceanography, this article underscores the indispensability of an integrated perspective for a true understanding of planetary dynamics.

2. Solid Earth as the Primary Driver: Tectonic Forcing on Climate and Oceans

The engine of plate tectonics, fueled by Earth's internal radiogenic and primordial heat, provides the first-order control on the geography and bathymetry of the planet. This tectonic architecture, evolving over tens to hundreds of millions of years, imposes a fundamental template upon which the atmospheric and oceanic circulation patterns are built [5].

2.1 Orogenesis and Atmospheric Circulation

The uplift of major mountain ranges and plateaus, such as the Himalayas-Tibetan Plateau and the Andes, represents one of the most significant ways the solid Earth influences climate. These massive topographic features act as formidable barriers to atmospheric flow, redirecting jet streams, creating rain shadows, and triggering monsoonal circulations [6].

The Tibetan Plateau, a product of the ongoing collision between the Indian and Eurasian plates, functions as an elevated heat source during the summer. This heating drives a powerful ascending air current, which draws in moist air from the Indian Ocean, resulting in the intense Asian Summer Monsoon. The monsoon is not merely a climatic phenomenon; it is a direct tectonic consequence. The erosional power of the monsoon, in turn, strips material from the Himalayan front, affecting the structural evolution of the orogen itself, a feedback we will explore in Section 3.

Similarly, the north-south oriented Andes force the strong Southern Hemisphere westerlies to diverge, creating a strong lee-side low-pressure system and influencing storm tracks across the South Atlantic. The uplift of the Central American Isthmus around 3-4 million years ago had a profound impact, shutting down the deep-water connection between the Atlantic and Pacific and strengthening the Gulf Stream, which is considered a pivotal event in the onset of Northern Hemisphere glaciation [7].

2.2 Ocean Gateways and Thermohaline Circulation

The configuration of the ocean basins is entirely dictated by plate tectonics. The opening and closing of strategic oceanic passages, or "gateways," can radically alter the global circulation of heat and salt, with dramatic climatic consequences.

The most cited example is the tectonic isolation of the Southern Ocean. The northward drift of Australia and South America away from Antarctica, culminating in the opening of the Tasmanian Gateway (~33-30 Ma) and the Drake Passage (~41-30 Ma), allowed for the establishment of the Antarctic Circumpolar Current (ACC). The ACC acts as a thermal barrier, isolating Antarctica from warmer equatorial waters and facilitating its transition from a forested continent to an ice-covered one, leading to the Cenozoic global cooling trend [8].

The geometry of ocean basins also controls the formation of deep water, the engine of the global ocean conveyor belt. For instance, the present-day formation of North Atlantic Deep Water (NADW) is sensitive to the bathymetry of the Greenland-Scotland Ridge. Tectonic changes in such regions can modulate the strength of the Atlantic Meridional Overturning Circulation (AMOC), a critical component of Earth's heat distribution system.

Furthermore, the sensitivity of the Atlantic Meridional Overturning Circulation (AMOC) to tectonic forcing extends beyond gateway openings. Modifications in the bathymetry of the Greenland-Scotland Ridge, due to regional volcanic activity and isostatic adjustments, can directly regulate the overflow of dense, saline water from the Nordic Seas into the North Atlantic. This overflow is a critical component of NADW formation and thus the overall vigor of the AMOC. Numerical modeling studies indicate that even subtle, tectonically-induced sill depth changes of a few hundred meters can modulate the AMOC strength by 15-20%, with profound implications for global heat distribution. A weaker AMOC, for instance, leads to reduced northward heat transport, resulting in amplified cooling in the North Atlantic region and a southward shift of the Intertropical Convergence Zone (ITCZ). This exemplifies how geologically slow processes can set the stage for climatic tipping points, the understanding of which is crucial for paleoclimatology and long-term climate projections [9].

2.3 Volcanism and Outgassing

Volcanism is the primary conduit for the transfer of solid Earth materials and volatiles (like CO_2, H_2O, and SO_2) into the atmosphere and oceans. On long timescales (≥1 Myr), the balance between volcanic outgassing of CO_2 and its consumption by silicate weathering (Section 3.1) is thought to regulate Earth's climate via the carbonate-silicate cycle.

