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Radiative Cooling Through the Atmospheric Window: a Third, Less Intrusive Geoengineering Approach

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Highlights:

- Passive radiative cooling should be seen as geoengineering method, cooling Earth
- The atmospheric window (8-14 µm) allows for heat transfer through the atmosphere
- Choices of suitable materials with long wavelength transparency are limited
- Experimental findings verified theoretical assessment and model simulation work
- Passive radiative cooling during daytime still presents a considerable challenge

Radiative Cooling Through the Atmospheric Window: a Third, Less Intrusive Geoengineering Approach

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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.

Keywords: Thermal radiation, Passive cooling, Atmospheric window, Geoengineering

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 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.

Fig. 1.

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].

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].

Fig. 2

Fig. 3

This resulted in a 10×10×10 cm³ 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 effect of SW solar irradiation, showed that temperatures inside the skylight (especially the upper compartment) were 2-5 °C below the temperature of the environment, depending on the gas used in the window and the temperature of the sky. The latter was determined from LW measurement using the pyrgeometer. The tests also confirmed the (earlier) Comsol simulations that on a clear night a passive cooling effect of 100 W/m² is certainly achievable when using HFC-125 [16,17]. The method and set-up tested at our institute performs well (and primarily suffers from the costs for ZnS, not yet mass-produced) but depends strongly on clear, cloudless skies and low humidity. This defines, for each wavelength, the height in the atmosphere with which the thermal radiation heat exchange takes place with respect to the Earth's surface. The effective wavelength-average of this defines the position of "the sky" as used in this paper.

Others have in the 1980s identified the atmospheric window as a potential access to a (very) low temperature reservoir. Besides CO_2, NH_3 has received considerable attention by e.g. Lushiku and Granqvist [21] who used a 10 cm gas "slab" contained by polystyrene (covered with reflecting Al foil) and a window composed of three polyethylene films that gave a transmittance $\tau \approx 0.75$ for the atmospheric window wavelength range. A temperature drop of 10-13°C below that of the ambient surroundings was reported, while heat flows of the order of 100 W/m^2 are mentioned to be obtainable using this passive cooling approach, as indeed we were able to realise.

As for the HFC-125 used in our earlier work that gave the best results: it is a refrigerant with zero ozone depletion potential but a significant global warming potential (GWP) used widely in modern refrigerant mix R407a. The recent Kigali agreement on phase out of HFCs [22] may soon put an end to its use – see [23] for the EU region. As an alternative for HFC-125 (GWP = 3450, atmospheric lifetime 29 y) HFC-1447fz ($C_5H_3F_7$, 3,3,4,4,5,5,5-heptafluoro-1-pentene, GWP = 0.19, atmospheric lifetime 8 days) can be considered [24], not listed in [23].

2.3. Transmittance of the atmosphere and atmospheric window

As noted above, cooling through the atmospheric window relies strongly on clear, cloudless skies and low humidity as the latter reduces the height in the atmosphere with which the thermal radiation heat exchange takes place, effectively increasing the temperature of the sky as shown below.

Dividing the (infrared) spectrum into four sections or wavelength bands, being SW < 4 µm and three LW bands 4 – 8 µm, 8 – 14 µm and > 14 µm, respectively, as suggested in [25] allows for singling out the atmospheric window. Each of these four bands has a transmittance $\tau = 1 - \varepsilon = 1 - \alpha$ with emissivity ε and absorptivity α, using $\alpha = \varepsilon$ for each wavelength (Kirchoff's law of thermal radiation) and neglecting reflectance.

Typical values are $\varepsilon_{<4\mu m} = 0.26$ for SW radiation and $\varepsilon_{4\text{-}8\mu m} = 1$, $\varepsilon_{8\text{-}14\mu m} = 0.55 \sim 0.65$ and $\varepsilon_{>14\,\mu m} = 1$, respectively, for LW radiation [26]. For SW radiation, the value 0.26 is an averaged value that depends on weather, climate, location and time of day. For LW radiation already Kondratyev treated the atmosphere as opaque except for the 8-14 µm atmospheric window [27]. Alternatively, a value for $\varepsilon_{8\text{-}14\mu m}$ can be calculated using a correlation given by Cucumo et al. [28] along the same lines as Kondratyev:

$$\varepsilon_{8-14\mu m} = 1 + \frac{107952 \cdot (1-\varepsilon_a)}{T_a^2 - 680.8 \cdot T_a + 73594.9} = 1 - \tau_{8-14\mu m} \tag{1}$$

for (ground level) air temperature T_a (K) and overall air emissivity ε_a. Using measured values for T_a and (obtained using a pyrgeometer) T_{sky} a value for ε_a can be found based on a LW radiation balance, with Stefan-Boltzmann constant $\sigma = 5.67\times10^{-8}$ W/m²·K:

$$\varepsilon_a \cdot \sigma \cdot T_a^4 = \sigma \cdot T_{sky}^4 \Rightarrow \varepsilon_a = \frac{T_{sky}^4}{T_a^4} = 1 - \tau_a \tag{2}$$

