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REVIEW PAPER

Geoengineering from the standpoint of uncertainty and related risks: science or science fiction?

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Abstract
In this opinion/comment we discuss the issues related to proposed geoengineering solutions to climate change. We argue, that while scientifically based, these proposals lack the rigorousness appropriate to the seriousness of the problem.

Keywords Geoengineering · Nonlinear effects · Climate dynamics

In the 1991 released science fiction movie *Highlander II: The Quickening*, the story line is that in 2024 industrial pollution has destroyed the ozone layer, leading to widespread deaths from ultraviolet light. To solve this problem a scientific team creates an electromagnetic shield to protect people from these harmful rays. However, while the shield initially saves the planet, after effects throw the planet into constant darkness, high temperatures, and high humidity, with deadly consequences. The after effects were worse than the engineers of the electromagnetic shield could have ever imagined or predicted. While only a movie, *Highlander II* makes a very important scientific point relevant to today's geoengineering proposals.

Geoengineering solutions to climate change that have been proposed in peer reviewed scientific journals can be divided into two categories: "space-based" (mirrors and shields, and recently dust from the moon), and "in-house", atmospheric (stratospheric aerosol injection, marine sky brightening, cirrus cloud thinning), and surface-based (modifying urban areas, agricultural land, grasslands, deserts, oceans, etc.); see e.g. Laurence et al. (2018). The first category includes proposals to interfere with the solar radiation before it reaches the planet. The second includes proposals to manipulate processes in the planet. These are not science fiction movies but adjudicated scientific papers based on math and physics. Such geoengineering solutions rarely consider the uncertainty associated with the nonlinear dynamics of the Earth system, and do not consider serious sensitivity analyses of "after effects".

Consider a couple of examples from "in-house "geoengineering proposals. One example proposes to make clouds whiter by seeding them with a fine mist of seawater (Bower et al. 2006; Kramer 2013). The seawater would make the cloud droplets much finer and more reflective, thus reducing the amount of radiation reaching the surface of the planet, and thereby cooling the planet and reducing global warming. Similar ideas have been proposed to dissipate hurricanes in order to save lives (Latham et al. 2012). Another example is carbon sequestration from the atmosphere and subsequent storage in the ground. Mother Nature does this rather effectively through forests, kelp beds, etc. and with no harmful after effects.

We see two issues with these proposals. First, as any climate scientist would testify, climate system dynamics are only approximately known. Most physical processes in atmospheric models are not well understood. A prime example is clouds. Cloud microphysics is represented in these models by linear parameterizations. This means that the actual physics and equations describing cloud development and cloud interactions with climate are approximated by linear equations. This is true of other processes such as heat fluxes between the oceans and the atmosphere,

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interaction between climate and ecosystems, and solar radiation absorption, scattering and reflection. In addition, there are self-organizing phenomena such as hurricanes. Self-organization in dissipative systems such as the atmosphere and ocean must exchange energy with the environment. Hurricanes involve huge amounts of energy yet no one has any idea of how the atmosphere and the ocean will be affected if the exchange of that energy is reduced. The other issue is that many of these "in-house" proposals require regular reseeding to be effective. Both the monetary and environmental costs are rarely adequately considered.

Other ideas/proposals include orbiting reflecting mirrors or solar shields, and ejecting moon dust near the Earth–Sun L_1 Lagrange point (Bromley et al. 2023; Early 1989; Hudson 1991; McInnes 2002) to limit the amount of solar radiation reaching the planet.

In essence, although peer reviewed, geoengineering proposals stray far from scientific reality, as they ignore the fact that the climate system's highly nonlinear character means extreme sensitivity to initial conditions (the butterfly effect) and to changes in system parameters. Even if we had the perfect climate model (which we don't have) or a climate theory (which does not exist), sensitivity to the initial conditions and parameter values will have unknown chaotic effects. Therein lies the whole problem with potential geoengineering solutions; i.e. the formulation of the climate system and its components is only approximately known.

