DETAILS
Title: CLYMERA Inc.
Institution: ZHdK Zurich University of the Arts
Program: MA Transdisciplinary Studies in the Arts HS22
Characters: 26.310
Words: 3.927
Language: English

1 **"From melting ice to carbon removal: how glaciers inspired Climeworks" (Climeworks, 2025)—this headline refers to the founding myth of the much-hyped ETH spin-off, renowned for its direct air capture technology. The company's co-founders, both avid mountaineers, describe witnessing climate change firsthand during their alpine expeditions. "Standing at the edge of glaciers that had visibly retreated since our previous visits was a visceral experience" (Climeworks, 2025).**

2 **Glenn Albrecht describes the "lived experience of negative environmental change" as *solastalgia* (Albrecht, 2020, p. 9). In its original formulation, he defines the term as "a form of homesickness one gets when one is still at 'home'" (Albrecht, 2005/2020, p. 11). The visible retreat of glaciers can provoke *solastalgia* in people who live nearby, leading to psychological distress as they realise that the landscape they love is under threat—from climate change, in this case. Although Albrecht developed the concept with resident communities in mind, a comparable response can arise in returning visitors who discover that a glacier associated with childhood memories has largely vanished. In this sense, the disappearing glacier becomes a powerful visual metaphor for global warming, grounding an otherwise abstract phenomenon in the mind's eye of the observer.**

3 **Climate engineering, often referred to as geoengineering, encompasses intentional, large-scale interventions in the Earth's climate system designed to counteract anthropogenic global warming. These predominantly technical measures are typically divided into two main categories: Carbon Dioxide Removal (CDR) and Solar Radiation Management (SRM) (Caldeira et al., 2013). CDR aims to remove carbon dioxide from the atmosphere through deliberate actions and to store it permanently in geological, terrestrial, or marine reservoirs. Approaches include afforestation, ocean fertilisation to stimulate planktonic productivity, and direct air capture, which extracts CO_2 from ambient air using chemical processes (Caldeira et al., 2013). SRM methods focus on reducing the amount of incoming solar radiation by reflecting it away from Earth's surface. Proposed strategies include the injection of aerosols into the stratosphere, artificially brightening marine stratocumulus clouds to increase their reflectivity, or deploying arrays of mirrors in orbit around Earth as space-based interventions (Caldeira et al., 2013).**

4 **According to the Intergovernmental Panel on Climate Change (IPCC), tipping points are "critical thresholds in a system that, when exceeded, can lead to a significant change in the state of the system, often with an understanding that the change is irreversible." For example, the collapse of the Greenland Ice Sheet is considered a tipping point that could be exceeded by the end of this century—with consequences measurable on a global scale, including disruptions to ocean currents and changes in tropical precipitation patterns (Zhong & Rojanasakul, 2024).**

5 **The Paris Agreement is a legally binding international treaty adopted by 196 parties at the UN Climate Change Conference (COP21) in Paris on 12 December 2015, with the overarching goal of limiting global warming to 1.5 °C above pre-industrial levels by the end of the century. However, current emissions trajectories and policy commitments indicate that the world remains on course for a temperature rise of approximately 2.5 to 2.9 °C by 2100 (UNEP, 2023).**

6 **The belief in technology as a universal problem solver is often referred to as the *technofix*. This form of techno-optimism is widespread in society, as we are continually assured that technological progress will lead to greater efficiency and, consequently, greater capacity to solve complex problems (Huesemann & Huesemann, 2011). In the context of climate change, this assumption is further reinforced by high-profile figures such as Bill Gates, who views "climate change as a technical problem that requires some kind of 'killer app', magical thinking according to some" (Hamilton, 2013, p. 76). Understandably, such narratives are readily embraced by society, as they offer the comforting idea that established lifestyles need not be altered or sacrificed. As Hamilton (2013) notes, "the lure of the technofix is irresistible" (p. 76). But this belief can have unintended consequence, as it may result in continued or increased greenhouse gas emissions, based on the assumption that technology will eventually provide a solution—thereby delaying urgent action on the climate crisis.**

