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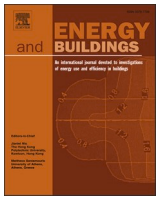

# Impacts of radiative cooling paints for $CO_2$ reduction and global warming mitigation

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ABSTRACT

Daytime radiative cooling has attracted significant interest recently because it uses the high reflection of sunlight and emission of thermal radiation to cool objects below the ambient temperature without power consumption. However, the year-round impact of modern daytime radiative cooling paints on carbon reduction and global warming mitigation as compared to conventional black roofs and previous cool roofs is not well understood. Here we choose ultrawhite $CaCO_3$ cooling paint used on buildings as a prototype system and conduct a comprehensive analysis of the impact of two distinct mechanisms on global climate. The first mechanism is carbon emission reduction at power plants due to building air conditioning power savings. The second mechanism is due to increased direct heat rejection by the ultrawhite roof to deep space, where the thermal effect is equivalent to $CO_2$ reduction from the atmosphere. Our results show that the impact of the paints on the climate was always positive for all climate zones, reducing up to 665 lbs of $CO_{2eq}$ from the atmosphere per $m^2$ of paint applied over a 100-year span. Additionally, the paints are most effective in hot/warm/mild and dry climates, and depending on climate zone, 0.94 % – 2.02 % coverage of the paint on the earth's total surface could stop the global warming trend.

## 1. Introduction

Despite the greenhouse gases (GHGs) emission reduction efforts of the 2015 Paris Agreement, current models suggest that the desired goal of limiting global temperature rise by 1.5 °C since pre-industrial levels is unlikely [1]. This global temperature rise leads to concerning trends in climate change such as increasing flooding, wildfires, and other forms of erratic weather. Solutions such as an increase in low-carbon electricity generation and reductions in the rate of fossil fuel burning have shown promise; however, more solutions are desired to reduce the impact of the changing climate to below 1.5 °C [1].

One potential solution is the use of passive cooling technologies such as radiative cooling. According to the United States Energy Information Administration, air conditioning accounted for around 12 % of total energy costs for residential buildings in the United States (US) in 2015 [2]. In 2021, about 61 % of this energy came from fossil fuels [3]. Therefore, a significant reduction in $CO_2$ emissions can come from shifting cooling requirements from the current form of active cooling, which requires an energy input, to passive cooling, which does not require an energy input. Radiative cooling (RC) is a type of passive cooling technology that works by two mechanisms: maximizing reflectance of incoming solar radiation, as well as maximizing emission in the spectral region of 8–13 μm, often referred to as the 'sky window.' The idea of using cooling systems, often white paint, to cool roofs has existed for centuries [4] and was first pursued scientifically in the 1970 s [5,6]. More recently, breakthroughs in daytime sub-ambient cooling have enabled new research and applications of RC technologies [7–22]. The Cool Roof Rating Council hosts a product directory of some of these novel cool roofs [23]. Some viable full-daytime radiative cooling technologies include porous polymers and cooling paints [7,13–15].

With the development of previous cool roofs and emerging daytime radiative cooling paints, research has been conducted to analyze how these technologies affect building energy demands. Tzempelikos and Lee found that cool roofs with 70 % solar reflectance result in cost savings in at least 14 out of the 16 ASHRAE representative climate zones for big box retail stores, school buildings, and office buildings [24]. Modeling

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showed that the more recent ultrawhite daytime $BaSO_4$ cooling paints demonstrated up to 46 % electricity savings for a typical residential building, but only studied the summer effects of the paint [25]. Another study also found energy savings but lower trends due to a strict setpoint and year-round data, citing dry, hot ASHRAE Zone 2B as having the highest energy savings of 6.2 % [26]. These findings were able to correlate whether energy was saved using the cooling degree days of the building [26]. Additionally, Raman et al. found that their photonic radiative coolers save more $/kWh than photovoltaics, highlighting RC as an attractive energy saving option [11]. Despite the previous studies in this field, a year-round study for multiple climate zones has not been done on the emerging ultrawhite daytime radiative cooling paints. Additionally, these previous studies focus on energy savings for building owners, instead of environmental impact through $CO_2$ emission reductions.