Values for southern Finland are T_{sky} = 265.6 K (-7.5°C) and T_a = 273.9 K (0.7°C), or T_{sky} = 276.8 K (3.7°C) and T_a = 290.8 K (17.6°C) were measured in February and July 2008, respectively. This gives $\varepsilon_a = 0.884$ ($\tau_a = 0.116$) and $\varepsilon_{8\text{-}14} = 0.668$ ($\tau_{8\text{-}14\mu m} = 0.332$) for February and $\varepsilon_a = 0.821$ ($\tau_a = 0.179$) and $\varepsilon_{8\text{-}14\mu m} = 0.516$ ($\tau_{8\text{-}14\mu m} = 0.484$) for July 2008, respectively [25].

Equations (1) and (2) allow for calculating the transmittance, τ, for the atmosphere overall and for the 8-14 µm atmospheric window as function of temperatures $T_{ambient}$ and T_{sky} as given in Fig. 4 left and right respectively. As an alternative for (2) [28] gives expressions that relate ε_a to air humidity; in (2) this is implicitely accounted for if experimental data for T_{sky} is used. The overall transmittance decreases with increasing sky temperature for a given ambient temperature, more dramatically so for the atmospheric window transmittance. For an ambient temperature above 20°C, where (passive) cooling would be welcomed, the transmittance of the atmospheric window is $\tau_{8\text{-}14} > 0.8$ if the temperature of the sky drops below -5°C, becoming $\tau_{8\text{-}14} = 1$ if $T_{sky} < -12$°C.

Fig. 4.

2.4. Cloudy skies, humidity, daytime vs. night-time

As mentioned, clouds and humidity strongly impair the transmittance of the atmosphere by simply blocking the "visibility" that is necessary for radiation heat transfer and giving an increased sky temperature as (in our work) measured by a pyrgeometer. More important for day-round application is the distinction daytime vs. night-time: a passive cooling effect based on LW radiation will be easily overruled by solar irradiation during daytime. Therefore, the experimental work with our skylight shown in Figs. 2 and 3 was carried out during night-time [16,17]. For a country like Finland, with (very!) short nights during summer this limits the passive cooling potential but many locations on Earth, especially near the equator (for example Kenya) have high temperatures still after sunset until sunrise [29].

As noted by Al-Obaidi et al. [30], tropical locations are often characterised by high humidity while arid and high-altitude regions that give a low sky temperature are often scarcely populated. A location at some distance from a populated region does not exclude the construction of equipment that employs passive cooling through the atmospheric window: the same applies to locations where large solar energy systems are constructed. Integrating such passive cooling with housing and office buildings does obviously imply that the technology is brought into towns and cities.

Daytime application of passive cooling usually implies increased reflection of thermal radiation, preventing heat from entering a building or other object rather than cooling it [30,31]. (Others aim at controlling the transmittance of windows for solar (SW) irradiation, see e.g. [32].) Methods and materials that involve photonic devices and micro/nanostructured materials have been developed that can accomplish significant passive LW radiation cooling during daytime but technical challenges and (presumably) costs will prohibit a wide market penetration [31]. Some significant scientific breakthrough will be required that simplifies technology that operates under significant solar irradiation to the level of complication of methods that employ only LW thermal radiation and the atmospheric window.

After all: 50% of the surface of the Earth faces away from the sun at all times, and passive cooling through the passive window can give a significant effect, not overwhelmed by solar irradiation, between sunset and sunrise at many hot locations.