7 **Timothy Morton defines global warming as a prime example of a hyperobject — something so vast and dispersed across time and space that it cannot be fully perceived by humans (Morton, 2013). Hyperobjects, according to Morton, share five defining characteristics: viscosity, nonlocality, temporal undulation, phasing, and interobjectivity. In this regard, geoengineering can itself be considered a hyperobject. For example, the deployment of sulphur dioxide (SO_2) into the stratosphere results in its dispersion across the globe, rendering the process *nonlocal*. These "uncanny" aerosols linger *viscously* in the air and "stick" to atmospheric processes — unseen, unfelt, yet potentially harmful. High concentrations of SO_2 in the stratosphere may contribute to ozone depletion (Heckendorn et al., 2009), resulting in increased UVB exposure. The potential development of skin cancer could be interpreted as an instance of *phasing* — a delayed, indirect consequence of geoengineering. Once the sulphates are "flushed away" from the stratosphere via acid rain, they accumulate in ecosystems, leading to acidification, and are further absorbed by crops, consumed, and digested. In this way, geoengineering unfolds *interobjectively*, interacting with the climate system and influencing weather patterns that, in turn, affect other entities elsewhere. The long-term unpredictability of geoengineering outcomes, combined with the dependency on continued SO_2 dispersal to avoid a termination shock — a rapid rebound in global warming that would severely stress biodiversity (Williamson et al., 2012) — highlights the characteristic of *temporal undulation*.**

Moving even further, as R. Emmenegger (personal communication, May 19, 2025) pointed out, geoengineering could be considered a hyperobject attempting to fix another hyperobject — an interpretation that opens up space for further reflection on technological attempts to fix complex and uncertain environmental problems.

8 **From a historical perspective, technological attempts to control nature—such as the channelisation of rivers—have rarely reduced human intervention. On the contrary, they have often led to overwhelming consequences, as the side effects and damages caused by such interventions required further technological measures for control and repair in order to stabilise the original modification (Böhme, 2008). The question now is whether geoengineering represents yet another act of technological control over nature—or an effort to stabilise the damage already done.**

9 **On 27 February 2023, more than 110 physical and biological scientists signed an open letter supporting research into potential methods for increasing the reflection of sunlight in the atmosphere, primarily referring to solar radiation management (SRM) (Climate Intervention Research Letter, 2023). While geoengineering is often viewed critically within the scientific community, its growing presence in research has led to the recognition that such considerations can no longer be avoided.**

10 **Representative Concentration Pathways (RCPs) are greenhouse gas concentration scenarios defined by their net energy imbalance in 2100, used to project future climate outcomes. These include RCP1.9 (compatible with the Paris Agreement, aiming to limit warming below 1.5 °C), RCP2.6, RCP4.5, RCP6.0 (representing moderate mitigation pathways), and RCP8.5 (a high-emissions, no-mitigation "worst-case" scenario).**

11 **Albedo (from the Latin *albus*, meaning "white") is a measure of the fraction of incoming sunlight that a surface reflects. It ranges from 0% (a perfectly dark, fully absorbing surface) to 100% (a perfectly reflective surface). For example, fresh snow reflects about 75–95% of incoming solar radiation, glacial ice about 30–45%, woodland 5–20%, and new asphalt roughly 5–10% (Häckel, 2021, p. 193, Tab. 12).**

12 **To bridge the gap until sufficient carbon dioxide can be removed from the atmosphere, SRM methods—such as stratospheric aerosol injection (SAI)—are often regarded as more effective due to their rapid deployment potential. The concept of SAI is inspired by observations of volcanic eruptions, which have demonstrated short-term global cooling effects through the release of sulfur dioxide (SO_2) into the stratosphere (Caldeira et al., 2013). The 1991 eruption of Mount Pinatubo is frequently cited in this context, as it led to a global temperature decrease of approximately 0.2 °C over a period of about 13 months, due to the reflective properties of the resulting aerosols (Boretti, 2024, p. 1). In contrast, land-based albedo enhancement is considered less effective at reflecting solar radiation and lacks the immediacy required for short-term climate intervention.**

13 **The difficulty of precisely controlling large-scale geoengineering implementations remains one of the principal concerns associated with these technologies. Although carbon dioxide removal (CDR) is generally considered to have fewer negative ecological impacts, certain methods—such as ocean fertilisation—remain highly controversial due to their interference with fragile ecosystems that are difficult to monitor. Nevertheless, SRM applications continue to raise the greatest concern, as their effects are particularly prone to escalation beyond control, primarily because of the challenges in modelling their impacts and the inability to rule out severe side effects. One possible consequence is the "whitening of the sky" (Kravitz et al., 2012, p. 1), a phenomenon observed after major volcanic eruptions and associated with the appearance of dramatic sunsets—such as those depicted in the paintings of William Turner (Zerefos et al., 2007).**

14 Although international governance frameworks—such as the London Protocol and WG 41 under GESAMP (GESAMP, 2019)—already exist to regulate research and deployment of ocean-based CDR and SRM methods, these frameworks are increasingly being challenged or circumvented by geoengineering proponents seeking to advance research and field experiments (CIEL, 2024)

15 A growing number of patents for geoengineering technologies are now held by private companies and individuals, and they "… are on track to become the *de facto* form of governance of geoengineering" (Hamilton, 2013, p. 80). The business opportunities associated with preventing climate catastrophe have motivated the rise of green-tech companies, many of which invest in patents believing that future demand for such technologies will yield significant financial returns (Hamilton, 2013).