Large Igneous Provinces (LIPs), representing massive, short-duration pulses of magmatism, have been repeatedly linked to major climatic perturbations and mass extinction events in Earth's history. The emplacement of the Siberian Traps at the Permian-Triassic boundary (~252 Ma) released enormous quantities of CO_2 and volatiles, leading to extreme global warming, ocean acidification, and the most severe extinction event of the Phanerozoic. Similarly, the Deccan Traps volcanism is implicated in the end-Cretaceous mass extinction [10]. The climatic impact is not solely from greenhouse gases; the injection of sulfate aerosols can cause short-term global cooling, as historically observed in eruptions like Mount Pinatubo in 1991.

Mid-ocean ridges, though less explosive, represent the largest volcanic system on Earth. The rate of seafloor spreading influences global outgassing fluxes; higher spreading rates are associated with increased volcanic activity and higher atmospheric CO_2, contributing to a warmer climate, as during the Cretaceous period.

3. Fluid Earth Feedback: Sculpting the Solid Planet

While tectonics sets the stage, the atmosphere and oceans are not passive actors. They are powerful exogenic forces that erode, transport, and deposit material, actively shaping the landscape and influencing deep Earth processes through a suite of feedback mechanisms.

3.1 Climate-Controlled Weathering and the Thermostat Hypothesis

Chemical weathering of silicate rocks is a primary long-term sink for atmospheric CO_2. The general reaction can be summarized as:

$$CaSiO_3 + 2CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^- + SiO_2$$

The dissolved products are transported by rivers to the oceans, where marine organisms use them to build calcium carbonate shells. The subsequent burial of carbonate sediments effectively sequesters carbon for millions of years.

This process is intrinsically climate-dependent. Higher temperatures and increased rainfall, often associated with higher CO_2 levels, accelerate chemical weathering rates. This creates a powerful negative feedback loop, known as the Walker, Hays, and Kasting (1981) thermostat or the "weathering thermostat." If Earth becomes too warm, weathering rates increase, drawing down CO_2 and cooling the planet. Conversely, if it becomes too cold, weathering slows, allowing volcanic CO_2 to build up and warm the planet. This feedback is crucial for maintaining Earth's long-term habitability [11].

The efficiency of this sink is also tied to tectonics. Mountain building exposes fresh, unweathered rock to the atmosphere, enhancing weathering drawdown. Raymo and Ruddiman (1992) proposed that the uplift of the Himalayas and Tibetan Plateau since the Miocene led to increased silicate weathering, which contributed significantly to the global cooling that culminated in the Pleistocene ice ages.

3.2 Glacial and Fluvial Erosion and Their Tectonic Feedbacks

Erosion does more than just wear down mountains; it can influence the very tectonic processes that build them. The theory of "tectonic aneurysms" and related concepts suggest that focused erosion can locally enhance rock uplift by removing mass and altering the stress field in the crust.

- **Glacial Erosion:** Glaciers are extremely efficient erosional agents. They carve deep U-shaped valleys and steep peaks, and they can incise rapidly into mountain belts. This glacial "buzzsaw" effect may limit the maximum height of mountain ranges in high-latitude and high-altitude regions. Furthermore, by stripping material, glacial erosion can decompress the underlying crust and mantle, potentially facilitating melting and magmatism. The isostatic rebound following ice-sheet melt (e.g., in Scandinavia and Canada today) is a direct, measurable deformation of the solid Earth in response to a surface fluid (ice/water) load [12].

- **Fluvial Erosion:** Rivers dissect landscapes, creating relief and transporting vast quantities of sediment from continents to ocean basins. The pattern of fluvial erosion is controlled by precipitation, which is itself influenced by the orography created by tectonics. This creates a two-way coupling: tectonics creates the relief that focuses precipitation, and that precipitation, in turn, erodes the landscape, influencing the pattern and rate of deformation. Numerical models show that spatially variable erosion can localize strain and influence the geometry of fold-and-thrust belts.

