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Radiative cooling through the atmospheric window: A third, less intrusive geoengineering approach

Ron Zevenhoven [a, *], Martin Fält [a, b]

[a] Åbo Akademi University, Thermal and Flow Engineering, Turku, Finland
[b] Elomatic Oy, Espoo, Finland

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ABSTRACT

Geoengineering methods based on either direct carbon dioxide removal (CDR) from the atmosphere or solar radiation management (SRM) that curtails solar irradiation are campaigned for as technical solutions that would slow down the global temperature rise and climate change. Except for a few CDR methods, this does not receive much interest from policy-makers as a result of a lack of evidence on net advantages and decision-making challenges related to boundary-crossing effects, not to mention costs. An alternative, third geoengineering approach would be enhanced cooling by thermal radiation from the Earth's surface into space. The so-called atmospheric window, the 8–14 μm bandwidth where the atmosphere is transparent for thermal radiation indeed offers a "window of opportunity" for technology that enables sending out thermal radiation at rates that significantly exceed the natural process. This paper describes work that addresses this, with focus on technical devices that combine materials with the properties required for enhanced long wavelength (LW) thermal radiation heat transfer from Earth to space, through the atmospheric window. One example is a skylight (roof window) developed and tested at our institute, using ZnS windows and HFC-type gas (performing better than CO_2 or NH_3). Suggestions for several other system layouts are given.

1. Introduction

Geoengineering (or climate engineering) that aims at limiting the currently ongoing global temperature rise to less than 2 °C can be divided into two approaches. The first is direct carbon dioxide, CO_2, removal (CDR) from the atmosphere followed by storage of the CO_2 (which includes direct air capture, DAC); the second is solar radiation management (SRM) which implies reflecting incoming solar radiation away from Earth [1–5]. Both approaches are still in a technology development phase and, for SRM more than CDR, are controversial, despite being considered relevant in the IPCCs 5th Assessment Report for reaching global temperature control goals [1]. Bioenergy with carbon capture and storage (BECCS) and afforestation are two CDR methods addressed under the IPCCs climate change mitigation scenarios while no SRM method is [1].

It is important to distinguish global warming from the wider range of effects of increased concentrations of CO_2 and other greenhouse gases (GHGs) on the environment and climate change in general. SRM would hardly interfere with ocean acidification, for example, not having an effect on (rising) atmospheric CO_2 concentrations as CDR would, aiming at directly influencing the global heat balance instead. The various CDR and SRM methods are very different from viewpoints of costs, time lag between implementation and effect (and options to control or stop a method), cross-boundary effects and political decision-making needed. As Williamson states "… *urgent attention must be given to clarification at the UN level of what is considered geoengineering and what is climate mitigation*" [6]. In the meantime, geoengineering has drawn the attention of the popular press [7].

Interestingly, the UNFCCC Paris Agreement of December 2015 has limiting the global temperature increase to 1.5–2.0 °C as the major feature, while envisioning "a pathway towards low greenhouse gas emissions" and "removals by sinks" without adding quantitative targets for that [8]. As noted by Horton et al. [9], this apparently makes SRM a more suitable approach to fulfillment of the Paris Agreement goals than for agreements on GHG emissions targets like the UNFCCC Kyoto Protocol of December 1997 [10]. However, Beyene and Zevenhoven argued several years ago that global temperature is only one of several indicators for climate

* Corresponding author.
E-mail address: ron.zevenhoven@abo.fi (R. Zevenhoven).

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change that cannot present a decisive reading: the enthalpy of the atmosphere would probably be the only accurate measure [11].

An alternative and less intrusive method of controlling the influence of solar irradiation on the global temperature is not to obstruct incoming radiation, but rather to enhance the thermal radiation that is emitted from Earth to space. Instead of stratospheric aerosol injection (SAI), cloud brightening or a large number of mirrors in the sky ("sunshade geoengineering") to block out or reflect incoming (short-wave, SW) solar irradiation [4], long-wavelength (LW) thermal radiation can be selectively emitted and transferred through the atmosphere into space. Of great significance is the so-called atmospheric window: the wavelength band 8–14 μm where the atmosphere (when not cloud-covered or very humid) is transparent for thermal radiation, offering a direct and strong driving force for heat transfer from Earth to space. After all, an imbalance between incoming SW (<4 μm) and outgoing LW (≥4 μm) thermal radiation gives a net heating or cooling effect, for the global climate system typically referred to as "radiative forcing".

This paper, building further on earlier work – much of which was presented at ECOS conference events since 2008 [12–16] – will address wavelength-selective and enhanced methods for thermal radiation from Earth to the sky and space beyond that. One example is a skylight (roof-window) design that contains a participating ("greenhouse") gas which results in significantly increased passive cooling [16,17]. This and a few other examples on how to "exploit" the atmospheric window to have access to a low temperature sink (i.e. the universe at 3–4 K), using participating gases/vapours are described below.