16 The chain of consequences resulting from a large-scale geoengineering intervention would be difficult to predict, raising serious ethical concerns. While such measures might bring beneficial effects in one region (e.g., fewer heat extremes), they could have unintended negative impacts elsewhere. Recent studies, for example, suggest that tropical stratospheric aerosol injection (SAI) may suppress monsoon precipitation in parts of Africa or Asia (Robock et al., 2008; Ferraro et al., 2014; Sun et al., 2020, as cited in Tracy et al., 2022). A parallel can be drawn with the use of agricultural pesticides: originally intended to stabilise food supplies and protect crops from parasites, these chemicals now pervade the world we live in—contaminating soil, water, and food, rendering rivers fishless and forests birdless. "We poison the gnats in a lake and the poison travels from link to link of the food chain and soon the birds of the lake margins become its victims" (Carson, 1962, p. 100). Another concern with geoengineering lies in issues of distributional justice, as such interventions risk deepening inequalities between wealthier countries and poorer regions (World Commission on the Ethicsof Scientific Knowledge and Technology [COMEST], 2023).

17 The debate surrounding the justification of geoengineering research is primarily driven by a set of frequently cited ethical arguments. One of the most prominent is the *buying-time argument*, often considered the main one in favour of further research or potential deployment. It comes from the recognition that the failure to reduce global CO_2 emissions is largely due to political laziness or the influence of lobbying interests. This argument calls for powerful new technologies—primarily SRM methods, such as sulphate aerosol injection—to control global warming, described as "… a necessary evil [to be] deployed to cut off a greater evil …" (Hamilton, 2013, p. 159). The *climate emergency argument* was prominently raised by Paul Crutzen, who sought to break the taboo surrounding geoengineering. He suggested that sulphate aerosol injection "… should not be used to justify inadequate climate policies, but merely to provide a way to combat potentially drastic climate warming" (Crutzen, 2006, p. 214). This argument is frequently cited in relation to the threat of climate tipping points, as solar filters could be deployed rapidly. The *best-option argument* frames geoengineering as a necessary trade-off before further irreversible damage occurs. From an economic perspective, this cost–benefit calculation often contrasts sharply with ethical considerations. As Hamilton (2013) notes, "… earlier economic exercises have concluded that geoengineering is cheaper than mitigation and almost as effective and therefore is to be preferred" (p. 160). The US–Israeli start-up *Stardust Initiative*, which aims to commercialise SRM, aligns closely with these arguments, boldly claiming that "we're running out of time" and "decarbonization alone is no longer enough" (Stardust, 2024)—controversially challenging the Convention on Biological Diversity's *de facto* moratorium on geo-engineering (CIEL, 2025).

18 In summer 2022, 23 days were identified as extreme-melt events because the mean anomaly in daily surface mass balance on Findelgletscher, Glacier de la Plaine Morte, and Rhonegletscher fell below −2.55 cm water-equivalent per day (w.e. d^{-1}). On those same days, individual stakes registered values as low as approximately −7 cm w.e. d^{-1} (Cremona et al., 2023, Figure 8), corresponding to a loss of about 3–8 cm of surface ice thickness per day (own calculation based on Cremona et al., 2023). Ice density is approximately 0.9168 g/cm^3 at 0 °C and standard atmospheric pressure.

19 The concept of restoring glaciers is already being tested by the NGO *Peru Glaciers*. By painting mountain slopes white with a mixture of water, sand, lime, and a small amount of soap, the team hopes to slow glacial retreat—or even trigger new ice formation—by lowering surface temperatures (Romo, 2011). Whether this method will prove effective over the long term remains unverified. A different approach is being implemented in the Ladakh region of northern India, where water sprinklers create artificial, cone-shaped glaciers known as ice stupas, helping to prolong the region's meltwater supply.

20 *Surface Mass Balance (SMB)*: the net difference between surface accumulation (such as snowfall and refreezing) and ablation (melting and sublimation) on a glacier over a specified time period.