The concept of a "tectonic aneurysm" provides a compelling mechanism for this feedback. In this model, exceptionally rapid river incision, often focused by intense monsoonal precipitation on the southern flank of the Himalayas, locally removes vast amounts of rock. This extreme exhumation reduces the overlying pressure on the lower crust and upper mantle, triggering a localized response [13]. The crust, buoyed by the underlying mantle, undergoes accelerated uplift to re-establish isostatic equilibrium. More profoundly, the decompression of the hot, deep crust can induce partial melting and rock weakening. This thermally softened crust then deforms more readily, further localizing the tectonic strain and creating a positive feedback loop where focused erosion begets focused uplift. The Nanga Parbat massif in the western Himalayas stands as a premier natural laboratory for this phenomenon, where some of the world's fastest exhumation rates are recorded, directly linking the power of fluvial erosion to deep crustal metamorphic and tectonic processes.

3.3 Sediment Loading and Basin Evolution

The sediments produced by erosion are deposited in sedimentary basins, which are themselves tectonic features (e.g., foreland basins, rifts, passive margins). The sheer weight of this sediment load causes the underlying lithosphere to subside isostatically, creating more accommodation space for further sedimentation. This positive feedback can lead to the accumulation of sediment sequences many kilometers thick.

On continental margins, sediment deposition influences slope stability, triggering submarine landslides that are among the largest mass movements on Earth. These events can remobilize vast volumes of sediment and can generate destructive tsunamis. Furthermore, the delivery of organic carbon and nutrients to the oceans via rivers is a critical link in the global carbon and nutrient cycles, supporting marine productivity and influencing oxygen levels in coastal waters and beyond [14].

4. The Carbon Cycle: A Central Paradigm of Coupling

The global carbon cycle is arguably the most vivid illustration of the deep integration between the geosphere, atmosphere, and oceans. It operates on timescales from days to billions of years, with each reservoir intimately linked to the others.

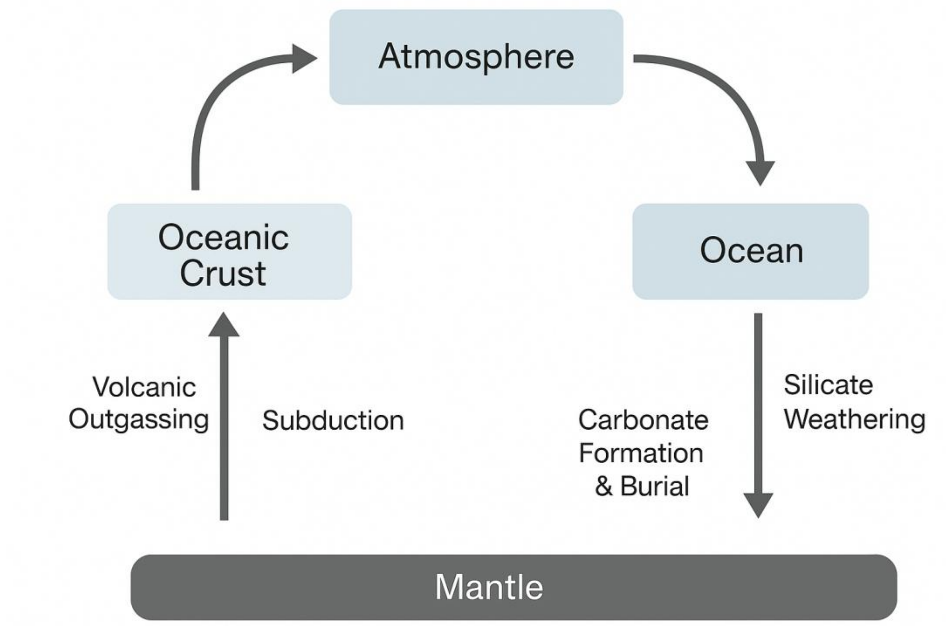

Figure 1. A Simplified Schematic of the Long-Term Geological Carbon Cycle

Figure 1 show the long-term carbon cycle, operating over millions of years, is driven by plate tectonics. Carbon is released from the Earth's interior via volcanism and mid-ocean ridges. It is drawn down from the atmosphere by silicate weathering on the continents and carbonate formation in the oceans. Subduction returns carbon to the mantle, while metamorphism in subduction zones can release some CO_2 back to the surface. This cycle acts as Earth's primary climate thermostat.

The cycle involves two main loops:

• **The Silicate-Weathering Thermostat:** As described in Section 3.1, this negative feedback loop stabilizes climate.

• **The Carbonate-Subduction Cycle:** Carbonate sediments deposited on the seafloor are eventually carried into the mantle at subduction zones. A portion of this carbon is released by metamorphic reactions and recycled back to the atmosphere via arc volcanism. The remainder is transported into the deep mantle. This recycling ensures that carbon is not permanently lost from the surface system.