More than 40 climate models are floating around in the climate community, and their predictions about general dynamics simply don't agree with each other. In a recent publication (Steinhaeuser and Tsonis 2013), the community structure (a reflection of dynamics) of 28 control and 70 forced climate simulations from 23 climate models was examined, using network theory, and the similarity of their community structure in four different fields (upper-level flow, sea-level pressure, surface air temperature, and precipitation) was evaluated. It was found that except for the upper-level flow, the agreement between the models was not good. Simply put the results proved that climate models are imperfect with significant differences in predictions of fundamental characteristics of the ocean and atmosphere. Even worse, none of the models compared well with actual observations.

An important note to be made here is that no geoengineering proposal has ever done a thorough analysis of the nonlinear effects of changing an input or of the uncertainty on the initial conditions in the climate system, including a realistic assessment of the related costs. Therefore, although interesting, if implemented without a better knowledge of the intricate dynamics of our climate system, geoengineering solutions could pose dangerous and unknown risks, like the unpredictable effects in the above mentioned science fiction movie.

It is worth noting that humans have already "geoengineered" climate by urbanization and deforestation. Urbanization and deforestation have altered 20% of the land surface, with obvious effects on the average albedo of the planet. Since 1850, about 30% of all CO_2 emissions are due to deforestation (Le Quéré et al. 2016). Deforestation has already made serious climate impacts. Trees release moisture that cools the air around them. This has contributed to more intense heat waves in North America and Eurasia (Lejeune et al. 2018). Did we know that would happen back in 1900? We had no clue about our climate system then. Today we know much more about the climate system, but do we know enough to risk having geoengineering proposals being taken seriously? Climate scientists have a good idea of the large-scale flow of ocean currents, but detailed measurements are not available. They know the basic physics of cloud formation and its thermodynamics but do not fully understand detailed cloud microphysics or the complex connections between climate and ecosystems. And with complex nonlinear systems, details are important. Time and effort spent on geoengineering would be better spent to improve understanding of the climate system and its components. When new car or plane models are proposed, rigorous testing procedures are executed and corrections are applied to ensure the products are safe to use and unwanted effects are minimized before they go in the market. Successful engineering is built on repeated failure. In contrast, it is not easy to undo geoengineering projects when they go wrong. The experiment is done and that's it. We better be right on the first go as we may have to live with disastrous consequences.

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Declarations

Competing interests The authors declare no competing interests.

References

Bower K, Choularton TW, Latham J, Sahraei J, Salter S (2006) Computational assessment of a proposed technique for global warming mitigation via albedo-enhancement of marine stratocumulus clouds. Atmos Res 82:328–336

Bromley BC, Khan SH, Kenyon SJ (2023) Dust as a solar shield. PLOS Clim 2(2):e0000133

Early JT (1989) Space-based solar shield to offset greenhouse effect. J Br Interplanet Soc 42:567–569

Hudson HS (1991) A space parasol as a countermeasure against the greenhouse effect. J Br Interplanet Soc 44:139–147

Kramer D (2013) Scientists alarmed by rapidly sinking Arctic ice cap. Phys Today 66(2):17–19. 10.1063.PT.3.1878

Latham J, Parkes B, Gardian A, Salter S (2012) Weakening of hurricanes via cloud brightening.Atmospheric Science Letters3(4), https://doi.org/10.1002/asl.402

Laurence MG et al (2018) Evaluating climate geoengineering proposals in the context of the Paris Agreement temperature goal. Nature Communications 9, Article number: 3734

Le Quéré C et al (2016) Global carbon budget 2016. Earth Syst Sci Data. https://doi.org/10.5194/essd-8-605-2016

Lejeune Q, Davin EL, Gudmundsson L, Wincler J, Senevirante SI (2018) Historical deforestation locally increased the intensity of hot days in northern mid-latitude. Nat Clim Change. https://doi.org/10.1038/s41558-018-0131-z

McInnes CR (2002) Minimum mass solar shield for terrestrial climate control. J Br Interplanet Soc 55:307–311

Steinhaeuser K, Tsonis AA (2013) A climate model intercomparison at the dynamics level. Clim. Dyn. https://doi.org/10.1007/s00382-013-1761-5