21 The shadow cast by the *Cryomancer* will likely create uneven melting around the device and the apparatus may begin to tilt after several days of operation. A change in the device's angle can cause water to spill over the cooling tray, reducing its ice-production capacity. If the tilt reaches a negative angle of about 4°, ice cubes may even be redirected into the unit itself, potentially jamming the rotating mechanism. Once the system is out of balance, manual intervention becomes inevitable.

22 This task can be linked to Sisyphus, the tragic figure who appears in Homer's *Odyssey*, who is condemned by the gods to push a boulder up a hill only to watch it roll back down—in a never ending cycle. This task of perpetual repetition makes him the paradigmatic "absurd hero" (Camus, 1942/2000, p. 142): he must endure eternal futility as the price for defying the gods and for the reckless, pleasure-seeking life that once defined him (Camus, 1942/2000). In a metaphorical sense, the *Cryomancer* bears the punishment for humanity's failure to respond to the climate crisis, rooted in its reluctance to give up unsustainable habits of consumption.

23 Inexpensive microcontrollers and powerful single-board computers, such as the Raspberry Pi, combined with AI-driven programming environments, now make small-scale automation projects widely accessible. A wide range of sensors and high-resolution cameras can be deployed, generating extensive environmental datasets that support remote monitoring. The real-time data collected by the *Cryomancer* on the glacier could contribute to "advancing understandings of environmental change" (Gabrys, 2016, p. 36). Whether monitoring temperature, humidity, light levels, meltwater presence, or simply functioning as a webcam with audio recording, the unit arguably holds scientific potential—as long as the power supply remains stable and the hardware proves sufficiently robust (Gabrys, 2016).

24 The cooling unit has a maximum production capacity of 12 kg of ice per day (24hrs) under perfect conditions.

25 Under the RCP2.6 scenario, the Swiss Alps are expected to lose around 65% of their total ice mass and area compared to 2017. In the medium RCP4.5 scenario, losses increase to approximately 75%, and under the RCP8.5 scenario, up to 95%, meaning the Alps will be largely ice-free by 2100 (Zekollari et al., 2019, Fig. 8). Alpine glacier area declined from roughly 3,350 km^2 in 1900 to less than 1,900 km^2 by 2011, with an acceleration in losses since the 1980s that has significantly impacted volume change (Huss, 2012, Fig. 5b). During the 2003 heatwave, Alpine glaciers experienced a negative mass balance of around −5.1 km^3 (Huss, 2012). To compensate for this volume loss, roughly 1.2 billion *Cryomancer* units would be required.

26 Microalgae are increasingly the focus of research in the context of carbon capture. Compared to terrestrial plants, algae exhibit higher photosynthetic efficiency and faster replication rates. Strains such as *Chlorella vulgaris* can double their biomass in approximately three days under optimal conditions, enabling them to capture CO_2 more efficiently (Li & Yao, 2024). Operating *Sequester* with artificial lighting, along with the energy demands of the pump and (optional) heater, may reduce its overall energy efficiency.

27 Algae can absorb carbon dioxide either directly from the atmosphere or by utilising flue gas from power plants. For more immediate carbon offsetting, CO_2 can also be purchased in compressed flasks from the supermarket and conveniently fed to the algae—effectively capturing emissions that would otherwise be released into the atmosphere.

28 According to an AI-based estimation, the weekly biomass yield of the *Sequester* contains approximately 0.2 to 0.4 kilograms of captured carbon dioxide.

29 The permanent storage of carbon dioxide remains a significant challenge. Recent modelling indicates that unless CO_2 is captured for at least 1,000 years, net-zero targets are likely to fail. Using the common 100-year "durability" benchmark, 6 $GtCO_2$ per year of residual emissions would still result in a global temperature increase of approximately 0.8 °C by the year 2500—enough to overshoot the targets of the Paris Agreement (Brunner et al., 2024). This required timescale is comparable to the challenge of nuclear waste disposal, where long-term containment must also be ensured. In Switzerland, for example, researchers at the Mont Terri rock laboratory—originally dedicated to studying Opalinus Clay as a potential host rock for nuclear waste—are now investigating its suitability as a caprock for long-term carbon storage (Zappone et al., 2021).

30 The voluntary carbon market (VCM) is a decentralised platform that enables companies and individuals to buy and sell carbon credits on a voluntary basis. These credits support projects that aim to reduce, avoid, or remove carbon from the atmosphere, such as reforestation, renewable energy initiatives, or biomass sequestration. The increasing demand from large corporations to offset emissions in pursuit of net-zero targets has motivated the emergence of green-tech start-ups eager to trade in these economically attractive assets. According to Church (2025), the VCM acts as an "open door for risky geoengineering technologies." The recent acceleration of ocean-based carbon dioxide removal experiments is closely linked to developments within this market (Church, 2025).