3. Passive cooling applications “employing” the atmospheric window

3.1. System requirements, using encapsulated passive gases

The possibility of passive cooling of an object’s surface (or a volume of a participating gas inside an at least partially transparent container) “through” the atmospheric window depends on the temperature of the object and, depending on the object’s optical properties, what fraction of the emitted thermal radiation is within the 8-14 µm bandwidth. Using the so-called blackbody radiation functions the blackbody radiation E_b (W/m^2) within the 8-14 µm band can be calculated:

$$E_{b,8-14\mu m} = f_{8-14\mu m} \cdot \sigma \cdot T^4 = (f_{0-14\mu m} - f_{0-8\mu m}) \cdot \sigma \cdot T^4 \qquad (3)$$

Here $f_{a\text{-}b}$(T) is the fraction of blackbody (or graybody) radiation from a surface within wavelength band *a* to *b* µm, which can be taken from tables; for this paper a polynomial approximation (using the first five terms) given by Chang and Ree [33] is used. This can be translated into the curves given in Fig. 5, showing that in a -30 to +60 °C temperature interval 30 – 40 % of the thermal radiation from a blackbody (or graybody) is within the atmospheric window. Moreover, the intensity for radiation within that window increases from ~ 60 W/m^2 for cold surfaces to > 200 W/m^2 for surfaces hotter than 40°C.

Fig. 5

Hossain and Gu [31] considers primarily solid surfaces for passive cooling application, pointing out that a participating gas would require an encapsulation which can be seen as a disadvantage. That encapsulation material needs to be at least partially transparent to LW radiation, in our work that initially involved using a thin poly ethylene (PE) sheet, later replaced by ZnS glass.

For the atmospheric window, the thermal radiation heat transfer flux $Q_{rad,8\text{-}14}$ (W/m^2) to the sky at temperature T_{sky} (K) through the atmospheric window is given by, using (3):

$$Q_{rad,8-14} = \varepsilon_{8-14} \cdot \tau_{8-14} \cdot E_{b,8-14\mu m} = \varepsilon_{8-14} \cdot \tau_{8-14} \cdot f_{8-14\mu m} \cdot \sigma \cdot (T^4 - T_{sky}^4) \quad (4)$$

for an encapsulated gas at temperature T (K) with emissivity $\varepsilon_{8\text{-}14}$ (-) with visual contact through an containing material window with transmittance $\tau_{8\text{-}14}$ (-). (It is assumed that the surface of the sky >> the surface of the window material.) This can be compared to the corresponding radiation from a solid (or liquid) surface with emissivity ε:

$$Q_{rad,8-14} = \varepsilon_{8-14} \cdot E_{b,8-14\mu m} \approx \varepsilon \cdot f_{8-14\mu m} \cdot \sigma \cdot (T^4 - T_{sky}^4) \quad (5)$$

which typically is a graybody with emissivity $\varepsilon_{8\text{-}14} \approx \varepsilon > 0.8$. Obviously, if $\varepsilon_{8\text{-}14} \cdot \tau_{8\text{-}14}$ for the encapsulated gas case is < than 0.8 then the heat transfer according to (4) is smaller than that calculated using (5). The advantage from the first case, however, comes from a higher temperature for the encapsulated gas compared to a solid (or liquid) surface, which can be maintained if the gas is moving between regions where it repeatedly takes up and gives of heat. This is accomplished in the skylight tested at our institute [16,17]; following the terminology of Geetha and Velraj [34] this is “movable thermal mass” which gives “natural displacement ventilation”.

While Al-Obaidi et al. [30] note that “mild winds can overwhelm the cooling effects of radiation” this won’t necessarily be the case with a gas-filled window system that allows the gas to move between spaces at different temperatures, such as the upper and lower sections of our skylight.

3.2. Other examples for passive cooling through the atmospheric window using participating gases or vapours

Several design or lay-out alternatives can be suggested for passive cooling using the atmospheric window, making use of suitable combinations of participating gases or vapours, and proper window materials. For all cases, the encapsulation should have at least one window, preferable positioned horizontally with visual contact to the sky above.

Apart from the skylight tested and developed at our institute (Figs. 2 and 3), several alternatives are given in Table 1. The systems would be operated primarily at night-time.

Table 1.

One feature should be mentioned still for a gas-filled system: if this is operated with a constant volume, then according to Gay-Lussac, for an ideal gas at pressure p, temperature T, the ratio p/T = constant and a temperature rise will lead to a pressure rise. If the goal is to operate at a constant pressure then volume must be allowed to vary, or some of the gas can, for example, be absorbed in a liquid such as in the ammonia + water system mentioned in Table 1.

HFC-type gases that are acceptable from health and environmental impact point of view have shown their potential for passive cooling applications and can be selected as to have high emissivity in the atmospheric window. For ammonia there are risks related to its use (similar to its use as refrigerant) by many customers in sky-lights and other smaller scale devices. Thus, HFC-1447fz apparently allows for a wider use by a wider audience while ammonia-containing systems would be larger and for deployment by experts (again, similar to use of ammonia as refrigerant).