Perturbations to this finely tuned cycle lead to major climate events. The Paleocene-Eocene Thermal Maximum (PETM, ~56 Ma) is a prime example, where a massive and rapid release of carbon (likely from methane hydrates or thermogenic sources) led to a global temperature increase of 5-8°C, ocean acidification, and a significant benthic foraminiferal extinction. The Earth system took over 100,000 years to recover, primarily through the slow action of the silicate weathering feedback [15]. This event serves as a potent analog for understanding the long-term consequences of current anthropogenic carbon emissions.

5. The Role of the Biosphere: The Living Integrator

Life is not a mere passenger on Earth; it is an active participant in the planet's physical and chemical evolution. The biosphere mediates many of the key couplings between the solid and fluid Earth.

• **Biological Enhancement of Weathering:** Land plants, and particularly the evolution of roots in the Devonian, dramatically accelerated soil formation and chemical weathering by secreting organic acids and physically fracturing rocks. This likely contributed to a significant drawdown of CO_2 and global cooling in the late Paleozoic.

• **The Oxygen Revolution:** The Great Oxidation Event (~2.4 Ga) was fundamentally a biological phenomenon, driven by cyanobacteria. The rise of oxygen transformed the atmosphere from reducing to oxidizing, which in turn altered the weathering processes on the continents and the mineralogy of sedimentary deposits, while also enabling the evolution of complex life [16].

• **Carbonate Biomineralization:** The majority of carbonate deposition in the oceans is performed by marine organisms, from planktonic foraminifera to reef-building corals. The biological pump, which exports organic carbon from the surface ocean to the deep sea, is a critical component of the short-term carbon cycle and influences atmospheric CO_2 on millennial timescales.

The co-evolution of life and the planet's physical environment-a concept known as geobiology-is a testament to the fully integrated nature of the Earth system.

6. Tools for Integration: Proxies, Models, and Observation

Quantifying the complex couplings within the Earth system requires a diverse and powerful toolkit that bridges traditional disciplinary boundaries.

• **Paleoclimatological and Paleoceanographic Proxies:** Geochemical signatures locked in geological archives serve as "paleo-thermometers" and "paleo-barometers." The $\delta^{18}O$ of foraminifera shells from deep-sea cores records past ice volume and ocean temperature. The Mg/Ca ratio in carbonates provides another independent temperature proxy. Alkenones, organic molecules from certain algae, are used to reconstruct past sea surface temperatures. These proxies allow us to reconstruct past climate states and correlate them with tectonic events [17].

• **Geodetic and Remote Sensing:** Satellite technology, such as GPS, InSAR (Interferometric Synthetic Aperture Radar), and GRACE (Gravity Recovery and Climate Experiment), allows us to measure modern-day interactions with high precision. We can now track the flexure of the lithosphere under ice sheets, the uplift of mountains in real-time, and changes in global sea level and water storage.

• **Numerical Modeling:** The ultimate integrative tool is the numerical model. Coupled Climate System Models (CSMs) are now being expanded into full Earth System Models (ESMs) that include dynamic vegetation, ice sheets, and even simplified representations of the carbon cycle and atmospheric chemistry. Some cutting-edge models are beginning to incorporate geodynamic components, aiming to simulate the two-way interaction between tectonics and climate over millions of years. These models are essential for testing hypotheses and projecting future changes [18].

A pioneering example of such integrative modeling is the use of coupled tectonic-climate landscape evolution models. These models simulate millions of years of tectonic uplift simultaneously with climate-driven precipitation and surface processes like river incision and sediment transport. They can successfully reproduce observed patterns of orographic rainfall and asymmetric mountain erosion, demonstrating the efficacy of the coupled approach. However, significant challenges remain in fully integrating the entire Earth system. A major frontier is the development of models that seamlessly link deep mantle convection and plate tectonics with surface climate and the biosphere over billion-year timescales. The computational cost is immense, and processes operating at vastly different timescales-from mantle convection (millions of years) to weathering feedbacks (hundreds of thousands of years) and anthropogenic changes (decades)-are difficult to reconcile within a single numerical framework. Furthermore, accurately parameterizing sub-grid scale processes, such as the biological enhancement of weathering or the complex mechanics of ice-sheet sliding, continues to be a primary focus of research. Overcoming these hurdles is essential for creating the next generation of Earth System Models capable of predicting the planet's response to both natural and anthropogenic forcings across all relevant timescales.