31 On 27 November 2024, the European Union established a voluntary Union certification framework for permanent carbon removals, carbon farming, and carbon storage in products (European Union, 2024). The primary objective of this regulation is to support "high-quality carbon removals and soil emission reductions while minimising the risk of greenwashing …" (European Union, 2024, p. 11).

To qualify under this framework, Sequester must demonstrate a permanent net carbon removal benefit. In essence, the device must remove more carbon dioxide from the atmosphere than would occur without it, and this removal must exceed all greenhouse gas emissions associated with the device over its entire lifecycle. Whether Sequester meets these requirements has yet to be proven.

32 The reactor mount and tables are made of MDF. Water spills may cause staining and potentially damage the material, as it is prone to absorbing moisture. Spills should be removed immediately.

33 The design intention and the way products or technologies are shaped can strongly influence how they are perceived and accepted by society (Eggink & Snippert, 2017). An algae photobioreactor, for example, could be constructed using a few PET bottles, some tubing, and an IKEA shelf. Functionally, such a DIY solution would operate in the same way as *Sequester*, but the aesthetic perception would be entirely different. In the context of large-scale climate engineering, this perception could have significant implications—especially when the aesthetics of a technology are consciously designed to promote public acceptance at the point of deployment.

34 Photographic images play a key role in the communication of products. As Szulc and Musielak (2023) show, elements such as lighting and resolution significantly influence how products are perceived, often enhancing their apparent quality and value. In a visually saturated world, highly aesthetic images can elevate ordinary products, making them appear more exclusive—or even more trustworthy.

35 The sharp-edged shape and reflective properties of the *Cryomancer*, in combination with its remote sensing capabilities, recall both the design and conceptual logic of military technology (e.g. F-117 Nighthawk stealth aircraft). It was the development of military systems such as satellite imaging that first enabled new perspectives on the planet: for the first time, Earth could be understood as a system in its entirety. This shift also contributed to the emergence of the aesthetic of the Anthropocene—one that, as Fressoz warns, risks "[feeding] more the hybris of a brutal geo-engineering than a patient, modest and ambitious work of involution and adaptation of the social" (Fressoz in Borsari, 2022, p. 248). As Demos (2015) similarly argues, "Anthropocene imagery tends to reinforce the techno-utopian position that 'we' have indeed mastered nature, just as we've mastered its imaging." The *Cryomancer's* internal sensors and front-facing camera deliberately illustrate what Demos (2015) refers to as the "human-driven alteration of Earth systems," reinforcing a sense of control over the represented object—in this case, the glacier.

36 The spikes on the *Cryomancer* serve primarily an aesthetic purpose, as their pointed tips cannot be securely fixed to the glacial surface. For proper height adjustment and levelling of the apparatus, telescopic feet must be mounted. The larger surface area of the round "duckfeet" allows them to be anchored using ice screws.

37 Access to a metal sheet laser cutting machine, a hydraulic press brake, and 3D-printing technology had a significant influence on the design of the device. The distinctive shape of the *Cryomancer* could only be realised through the specific manufacturing processes available at the time it was built. The extent to which fabrication shapes design is most evident in the 3D-printed components used for the internal mechanics. Designing for 3D printing requires careful consideration of factors such as overhang angles, the placement and minimisation of support structures on critical parts, and the orientation of the model on the print bed—all of which must align with the limitations and possibilities of the process, resulting in specific design outcomes.

38 "Almost nothing of what we see in our everyday environment [of capitalist technological civilization] … do we see simply as it would appear by itself … Everything is staged through lighting technology, that is, illuminated with aesthetic intent." (Böhme, 1995/2013, p. 158, AI translation). Light plays an essential role in shaping how we perceive technology. A telling example is the illuminated Apple logo on older MacBooks, which wasn't lit by a dedicated light source but by the display's backlight—an unintended technical detail that became a brilliant marketing feature. The subtle glow of *Sequester* lends the product a sense of distinction and prestige, turning a functional by-product into an atmospheric signature.

39 In reference to the kinetic sculpture by the Chinese contemporary artist duo Sun Yuan and Peng Yu, in which a robotic arm endlessly sweeps up a blood-like liquid leaking from its own core (Sun & Peng, 2016).

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