A passive cooling window may also be used in the roof of a car or other vehicle, reducing air conditioning costs or limit the temperature rise when parked under direct sunlight. A double glass skylight with (for example) poly ethylene covered ZnS as top window and regular glass as lower window, with a passive gas filling a spacing of a few cm will give a cooling effect. Through the choice of window surface this effect can be small or more significant. This will be addressed in future work.

3.3 .Large-scale deployment

As for the necessary scale of deployment for a sizeable contribution: current radiative forcing as a result of well-mixed greenhouse gases is of the order of 3 W/m^2 [35]. A technology with significant impact would counter-effect at least 10% of this, say 0.3 W/m^2. With 100 W/m^2 as a demonstrated passive cooling effect, a surface coverage of 0.3% would then be needed, or 1% of Earth's land mass surface. If half of it would be installed in urban, built areas which cover roughly 3% of the Earth's land mass, a 17% coverage would be needed there, with the remainder being installed in rural areas. A significant number that nonetheless leaves space for other solar thermal and solar PV equipment on rooftops and other urbanised surface area.

4. Conclusions

Passive cooling systems that make use of the 8-14 µm atmospheric window for thermal radiation have been suggested and tested since the 1980s, including work carried out at our institute. It was theoretically deduced and also experimentally verified that cooling heat transfer rates of the order of 100 W/m^2 can be achieved. This paper addresses several features of that, studying the thermal radiation that may possible occur "through" the atmospheric window, depending on the temperature of the sky and (objects at) the Earth' ground level. Optical and mechanical properties of gases and (encapsulating) window materials are addressed, as well as the limiting effects of cloudiness and air humidity.

It was noted that moving volumes of gases are beneficial, allowing for achieving passive cooling rates that were earlier suggested as theoretical possibilities as experimental results at our institute. Finally, for future work several system lay-out options were given for systems that primarily operate during night-time: more advanced systems that also during daytime give a considerable passive cooling effect will be much more complicated and hence expensive.

Similar to (other) geoengineering methods the impact will not only depend on the heat transfer effects per m^2 are but must be multiplied with the total surface area of the Earth that is affected. Many buildings, vehicles or other objects need to be adapted besides the construction of larger, dedicated passive cooling devices that employ the atmospheric window until a significant effect is obtained.

Returning to the title of this paper: the technology and methods described here operate locally (apart from possible vehicle roof application), do not involve chemical conversion of CO_2 or other chemicals, and will not cause cross-boundary effects besides the overall effect on global temperature it aims at. It would hardly need legislation, if at all, and, probably most important: this geoengineering approach can be switched off if needed, to stop the passive cooling effect instantaneously. This separates it from most of the suggested SRM and CDR methods.

To finalise with a word of caution: continued emissions of CO_2 and CH_4 into the atmosphere may eventually "close" the atmospheric window, so some urgency should be considered.

Nomenclature / Glossary

BECCS	Bioenergy with carbon dioxide capture and storage
CCS	Carbon dioxide capture and storage
CDR	Carbon dioxide removal (from the atmosphere)
DAC	Direct air capture (of carbon dioxide)
GHG	Greenhouse gas
GWP	Global warming potential
HFC	Hydrofluorocarbon
IPCC	Intergovernmental Panel on Climate Change
LW	Long wavelength (≥ 4 µm)
PE	Polyethylene
SAI	Stratospheric aerosol injection
SRM	Solar radiation management
SW	Short wavelength (< 4 µm)
UNFCCC	United Nations Framework Convention on Climate Change
E_b	blackbody radiation, W/m^2
f	blackbody radiation function
Q	heat transfer, W/m^2
p	pressure, Pa
T	temperature, K

Greek symbols

α	absorptivity, -
ε	emissivity, -
σ	Stefan-Boltzmann constant, $5.67 \cdot 10^{-8}$ $W/(m^2 \cdot K)$
τ	transmittance, -

Subscripts and superscripts

a	overall for air (or the atmosphere)
rad	radiation
sky	sky

References

[1] IPCC Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, 2014. p. 89 Available at: https://www.ipcc.ch/report/ar5/syr/ [accessed 31.10.2017]

[2] Fuss, S., Jones, C.D., Kraxner, F., Peters, G.P., Smith, P., Tavoni, M., van Vuuren, D.P., Canadell, J.G., Jackson, R.B., Milne, J., Moreira, J.R., Nakicenovic, N., Sharifi, A., Yamagata, Y. Research priorities for negative emissions. Environ. Res. Lett. 2016;11:115007 doi:10.1088/1748-9326/11/11/115007