Work has also been done to understand the effects of radiative cooling material on the global climate. One work estimated that increasing the albedo/reflectance of urban centers by 0.1 (10 %) could offset around 44 Gt of $CO_2$ emissions through radiative forcing [27]. Similarly, Menon et al. found in 2010 that increasing the albedo by 40 % resulted in an effective difference of −130 kg $CO_2$ per $m^2$ of roof area [28]. A study by Pirvaram et al. built upon previous re69sults from Kolokotroni et al. and examined both the HVAC (heating, ventilation, and air conditioning) and albedo impacts of the paint in a life-cycle assessment for 3 countries, finding the maximum impact of the paint to be a reduction of 20 tons (40,000 kg) of $CO_{2eq}$ for one house over 20 years in Jamaica [29,30]. To our knowledge, this is the only work that has combined the effects of HVAC and radiative forcing on environmental impact of cooling technology. However, this work utilized previous cooling technology with a reflectance of 82 % and thermal emittance of 0.90, didn't consider heating of the buildings, was limited to only a few climate types, and importantly, considered a consistent cooling power of 80 W/$m^2$, therefore decoupling the HVAC and radiative forcing impacts by not considering the variable roof temperature/emittance [29,30]. A rough estimation showed that if only radiative forcing is considered, about 1 % of the earth surface would need to be covered with radiative cooling material with a generic net cooling power of 100 W/$m^2$ to fully reverse the ongoing effects of climate change [31]. This estimation did not consider different climate zones, realistic weather, or HVAC impact. Considering existing studies, it is clear that the impact of the emerging ultrawhite below-ambient radiative cooling paints on $CO_2$ reduction and a comparison to black roofs and previous cool roofs have not been understood under different climates and realistic year-round weather conditions.

This paper intends to build upon these previous works and provide an in-depth analysis of two different mechanisms in which the ultrawhite daytime $CaCO_3$-based radiative cooling paints could address climate change. We utilize a single-story ranch house and perform simulations with the TRNSYS modeling software. The first mechanism we study is how much HVAC power consumption is avoided through the implementation of RC paints, hence how much $CO_2$ emission is reduced by the lessened power generation at power plants. The second mechanism is the quantification of the change in radiative forcing that reduces the amount of heat trapped on earth by the house, for 16 different climate zones, which represents a broader study than any known literature by the authors. To our knowledge, this is also the first time these two effects have been coupled, by considering the HVAC's impact on the roof's temperature to determine LWIR emission. We combine the total effect of both parts through global warming potential (GWP), which measures the change in heat flux through a $CO_2$ standard, to get a total impact due to the addition of RC paints.

## 2. Methods

### 2.1. Overview of the two mechanisms in a coupled manner

The first potential mechanism ('Part 1') that we study is $CO_2$ reduction at power plants due to HVAC power savings, and the second ('Part 2') is losing heat directly to deep space instead of maintaining heat within the Earth's atmosphere, which leads to an equivalent $CO_2$ reduction. To illustrate the two mechanisms, an 1800 $ft^2$ single-story ranch style home adapted from Holloway was used, as shown in Fig. 1. [25,32] One may confuse the two parts, but they are very different. In Fig. 1, we attempt to demonstrate this by showing that Part 1 leads to a reduction in emissions needed to run the HVAC system, while Part 2 leads to less heat output by the HVAC system.[i] In this work, we quantify this reduction in heat output through a calculation of the radiative forcing per $m^2$, however, this is equivalent to the reduction in heat output from the HVAC system.

Although the second mechanism does not reduce real $CO_2$, the net cooling effect of the process is equivalent to removing $CO_2$ from Earth's atmosphere from a thermal perspective. We can define an equivalent $CO_2$ reduction for this mechanism by matching the net thermal effect to that of $CO_2$. This can be done with the consideration of the global

