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COMMENTARY

Tackling Climate Change through Radiative Cooling

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Jeremy Munday is currently an associate professor at the University of Maryland, College Park, and his work focuses on demonstrating new technologies based on novel physics and engineering. He received his PhD from Harvard University in 2008 and was a postdoctoral scholar at Caltech prior to his appointment at Maryland. Dr. Munday is the recipient of several awards including the DARPA Young Faculty Award, NSF CAREER Award, ONR YIP Award, the OSA Adolph Lomb Medal, the IEEE Photonics Society Young Investigator Award, the SPIE Early Career Achievement Award, and the NASA Early Career Faculty Space Technology Research Award.

Despite growing public concerns and international agreements, few concrete actions have been taken to fix our changing climate. In fact, the Earth is now warming faster than expected, and greenhouse gas emissions are still on the rise. The path forward has been clear: a reduction in CO_2 emission is needed through an increase in energy efficiency and cleaner power production. However, failure to act is making these solutions harder to realize, because the CO_2 that we put in the atmosphere today can persist for decades. The Earth has already warmed by 1°C above pre-industrial levels and is expected to reach 1.5°C in the next 10 to 20 years.[1,2] With time running out, we may need to turn to additional mitigation strategies.

One dramatic option is climatic geoengineering, where humans deliberately intervene to help force the Earth's climate in a particular direction. This concept usually takes on one of two routes: (1) capture and store the current atmospheric greenhouse gases or (2) reduce the amount of solar illumination absorbed by the Earth. While neither of these options address the core problem that our energy economy is driven by fossil fuels, there are a number of research groups pursuing them, especially the question of large-scale, economically feasible CO_2 capture and sequestration. The second option has been more controversial, and perhaps for good reason. A reduction in solar absorption is usually proposed through the injection of reflective aerosols into the atmosphere; however, serious concerns have been raised regarding side effects of these forms of geoengineering and our ability to undo any of the climatic changes we create. Other options including increasing reflectivity by painting roofs white or deploying giant reflective surfaces in space, although the increased reflectivity likely falls short of what is needed and comes at a high financial cost.

As an alternative geoengineering approach, we consider increasing the radiative heat emission from the Earth