[3] Irvine, P.J., Kravitz, B., Lawrence, M.G., Gerten, D., Caminade, C., Gosling, S.N., Hendy, E., Kassie, B., Kissling, W.D., Muri, H., Oschlies, A., Smith, S.J. Towards a comprehensive climate impacts assessment of solar geoengineering. Earth's Future, 2016; 5. doi:10.1002/2016EF000389

[4] Irvine, P.J., Kravitz, B., Lawrence, M.G., Muri, H. An overview of the Earth system science of solar geoengineering. WIREs Clim Change 2016; 7:815–833. doi: 10.1002/wcc.423

[5] Keith, D.W., Irvine, J.P. Solar geoengineering could substantially reduce climate risks—A research hypothesis for the next decade. Earth's Future, 2016; 4, 549-5559. doi:10.1002/2016EF000465

[6] Williamson, P. Scrutinize CO_2 removal methods. Nature, 2016; 530: 153-155. Available at: http://www.nature.com/news/emissions-reduction-scrutinize-co2-removal-methods-1.19318 [accessed 31.10.2017]

[7] Porter, E. Cooling the planet with technology. New York Times – Int. Edition, April 6, 2017, p.15

[8] United Nations, 2015, Framework Convention on Climate Change, Paris agreement FCCC/CP/2015/L.9 Available at: https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf [accessed 31.10.2017]

[9] Horton, J.B., Keith, D.W., Honegger, M. Implications of the Paris Agreement for Carbon Dioxide Removal and Solar Geoengineering. Belfer Center for Science and International Affairs, Harvard Kennedy School (Policy Briefs). Available at: http://www.belfercenter.org/sites/default/files/legacy/files/160700_horton-keith-honegger_vp2.pdf [accessed 31.10.2017]

[10] United Nations, 1998, Framework Convention on Climate Change, Kyoto Protocol. Available at: http://unfccc.int/resource/docs/convkp/kpeng.pdf [accessed 27.1.2017]

[11] Beyene, A., Zevenhoven, R. Thermodynamics of climate change. Int. J. of Global Warming 2013; 5(1):18-29. doi: 10.1504/IJGW.2013.051467

[12] Zevenhoven, R. Can the infrared radiation that causes the enhanced greenhouse effect be put to better use? in: American Institute of Physics Conference Proceedings volume 1033 "Meeting the Entropy Challenge", Melville, NY, 2008, 356-360

[13] Zevenhoven, R. Modifying and using the thermal infra-red radiation that causes the enhanced greenhouse effect. In: ECOS2008 Proc. of the 21st Int. Conf. on Efficiency, Cost, Optimization, Simulation, and Environmental Impact of Energy Systems, 2008, June 24-27, Krakow-Gliwice, Poland; 1475-1482

[14] Zevenhoven, R., Sakeye, M. Recovery of heat from thermal infra-red radiation: the role of heat conduction and convection, window material and system lay-out. In: ECOS2009 Proc. of the 22nd Int.

Conf. on Efficiency, Cost, Optimization, Simulation, and Environmental Impact of Energy Systems. 2009, August 31 – September 23, Foz du Iguacu, Brazil; 223-231 (paper 02.11)

[15] Fält, M., Zevenhoven, R. Radiative cooling in northern Europe for the production of freezer temperatures. In: ECOS2010 Proc. of the 23rd Int. Conf. on Efficiency, Cost, Optimization, Simulation, and Environmental Impact of Energy Systems, 2010, June 14-17, Lausanne, Switzerland; 413-419

[16] Fält, M., Zevenhoven, R. Experimentation and modeling of an active skylight. In: ECOS2015 Proc. of the 28th Int. Conf. on Efficiency, Cost, Optimization, Simulation, and Environmental Impact of Energy Systems. 2015, June 30 – July 3, Pau, France; paper 52533

[17] Fält, M. The utilization of participating gases and longwave thermal radiation in a passive cooling skylight. [dissertation] Turku Finland: Åbo Akademi University; 2016. Available at: https://www.doria.fi/handle/10024/125709 [accessed 31.10.2017]

[18]Figure by Global Warming Art project (2007). Available at: https://commons.wikimedia.org/wiki/File:Atmospheric_Transmission.png [accessed 31.10.2017]

[19] Fält, M., Pettersson, F., Zevenhoven, R. Modified predator-prey algorithm approach to designing a cooling or insulating skylight. Build. Environ. 2017; 126:331-338. doi: 10.1016/j.buildenv.2017.10.005