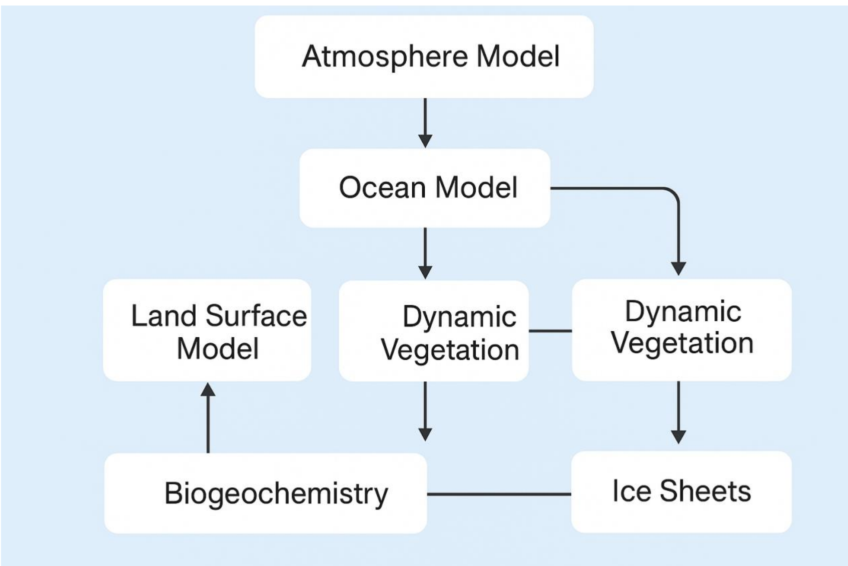

Figure 2. A Conceptual Framework of an Integrated Earth System Model

Figure 2 show Schematic of a modern Earth System Model (ESM). While most ESMs focus on the fluid envelopes and biosphere over decadal to centennial timescales, the frontier is to more fully integrate components representing solid Earth processes (geodynamics, weathering) to simulate interactions across all timescales.

7. Conclusion and Future Perspectives: The Anthropocene as an Integrated Perturbation

The evidence is overwhelming and incontrovertible: the solid Earth, the atmosphere, and the oceans form a single, deeply coupled system. Tectonics provides the long-term boundary conditions for climate and ocean circulation, while the fluid envelopes, through weathering and erosion, sculpt the landscape and influence the very dynamics of the plate tectonic engine. The carbon cycle sits at the nexus of this coupling, regulated by geological processes and stabilizing the climate over millions of years.

This integrated view is no longer just an academic pursuit; it is critical for understanding the current era, often termed the Anthropocene, where human activities have become a dominant force of global change. The anthropogenic release of geologically sequestered carbon is a perturbation to the carbon cycle on a scale and rate rivaling the largest natural events in Earth's history (e.g., the PETM). However, our actions are also directly modifying other parts of the system: deforestation alters evaporation and weathering rates, river damming disrupts sediment transport to the oceans, and groundwater extraction is causing measurable isostatic adjustment.

Predicting the full Earth system response to these multi-faceted perturbations requires the very integrated science outlined in this review. We cannot understand future sea-level rise without considering the isostatic and gravitational effects of melting ice sheets. We cannot project the long-term fate of anthropogenic CO_2 without models that accurately represent the coupled climate-weathering-carbon cycle system. The challenge for the next generation of Earth scientists is to break down the remaining disciplinary silos, develop ever more sophisticated coupled models, and continue to read the rich geological record to inform our path forward. By truly embracing Earth as an integrated system, we equip ourselves with the knowledge to navigate the complex planetary changes that lie ahead.