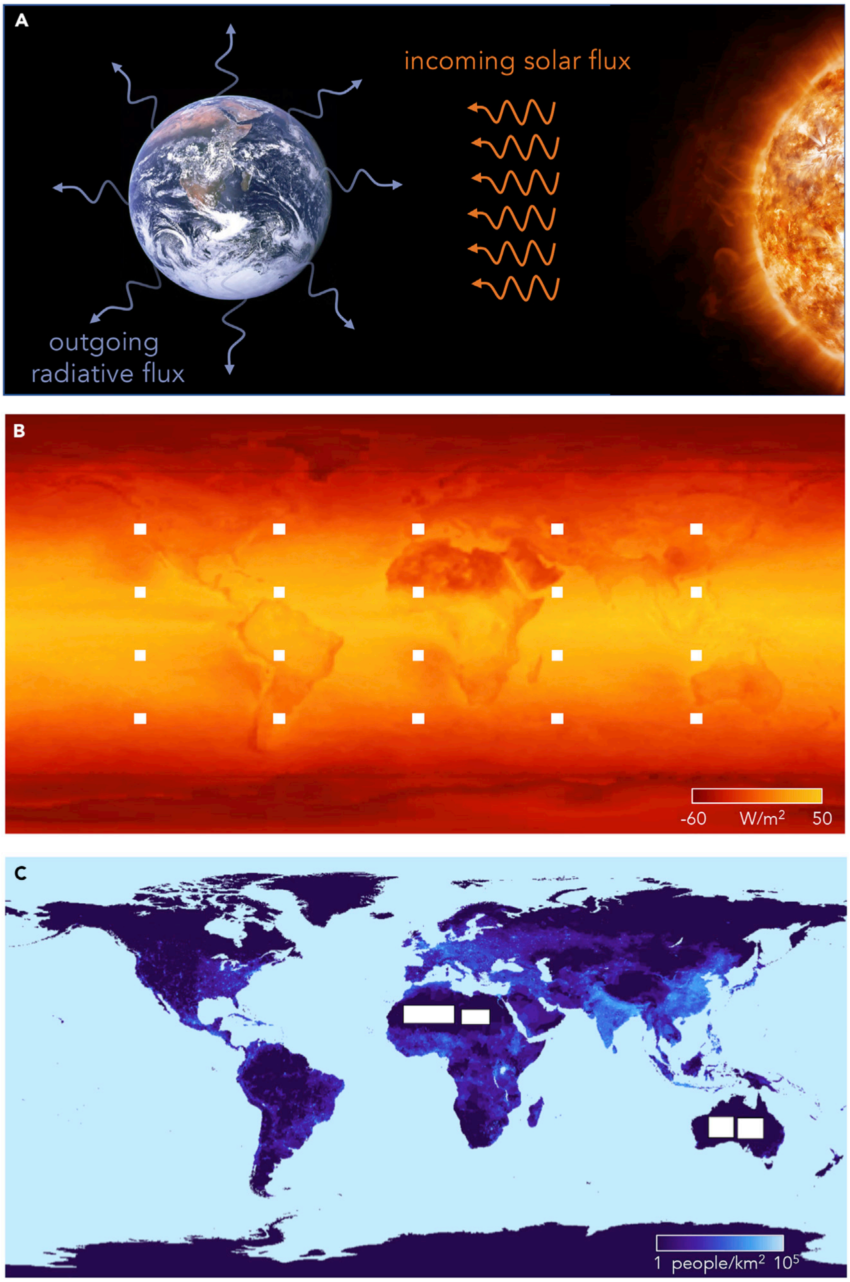

Figure 1. A Delicate Balance of Heat Flow Determines the Earth's Temperature

(A) Incoming radiation from the sun heats the Earth, while the emission from the Earth causes cooling.

(B) Net radiation (incoming from the sun and outgoing from the Earth) for 2017 from monthly averages.[3] If an area of the Earth equivalent to the regions depicted by white rectangles (total area of 5×10^{12} m^2) were covered by currently available radiatively emitting surfaces, the total global heat flux could be reduced by nearly 1 W/m^2, potentially enough to stop the increase of global temperatures.

(C) Population density map.[4] White rectangles represent four desert regions with populations densities < 1 person/km^2 and a total area of 5×10^{12} m^2 (same as in B). The actual implementation of this strategy would be broken into several smaller regions globally rather than the white boxes depicted in (B) and (C), which are shown for simplicity.

rather than merely decreasing its solar absorption (Figure 1). Radiative heat from the sun is absorbed by the Earth and heats it. Simultaneously, the Earth emits heat to space and cools. When the incoming heat is balanced by the outgoing heat, the Earth reaches a stable, steady-state temperature. Currently the Earth is absorbing ~1 W/m^2 more than it is emitting,[5] which leads to an overall warming of the climate. By covering the Earth with a small fraction of thermally emitting materials, the heat flow away from the Earth can be increased, and the net radiative flux can be reduced to zero (or even made negative), thus stabilizing (or cooling) the Earth.

Over the last few years, researchers have developed thermally emissive materials that can radiate ~100 W/m^2 out to space through the atmospheric transparency window.[6–10] The idea is to make a material that is reflective to the sunlight, yet emissive to the wavelength range of 8–20 μm. In doing so, no solar radiation is absorbed, and only radiative cooling occurs (during both day and night). These materials can be printed roll-to-roll or deposited as a paint.[8,9] If only 1%–2% of the Earth's surface were instead made to radiate at this rate rather than its current average value, the total heat fluxes into and away from the entire Earth would be balanced and warming would cease.