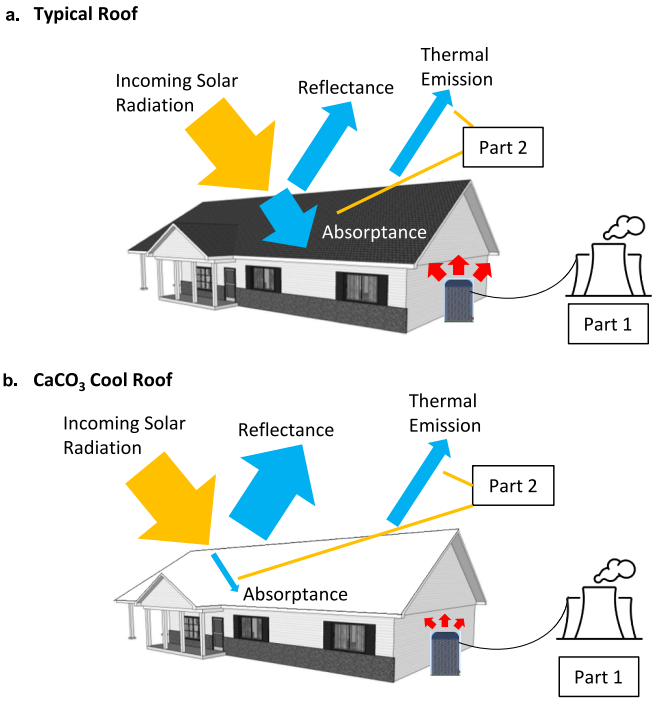


**Fig. 1.** Schematics of a typical roof and a cooling roof. (a) and (b): Two mechanisms of reducing $CO_2$ and mitigating climate crisis from a typical black tile roof (a) to a roof painted with $CaCO_3$ radiative cooling paints (b), on a ranch-style home model which was originally retrieved from Google Sketchup 3D Warehouse by Seth Holloway[32]. Part 1: reduced $CO_2$ at power plants due to HVAC energy savings; Part 2: equivalent $CO_2$ reduction due to reflecting sunlight and emitting heat directly to deep space.

[i] Another way to think of these differences is to think of the $CO_2$ reductions from an oven. When run in the summertime, a more efficient oven will not only draw less electricity from the electric grid, reducing $CO_2$ demand (Part 1), but it will also release less heat into the kitchen, meaning that it will take less cooling to bring the kitchen back to the desired temperature (Part 2). These two parts, while connected, are inherently different, and have separate impacts on the system as a whole.

warming potential (GWP) of each mechanism. GWP is a measurement of how much a gas or material changes the heat gain in the atmosphere: For instance, $CO_2$, which is the gas that is used as a baseline of comparison for all other gases, has a GWP of 1.

The computation used to quantify GWP in this work uses a similar process to Pirvaram et al. [30]. First, the net cooling data of the paint is gathered. Then, the absolute GWP (AGWP) over 20 and 100 years is calculated by:

$$AGWP_{RCi}(H) = -\int_0^H \frac{P_{netcooling,i}}{A_{RCi}}\left(\frac{1}{A_{tropopause}}\right)dt$$

Finally, the $AGWP_{20}$ and $AGWP_{100}$ are used to find the $GWP_{20}$ and $GWP_{100}$ using the equation shown below. The values of AGWP for pure $CO_2$ ($AGWP_{CO_2,20}$ and $AGWP_{CO_2,100}$) are retrieved from Ref. [30].

$$GWP_{RCi}(H) = \frac{AGWP_{RCi}(H)}{AGWP_{CO_2}(H)}$$

Another way to make this conversion is explored in Fig. S1, wherein global radiative forcing effects were compared with the amount of $CO_2$ in the atmosphere. However, this was not presented in the main text due to the prevalence of GWP in the literature.

### 2.2. Part 1: Cooling and heating energy savings

To quantify the effect of Part 1 on the atmosphere, a TRNSYS model was created based on previous literature used to model the effects of $CaCO_3$ paints on building cooling needs [25]. TRNSYS is a building simulation software developed by the University of Wisconsin Solar Energy Laboratory and Thermal Energy System Specialists that allows for detailed weather, envelope, and heat transfer calculations [33]. In this study, it was used to output the HVAC demands for $CaCO_3$ radiative cooling (RC) and typical (typ) buildings for an entire year in a representative city for the 16 ASHRAE climate zones, listed in Table 1 [34]. To convert these demands into $CO_2$ emissions, an average U.S. emissions value of 0.855 lbs $CO_2$/kWh was used.