[20] Bathgate, S.N., Bosi, S.G. A robust convection cover material for selective cooling applications. Sol. Energy Mater. Sol. Cells. 2011; 95:2778-2785. doi:10.1016/j.solmat.2100.05.027

[21] Lushiku, E.M, Granqvist, C. Radiative cooling with selectively infrared-emitting gases. Appl. Optics, 1985; 23(11):1835-1843. doi: 10.1364/AO.23.001835

[22] Kigali deal on HFCs is big step in fighting climate change. The Guardian (2016) Available at: https://www.theguardian.com/environment/2016/oct/15/kigali-deal-hfcs-climate-change [accessed 31.10.2017]

[23] European Commission EC COM/2017/051 final - 2017/016 (NLE) (2.2.2017) Proposal for a Council Decision on the conclusion of the agreement to amend the Montreal Protocol on substances that deplete the ozone layer adopted in Kigali. Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52017PC0051 [accessed 31.10.2017]

[24] Jiménez, E., González, S., Cazaunau, M., Chen, H., Ballesteros, B., Daele, V., Albaladejo, J. Mellouki, A.. Atmospheric degradation initiated by OH radicals of the potential foam expansion agent, $CF_3(CF_2)_2CH=CH_2$ (HFC-1447fz): Kinetics and formation of gaseous products and secondary organic aerosols. Environ. Sci. Technol. 2016; 50:1234-1242. doi: 10.1021/acs.est.5b04379.

[25] Zevenhoven, R., Fält, M., Gomes, L.P., Thermal radiation heat transfer: Including wavelength dependence into modelling. Int. J. Therm. Sci., 2014; 86: 189-197. doi: 10.1016/j.ijthermalsci.2014.07.003

[26] Sørensen, B. Renewable energy its physics, engineering, use, environmental impacts, economy, and planning aspects. Amsterdam, the Netherlands: Elsevier 2004, p. 952.

[27] Kondratyev, K.Y.A., Radiative heat exchange in the atmosphere. London, UK: Pergamon Press, 1965; pp. 411

[28] Cucumo, M.; De Rosa, A.; Marinelli, V. Experimental testing of correlations to calculate the atmospheric "transparency window" emissivity coefficient. Sol. Energy, 2006; 80:1031-1038.

[29] Zevenhoven, R., Fält, M. Passive cooling against the (night) sky. J. of Sustainable Res. in Eng. 2014; 1: 49-54 Available at: sri.jkuat.ac.ke/ojs/index.php/sri/article/view/13/9 [accessed 31.10.2017]

[30] Al-Obaidi,K.M., Passive cooling techniques through reflective and radiative roofs in tropical houses in Southeast Asia: A literature review. Front. Archit. Res. 2014; 3(3)283-297 doi: 10.1016/j.foar.2014.06.002

[31] Hossain, M.M., Gu, M. Radiative cooling: principles, progress and potentials. Adv. Sci. 2016; 3: 1500360. doi:10.1002/advs.201500360

[32] Kim, J.T, Todorovic, M.S. Tuning control of buildings glazing's transmittance dependence on the solar radiation wavelength to optimize daylighting and building's energy efficiency. Energy & Build. 2013; 63:108-118, doi: 10.1016/j.enbuild.2013.03.036

[33] Chang, S.L., Rhee, K.T. Blackbody radiation functions. Int. Comm. Heat Mass Transf., 1984; 11:451-455

[34] Geetha, N.B., Velraj, R. Passive cooling methods for energy efficient buildings with and without thermal energy storage – a review. Energy Educ. Sci & Technol. Part A: Energy Sci. and Res. 2012; 29(2):913-946

[35] IPCC Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, 2013. Chapter 8. Available at: https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter08_FINAL.pdf / [accessed 21.2.2018]

Figure

Radiative Cooling Through the Atmospheric Window: a Third, Less Intrusive Geoengineering Approach

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Figures:

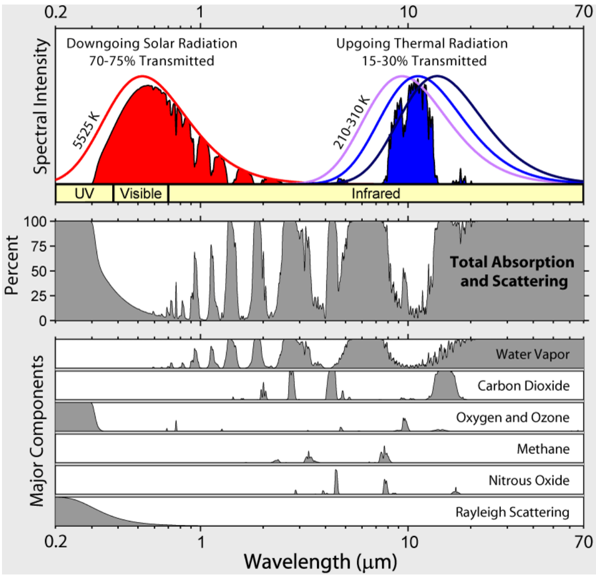

Fig. 1. Radiation transmitted by the atmosphere [18] showing the atmospheric window in blue colour at 8 – 14 µm.

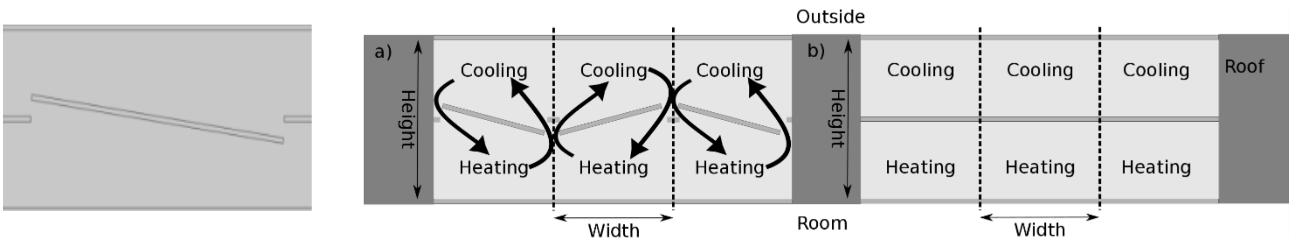

Fig. 2 Schematic cross-sections (2-D) of (left) a single skylight unit for passive cooling operation showing top, bottom and (movable) centre windows [16] and (right) of a modular skylight design in cooling mode a) with arrows indicating convection of the gas, and in insulating mode b) [17].

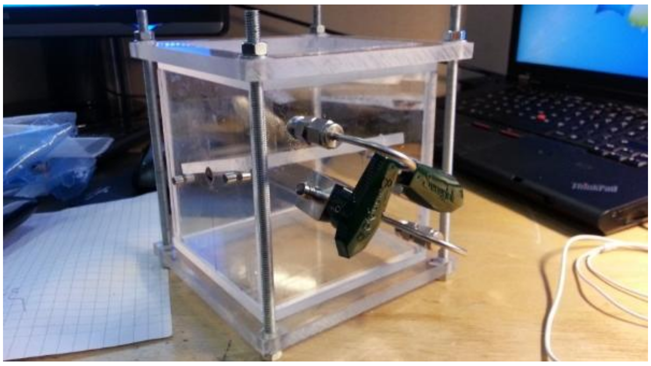

Fig. 3 The 10 x 10 x 10 cm³ test skylight [17].

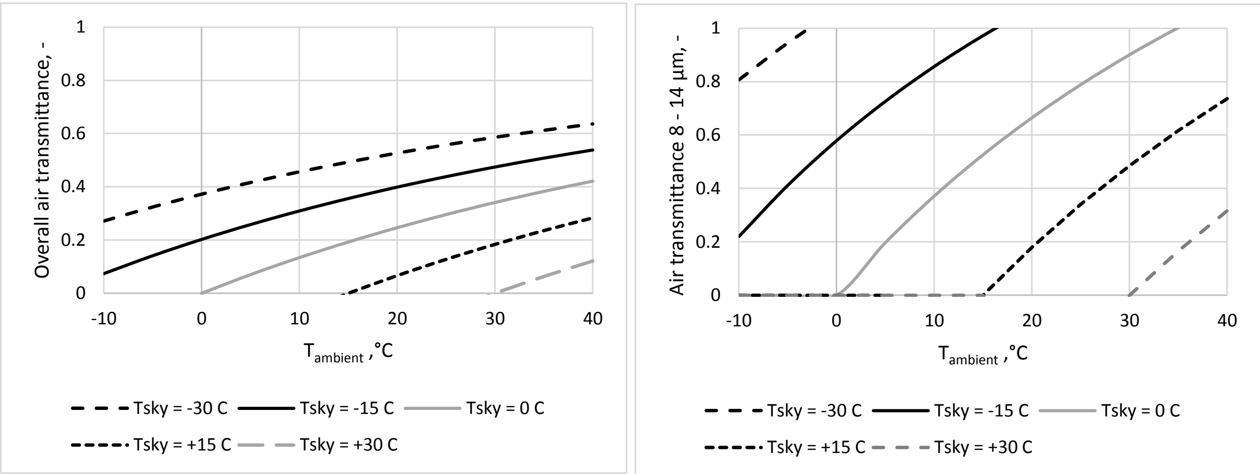

Fig. 4. Transmittance of the atmosphere overall (left) and for the 8-14µm atmospheric window (right) as function of the temperature of the sky and the ambient.