2. Passive cooling and the atmospheric window

2.1. The atmospheric window

Thermal radiation to/from the Earth's surface, through the atmosphere can be divided into SW incoming solar radiation (including visible light) and LW radiation that cools the surface. Here, SW and LW are taken to be < 4 μm and ≥4 μm (up to ~ 100 μm), respectively, roughly following the typical division between the wavelength bands covered by so-called pyranometers and pyrgeometers for SW and LW thermal radiation measurement, respectively.

Enabling thermal radiation to pass the atmosphere gives direct (visual) contact for thermal radiation heat transfer to the universe. As shown in Fig. 1, several of the gases (besides fine particles and droplets) that make up the atmosphere absorb and re-emit thermal radiation in certain wavelength bands. Clearly visible is the band around 15 μm for CO_2 which (while becoming wider with increasing CO_2 concentration) plays an important role in what is known as the "enhanced greenhouse effect" driven by anthropogenic emissions.

One early suggestion for turning this feature into a method for cooling Earth is to have pure CO_2 in preferably a pressurised container, with at least one side (for visual contact with the sky) composed of a material that is transparent for LW radiation of roughly 10–20 μm. Pure CO_2 at 300 K, 5 bar, 0.1 m thickness (optical path) would absorb/emit in the bandwidth 13.3–17.0 μm while the atmosphere containing ~ 0.04%-vol CO_2 (at pressures ≤ 1 atm) would absorb/emit in the more narrow bandwidth 14–16 μm (roughly). Thus, thermal radiation in the bandwidth flanks 13.3–14.0 μm and 16.0–17.0 μm would not be absorbed by atmospheric CO_2, a transparency that results in an overall cooling effect [12,13].

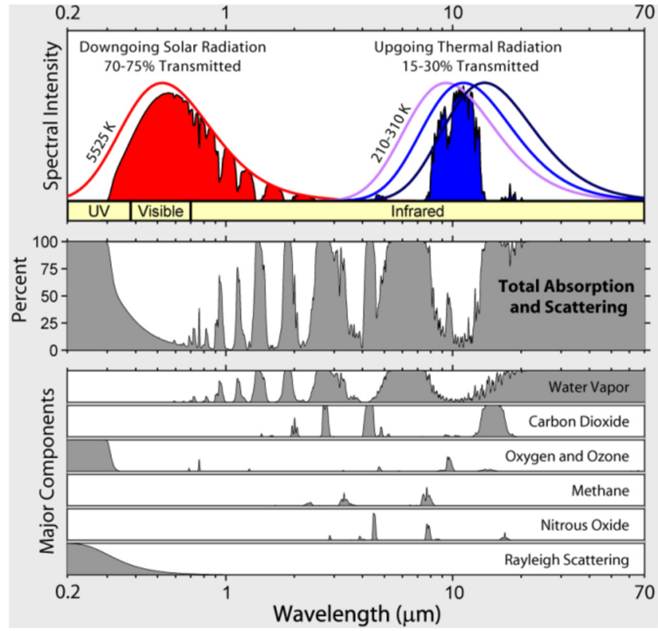

Fig. 1. Radiation transmitted by the atmosphere [18] showing the atmospheric window in blue colour at 8–14 μm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Heat transfer through the atmospheric window: passive cooling

Earlier simulation (Comsol Multiphysics®) and experimental work at our institute involved the testing of CO_2, ammonia (NH_3) and eventually HFC-125 (C_2HF_5, pentafluoro ethane) in comparison with air in a passive cooling skylight, positioned in the roof of an office or residential building. In our case it was tested on the roof of our institute next to a weather station equipped with a pyranometer that recorded SW (solar) irradiation while a pyrgeometer (CGR3, Kipp&Zonen) was used to measure downward atmospheric LW radiation (4.5–42 μm). Fig. 2 shows a schematic of the skylight to be used during summer for enhanced passive cooling and during winter for improved insulation [16,17]. (We recently reported on a skylight design optimisation for these apparently conflicting objectives [19].)

The design of the skylight involved not only the selection of a suitable gas (high absorptivity/emissivity in the atmospheric window band while transparent for visible light) to fill the space between the windows but also the selection of window material that is transparent for LW thermal radiation in the atmospheric window band. After initial testing with a thin polyethylene sheet material with good LW transmittance but little mechanical strength, a ZnS glass was found (Cleartran®) that offers mechanical strength as well as good optical properties [16,17]: ZnS was experimentally found to have a transparency $\tau = 0.64$ in the 8–14 μm interval when 4 mm thick [20].

This resulted in a 10 × 10 × 10 cm^3 test skylight as depicted in Fig. 3, built of acrylic plastic (non-transparent for LW radiation) except for two ZnS windows as the top and cover. A third centre window (also made of acrylic plastic) with adjustable angle separates the skylight into sections that take up and give off heat, guiding the thermal radiation-driven (natural) convection while avoiding (excessive) turbulence. For the insulating (winter) mode the centre window is used to close off the two sections and stop the convection [16,17].

Experimental work, done during night-time as to exclude an