The building envelope parameters and HVAC system were adopted from the "Typical Building" model (R-18, 6" roof; R-11, 4" exterior walls) described in Ref. [25]3e. The emissive properties for the $CaCO_3$-acrylic paint were taken from Ref. [7] and included as an external heat flux in the TRNSYS model. A year-round simulation for heating and cooling loads was run for each of the 16 representative cities for RC and typ roofs. The same building model assumptions, including insulation, were assumed for all 16 ASHRAE climate zones: While this is not representative of insulation throughout the US, it was designed to show the overall performance of the RC paint in cold and warm scenarios. Note that the cooling demand (electricity consumption) can be found by dividing the cooling load by an assumed constant coefficient of performance (COP) of 3.5. Additional building parameters are highlighted in Table S1.

**Table 1**
DOE Representative Cities for each of the 16 climate zones[34].

| Climate Zone | Representative City |
|---|---|
| 1A | Miami, Florida |
| 2A | Houston, Texas |
| 2B | Phoenix, Arizona |
| 3A | Atlanta, Georgia |
| 3B-Coast | Los Angeles, California |
| 3B | Las Vegas, Nevada |
| 3C | San Francisco, California |
| 4A | Baltimore, Maryland |
| 4B | Albuquerque, New Mexico |
| 4C | Seattle, Washington |
| 5A | Chicago, Illinois |
| 5B | Boulder, Colorado |
| 6A | Minneapolis, Minnesota |
| 6B | Helena, Montana |
| 7A | Duluth, Minnesota |
| 8A | Fairbanks, Alaska |

To model the cooling demands, the following model parameters were used: TRNSYS's Type 921 air conditioner [25], a setpoint of 23 ℃ for cooling and 20 ℃ for heating, an internal gains schedule based on ASHRAE 90.2 [25], a view factor of the building roof to the sky of 0.9 [25], a view factor of the walls to the sky of 0.5 (based on the building's height to width ratio and Table 13-1 in Ref. [36]) [25], and an infiltration rate from ASHRAE 62.2 [25]. Additionally, the radiative cooling model described in Ref. [25] was modified for $CaCO_3$ paints.

The heating requirements were calculated using the same model and assumptions as the cooling requirements. Instead of using a pre-built 'Type' in TRNSYS, heating needs were directly quantified. If a climate zone was assumed to use gas heating, an efficiency of 92 % for a gas furnace was assumed. Otherwise, the output wasn't modified further: an assumption was made to not account for gas and electricity inefficiencies. Climate Zones 1A-3C (hot to warm climates) were assumed to use electric heating and climate Zones 4A-8A (mild to cold climates) were assumed to use gas heating, as approximately half of the US uses natural gas for space heating [35].

### 2.3. Calculations of Part 2: Direct cooling of the earth system by sending the heat to deep space

To quantify the net cooling effect of the paint on the environment, the simulation for Part 2 was split into two separate parts, defined here as the absorbed solar irradiation and the surface's thermal emission. An important note to make is that here we need to consider the impact on the earth system (building, surroundings, and atmosphere) instead of just the building, as we did in Part 1. Since we consider a sloped roof of the house, the absorbed solar irradiation by the earth system not only includes the absorption on the roof, but also the portion that is reflected by the roof and redirected to the ground and absorbed. The reflected solar irradiation is given by

$$Q_r = \frac{GHR^*R^*\frac{145}{180}}{1.22}$$

and the total absorption by the earth system is given by

$$Q_a = Q_{a,roof} + Q_{a,ground} = \frac{GHR^*\alpha}{1.22} + \frac{GHR^*R^*35/180}{1.22}$$

where the percent absorption is α, the RC roof's reflectance $R$ is 95.5 % and the typical roof's $R$ is 20 %, and GHR is defined as Global Horizontal Radiation with units of $Wh/m^2$. Assuming a 35-degree slope of the roof, a factor of 1/1.22 is used to obtain the projected area of the roof normal to the incoming solar irradiation, and a factor of (180–35)/(180) was included to account for the amount of reflected radiation that goes to deep space instead of being 'grounded'. This concept is further illustrated in Fig. S2.