Refrerences

[1] Walker, J. C. G., Hays, P. B., & Kasting, J. F. (1981). A negative feedback mechanism for the long-term stabilization of Earth's surface temperature. Journal of Geophysical Research: Oceans, *86*(C10), 9776–9782. https://doi.org/10.1029/JC086iC10p09776

[2] Berner, R. A. (2003). The long-term carbon cycle, fossil fuels and atmospheric composition. Nature, *426*(6964), 323–326. https://doi.org/10.1038/nature02131

[3] Raymo, M. E., & Ruddiman, W. F. (1992). Tectonic forcing of late Cenozoic climate. Nature, *359*(6391), 117–122. https://doi.org/10.1038/359117a0

[4] Boos, W. R., & Kuang, Z. (2010). Dominant control of the South Asian monsoon by orographic insulation versus plateau heating. Nature, *463*(7278), 218–222. https://doi.org/10.1038/nature08707

[5] Cane, M. A., & Molnar, P. (2001). Closing of the Indonesian seaway as a precursor to east African aridification around 3–4 million years ago. Nature, *411*(6834), 157–162. https://doi.org/10.1038/35075500

[6] Scher, H. D., & Martin, E. E. (2006). Timing and climatic consequences of the opening of Drake Passage. Science, *312*(5772), 428–430. https://doi.org/10.1126/science.1120044

[7] DeConto, R. M., & Pollard, D. (2003). Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO_2. Nature, *421*(6920), 245–249. https://doi.org/10.1038/nature01290

[8] Burgess, S. D., & Bowring, S. A. (2015). High-precision geochronology confirms voluminous magmatism before, during, and after Earth's most severe extinction. Science Advances, *1*(7), e1500470. https://doi.org/10.1126/sciadv.1500470

[9] Müller, R. D., Seton, M., Zahirovic, S., Williams, S. E., Matthews, K. J., Wright, N. M., Shephard, G. E., Maloney, K. T., Barnett-Moore, N., Hosseinpour, M., Bower, D. J., & Cannon, J. (2016). Ocean basin evolution and global-scale plate reorganization events since Pangea breakup. Annual Review of Earth and Planetary Sciences, *44*, 107–138. https://doi.org/10.1146/annurev-earth-060115-012211

[10] Zeitler, P. K., Koons, P. O., Bishop, M. P., Chamberlain, C. P., Craw, D., Edwards, M. A., Hamid, S., Jan, M. Q., Khan, M. A., Khattak, M. U. K., Kidd, W. S. F., Mackie, R. L., Meltzer, A. S., Park, S. K., Pecher, A., Poage, M. A., Sarker, G., Schneider, D. A., Seeber, L., & Shroder, J. F. (2001). Crustal reworking at Nanga Parbat, Pakistan: Metamorphic consequences of thermal-mechanical coupling facilitated by erosion. Tectonics, *20*(5), 712–728. https://doi.org/10.1029/2000TC001243

[11] Brozović, N., Burbank, D. W., & Meigs, A. J. (1997). Climatic limits on landscape development in the northwestern Himalaya. Science, *276*(5312), 571–574. https://doi.org/10.1126/science.276.5312.571

[12] Kelemen, P. B., & Manning, C. E. (2015). Reevaluating carbon fluxes in subduction zones, what goes down, mostly comes up. Proceedings of the National Academy of Sciences, *112*(30), E3997–E4006. https://doi.org/10.1073/pnas.1507889112

[13] Zeebe, R. E., Zachos, J. C., & Dickens, G. R. (2009). Carbon dioxide forcing alone insufficient to explain Palaeocene–Eocene Thermal Maximum warming. Nature Geoscience, *2*(8), 576–580. https://doi.org/10.1038/ngeo578

[14] Berner, R. A. (1997). The rise of plants and their effect on weathering and atmospheric CO_2. Science, *276*(5312), 544–546. https://doi.org/10.1126/science.276.5312.544

[15] Lisiecki, L. E., & Raymo, M. E. (2005). A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. Paleoceanography, *20*(1), PA1003. https://doi.org/10.1029/2004PA001071

[16] Bartoli, G., Sarnthein, M., Weinelt, M., Erlenkeuser, H., Garbe-Schönberg, D., & Lea, D. W. (2005). Final closure of Panama and the onset of Northern Hemisphere glaciation. Earth and Planetary Science Letters, *237*(1-2), 33–44. https://doi.org/10.1016/j.epsl.2005.06.020

[17] Broecker, W. S. (1991). The Great Ocean Conveyor. Oceanography, *4*(2), 79–89. https://doi.org/10.5670/oceanog.1991.07

[18] National Research Council. (2001). Basic Research Opportunities in Earth Science. The National Academies Press. https://doi.org/10.17226/9981