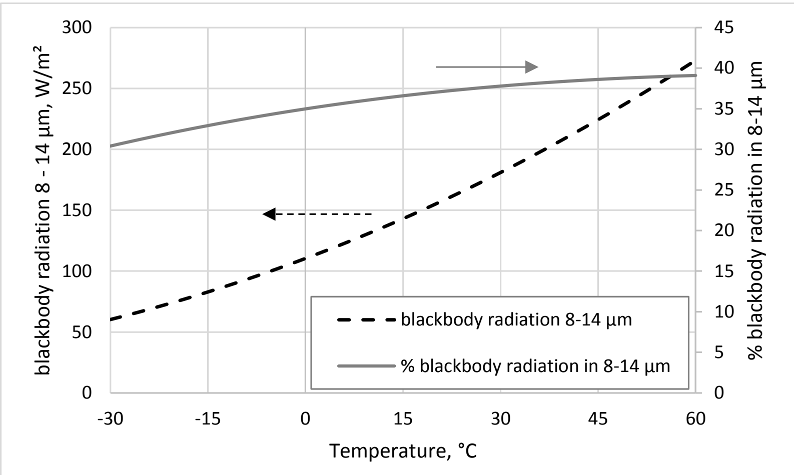

Fig. 5 Maximum (blackbody) thermal radiation intensity within the 8-14 µm atmospheric window and % of the thermal radiation within the atmospheric window, vs. object (surface) temperature.

Figure

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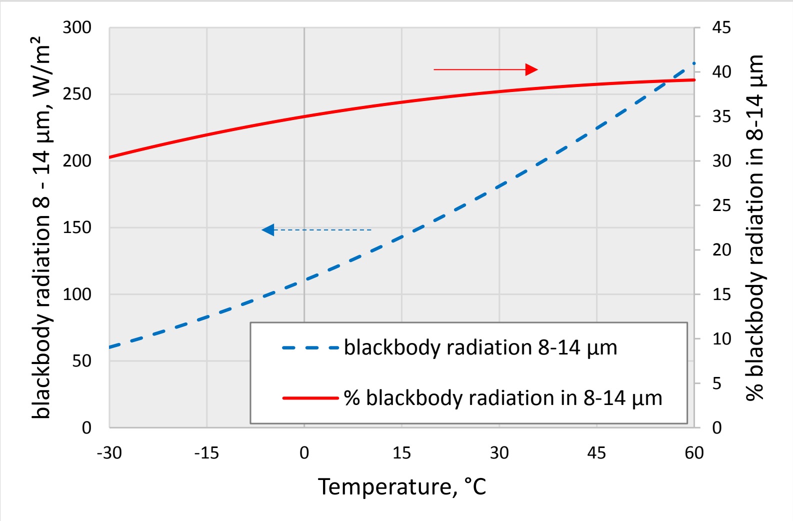
Graphical abstract:



Table

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Tables:

Table 1. A few application alternatives for passive cooling through the atmospheric window using participating gases or vapours. (Some issues to be resolved in italic).

Gas/vapour → "Window" ↓	HFC-1447fz	*NH_3*	*NH_3 + NH_3/water solution*
ZnS box cover	No chemical attack on HFC-125 was seen at our institute. Box with ZnS top window bottom of same material or a good thermal conductor	*Is ZnS stable with NH_3?*	*Is ZnS stable with humid NH_3?*
ZnS covered with PE film used as cover	Same as above	Gives better stability against NH_3 gas.	Depending on temperature, NH_3 can be released from or absorbed in water: this affects gas emissivity
PE film used as cover	*No chemical attack?* Same as above, allow for operation at constant pressure	Was tested at our institute – no effect of NH_3 on PE	Absorption in water gives emissivity control
PE film used as balloon (lower half opaque other material)	*No chemical attack?* HFC-1447fz can be mixed with natural gas (also a participating gas) as to obtain buoyancy in air	As for HFC-1447fz. Again, there should be no effect of NH_3 on PE	Same as above.