For the thermal emission calculations, the TRNSYS model in Part 1 was modified to output the temperature of the roof at each hour throughout a year. With this roof temperature, the total thermal radiation as well as the fraction of power in the sky window were calculated according to the equations below for the noted wavelengths [36]:

$$E_{\lambda,b}(\lambda,T) = \pi I_{\lambda,b}(\lambda,T) = \frac{C_1}{\lambda^5[exp(C_2/\lambda T)-1]}$$

$$F_{(\lambda_1\to\lambda_2)} = \frac{\int_0^{\lambda_2} E_{\lambda,b}d\lambda - \int_0^{\lambda_1} E_{\lambda,b}d\lambda}{\sigma T^4} = F_{(0\to\lambda_2)} - F_{(0\to\lambda_1)}$$

$$E_{b,8\to13} = \sigma T^4 \varepsilon_{Paint} F_{\lambda_1\to\lambda_2}$$

Now the emission can be known within the sky window of 8–13 μm. From this, the average annual emission in each climate zone was calculated, and as with the reflected solar irradiation, a factor of

(180–35)/(180) was applied to account for emission going to deep space instead of grounded, assuming a roof angle of 35 degrees and a directionally uniform emission.

The net cooling power is then calculated as:

$$Q_c = E_{b,8\to13} - Q_a$$

The process behind finding this final emission is visualized in Fig. S3.

This process is notably focused on our specific case of a single residential building with a slanted roof. For different scenarios, calculations would change slightly depending on the specifications of each individual building studied. Notably, the considerations would change based on roof type, the HVAC units used by the buildings, the original roof coating on the building (in this case, named "typical"), as well as the visibility of the building to the sky that could be affected by other buildings or plant life (where in this case, we assume 100 % visibility). Specific calculations in this study could be altered as desired to account for these different scenarios.

## 3. Results

### 3.1. Part 1: $CO_2$ reduction at power plant due to HVAC power savings

Hourly HVAC loads in Phoenix, AZ, including cooling and heating separately, for a representative day in summer and winter are shown in Fig. 2a-b. In the summer day, cooling is the primary need, and RC technologies considerably reduce the cooling load, while no heating is needed throughout the 24-hour period. Interestingly, in the representative winter day, RC shows considerably less cooling load than typ roofs during peak daylight hours, and a similar heating load during nighttime, leading to an overall reduction in HVAC loads for that day. This indicates that in very hot climates, RC can have net daily benefits even in winter, opposite to the common thinking that it brings overall benefits each day in summer but penalty each day in winter. Table S2 intends to expand upon this idea by breaking down the monthly difference in load for all winter months, and shows that November and January both have a net reduction in energy usage. In both seasons, the greatest difference in HVAC loads can be seen during the peak daylight hours, due to the large difference between the RC and typ roofs' solar reflectance, which is greatest when the solar irradiation is highest. The benefits of RC are further shown in Figs. S4 and S5 and explained in Note S1 through the calculation and comparison of balance point temperature and the percentage of time in cooling, heating, or neither mode.

In Fig. 2c, we introduce a separation between our 'typical' case, which models a typical black roof, and a 'white typical' case, which models a typical white roof, standard in some larger industry buildings. While the focus of this work will remain on the black typical case, we would like to also provide potential benefits of switching from a typical white roof to a RC roof in this case for building owners.

The annual cooling load and $CO_2$ production for RC and both kinds of typical buildings in the 16 representative cities are shown in Fig. 2c. The $CO_2$ calculations are derived from the cooling demand (or energy consumption), which is obtained by dividing the cooling load by a constant COP of 3.5 assumed in this work. As expected, as the temperature in the climate zone decreases (as one travels away from the origin along the x axis), the cooling load generally decreases. The cooling load of buildings painted with $CaCO_3$ paints is always less than that of buildings with a typical black tile roof.

Annual heating load and $CO_2$ output, using the same building structure and assumptions as for cooling load above, are shown in Fig. 2d-e respectively. As expected, the heating load in buildings with RC is always higher than the white typ buildings, which is higher than the black typ buildings, regardless of the climate zone. Although the heating load about doubles from 3C to 4A in Fig. 2d, the $CO_2$ production from heating shown in Fig. 2e decreases because gas heating is utilized instead of electric starting in Zone 4A, and gas heating has a lower $CO_2$ per kWh output. Because the COP for heating is assumed to be around 1, the $CO_2$ production is relatively much higher than that of cooling.