As a simplified example of how this concept might work, we first consider what land resources it would take to implement. To offset 1 W/m^2 globally, we need approximately 5×10^{12} m^2 of surface coverage with 100 W/m^2 radiative emitters (the exact needs will depend on where the emitters are placed and what original flux they offset). If used as one continuous area, it corresponds to a little more than half the size of the Sahara Desert. Ideally this area would be broken into several small regions globally (including roofs and other sky-facing surfaces). For illustrative purposes only, we consider two simple distributions to get a better sense of the areas involved. First, we show 20 equal area regions distributed evenly across the Earth (Figure 1B). This distribution covers both land and sea as well as populated and unpopulated areas. Next, we consider the case of land masses with a population density < 1 person/km^2 and those that represent desert climates to facilitate clear/dry environments that are most conducive to radiative transfer (note: some deserts naturally promote radiative emission and the total land requirement and effectiveness of the radiative coolers will depend on this value). For this case (Figure 1C), we divided the same total area into only four sub-areas and distributed them across the Sahara and Australian deserts. The actual radiative flux of the emitters will also be dependent on local weather conditions (including temperature, humidity, and cloud cover) and will vary by season and specific global position, requiring potentially larger or smaller areal coverage to meet a particular radiative flux goal. All of these factors will need to be considered when choosing the actual area distribution.

Next, we consider the potential costs. Large-scale polymer sheets are commercially available for <\$0.25/m^2, and roll-to-roll processing of radiative films has been estimated at \$0.25 to \$0.50 per square meter,[11] or \$1.25 to \$2.5 trillion for the total area we considered (although significant price reductions are conceivable at this scale). This cost corresponds to about 10% of US GDP or 3% of global GDP and is a small investment compared to the estimated \$20 trillion global benefits predicted by limiting global warming to 1.5°C rather than 2°C.[12] Additional encapsulation, mounting, labor, etc. would increase the total costs; however, the polymer itself could be used for support,[8] or alternative versions involving paint-like processes[9] could be used at potentially lower costs. Further studies are also needed to understand degradation processes and potential maintenance in these newly developed materials.

Despite the potential benefits and promise, we should proceed with caution when trying to engineer the global climate. Large cooling structures could also lead to uneven temperature variations that may result in further climatic and environmental changes on a variety of length scales that would need to be studied. There are also many land use issues given the large areas involved, ranging from property rights to environmental concerns for local flora and fauna. Unexpected effects will likely occur, but fortunately, these structures can be removed immediately if needed, unlike methods that involve dispersing particulate matter into the atmosphere, which can last for decades. Further, radiative cooling cannot be a complete, standalone solution, but rather is part of a more comprehensive approach that must include CO_2 reduction. Otherwise, the radiative balance will not last long, and the potential financial benefits of mitigation will not fully be realized because of continued ocean acidification, air pollution, and redistribution of biomass.

We note that the simple analysis presented here is merely a first step showing the potential of such an approach and further detailed techno-economic analysis is needed. Unlike mature sky-facing technologies such as photovoltaics, the preferred embodiment of the radiative emitter is still a work in progress and needs further development before any accurate cost models can be determined. The spectral dependence of the emitter must also be carefully designed to ensure that the emission is *through* the atmospheric transparency window and out to space, rather than just *to* the atmosphere, which would allow for local but not global cooling. Similarly, research is needed into the yearly averaged radiative heat flux for emitters at different locations and how the resulting changes in weather patterns may influence emission. To move forward, physicists and engineers working on photonic engineering of radiative emitters can learn from techniques and analysis within the photovoltaics community while simultaneously collaborating with climate scientists, environmental engineers, and policy makers to help determine the potential global impact of such strategies.

Mitigating climate change is a tall task, and we are reaching a point where all options should be on the table.

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COMMENTARY

Meeting U.S. Solid Oxide Fuel Cell Targets

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Introduction

Solid oxide fuel cells (SOFCs) are highly efficient, scalable, high-temperature (typically greater than 600°C), solid-state devices that, through an electrochemical reaction, convert hydrocarbon or hydrogen fuels into electricity and thermal energy. Without compromising efficiency, SOFCs can be connected, and interconnects electrically joined, to form stacks that meet demand. Commercial SOFC systems are capable of operating on hydrogen, natural gas, propane, and