When considering both cooling and heating demands across all climate zones, RC roofs exhibit expected trends of reduced cooling requirements and increased heating needs: However, the disparity in cooling demand is more pronounced in warmer climates, and the disparity in heating demand is more pronounced in colder climates, leading to the overall preference for each climate's roofs. While climate zone temperatures generally decrease as their number increases, other weather conditions such as humidity also play a role, causing the different trends seen in Fig. 2c-d. For instance, climate Zones 4A, 4B, and 4C are all considered mild climates, but 4A is humid, 4B is dry, and 4C is marine. Therefore, the higher temperature variations in the drier climates lead to increases in heating and cooling loads. These loads were translated to cost estimates for the 16 climate zones in Fig. S6, wherein they were broken into cooling savings (a), heating savings (b), and total savings (c). Notably, employing RC paints in all but two climates (4C and 7A) lead to cost reduction for homeowners.

The total GWP reduction from implementing the RC paint, as opposed to the typ roof, for Part 1 is shown in Fig. 2f. It can be observed that radiative cooling paints can overall reduce or increase GWP depending on the climate of the area. For a majority of the climate zones, particularly warm zones, our paints will decrease GWP through a reduction in HVAC demands. The humidity of the area can have a more complicated effect on the total results compared to the temperature depending on many factors such as when the humidity is apparent (time of day and year) as well as the intensity and duration of the humidity. It is also worth noting that if the cooling paints can reduce heat gain locally, the GWP could reduce even further, because the RC paints are able to combat the heat island effect and cool urban climates, making ambient temperature lower and AC units more efficient. This additional benefit is not considered in the current study. Exact data for Fig. 2c-f are shown in Table S3 for reference.

### 3.2. Part 2: Directly cooling the planet by sending heat to deep space

The hourly solar absorption, thermal emission, and net cooling energy for the RC roof and typ roof for one represented day in the summer are shown in Fig. 3a, as well as one winter day in Fig. 3b. For both graphs, as the solar irradiation on the roof increases, there is a larger difference between the RC and typ roofs' solar absorption, as the sloped radiative cooling roof absorbs around 17.7 times less than the typical roof. It can also be noted that this difference is larger in the summer, when the solar irradiation is larger. Additionally, the thermal emissions of the roofs are noted, where the typ roof has a higher output due to its warmer surface. Lastly, it is found that there is significant heating for the typ roof during the daytime in both seasons (though more pronounced in summer), while the RC roof provides net cooling of the Earth system due to its substantially lower solar absorption. A graph that compares the reflectance and absorption of the RC and typ roofs directly is presented in Fig. S7.

The average cooling power from Part 2 for the 16 climate zones is shown in Fig. 3c. Exact data for this figure is shown in Table S3 for reference. The cooling power combines the effects of reflection and emission by the RC and typ roofs. This figure shows that Part 2 always has a large, positive effect on the global heat balance when the paint is applied anywhere within the United States. The reflected and emitted energies are shown separately in Fig. S8T.

Based on the assumptions that the earth currently experiences ~ 1 $W/m^2$ excess heating and radiative cooling could provide 50–100 $W/m^2$ cooling power, previous literature [31] provided a simple estimation

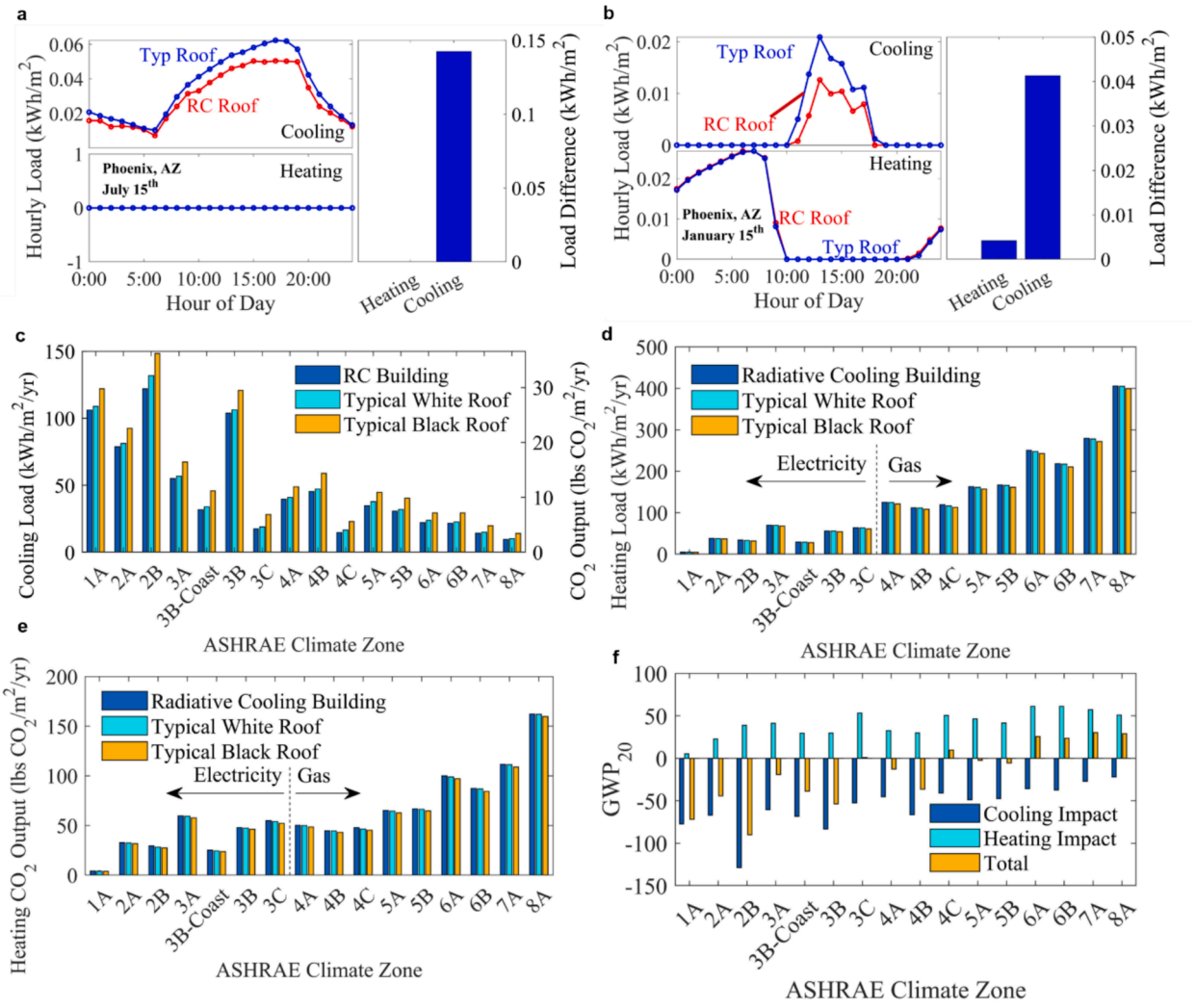


**Fig. 2.** Impact of radiative cooling paints on the HVAC load of a building and associated $CO_2$ emission. (a) and (b): hourly cooling and heating loads throughout a single day in the winter and summer, respectively for Phoenix, AZ. Note that the cooling energy consumption can be found by dividing the cooling load by an assumed constant COP of 3.5. (c): annual cooling load for the 16 different ASHRAE climate zones and annual $CO_2$ production rate. (d) and (e): the heating demand in these zones and lbs $CO_2/m^2$, respectively. (f): the final $GWP_{20}$ impact of the effect of radiative cooling paints on HVAC demands over a lifespan of 20 years across the 16 ASHRAE climate zones.

that covering 1–2 % of the earth's surface could offset earth's excess heating and stop the warming trend. In this work, our Part 2 model offers a sophisticated and quantitative study accounting for different climate zones, building parameters, and realistic weather conditions.[ii] The values of coverage are presented in Table S4 and generally align with the previous estimation. Beyond that, our results show that hot/warm/mild, dry climates are the most effective with less than 1 % coverage accomplishing this goal.

### 3.3. Total impact of RC cooling paints on a Single-Story roof

Fig. 4a shows how the $CaCO_3$ paint affects the earth over a period of 20 years in the city of Phoenix, AZ. This graph visualizes a few important differences between the two mechanisms that must be understood to fully appreciate the results of this work. To compare these, a lifetime of 10 years is assumed for the paint in our analysis, and the paint is considered to be remade and reapplied every 10 years. This is comparable to our control value of the typical black roof, which would also need reapplication at the same rate. A summary of these characteristics is shown in Table 2. No degradation or maintenance is accounted for over the 10-year lifespan, as the control will also experience similar levels of these effects. Part 1 reduces real $CO_2$ in the atmosphere at the time of paint fabrication. This reduction is permanent; hence the associated cooling effect is cumulative and forever, even after the paint reaches its lifespan. Part 1 also reduces real $CO_2$ in the atmosphere, but the reduction is cumulative instead of instant because the paint continuously saves HVAC power and the associated $CO_2$ at power plant over the entire lifespan. This reduction is cumulative and permanent; hence the associated cooling effect is cumulative and permanent. Part 2 has a significant difference from Part 1: once it is installed, the cooling effect occurs in full and cumulatively, and this is equivalent to a one-time instantaneous removal of $CO_2$ from the atmosphere. Therefore, Part 2 removes $CO_{2eq}$ instead of real $CO_2$. For this reason, when the paint reaches its end of life and is removed, the cooling effect vanishes and so does the effect of $CO_{2eq}$ reduction. The cooling effect of the earth is cumulative over the lifespan of the paint though.

All three parts were placed together for the 16 climate zones in Fig. 4b and 4c for $GWP_{20}$ and $GWP_{100}$, respectively, to understand their

[ii] Notably, large-scale changes in Earth's reflectivity could significantly impact both local and global climates, ultimately influencing analyses of individual buildings. While these effects fall outside the scope of the current work, they certainly warrant future studies.

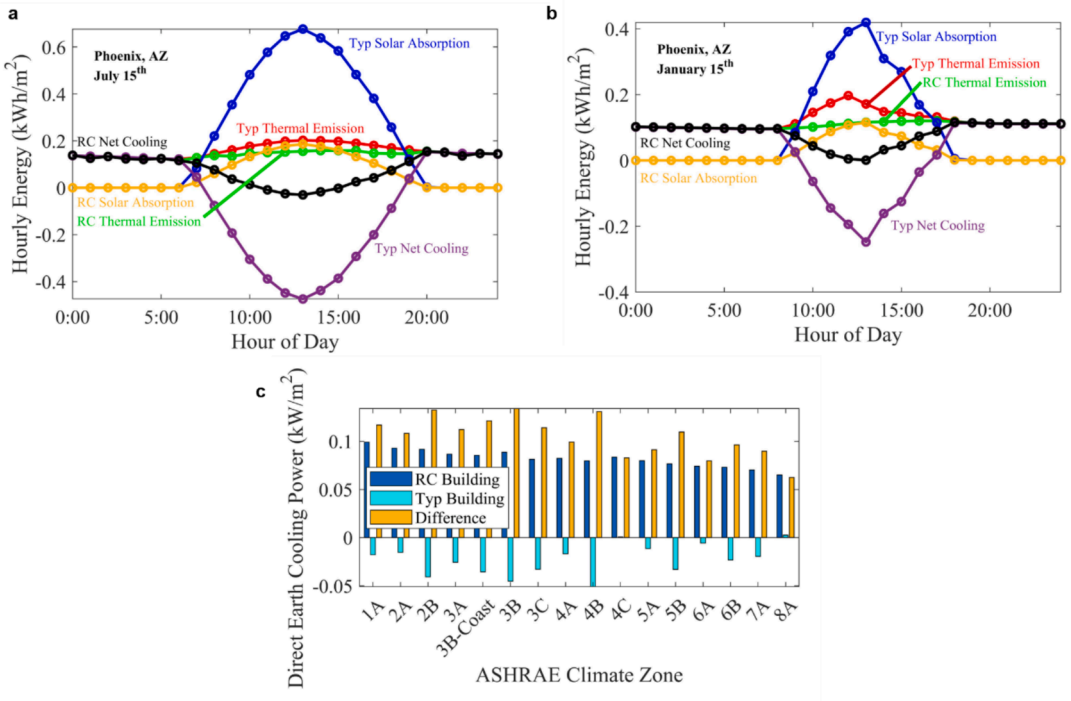


**Fig. 3.** The impact of radiative cooling paints on the direct cooling of the planet due to sending heat to deep space. (a) and (b): hourly energy throughout a single day in the summer and winter respectively, for relevant energy transfer processes. (c): direct cooling power on the earth system from RC roof, typ roof, and their difference.

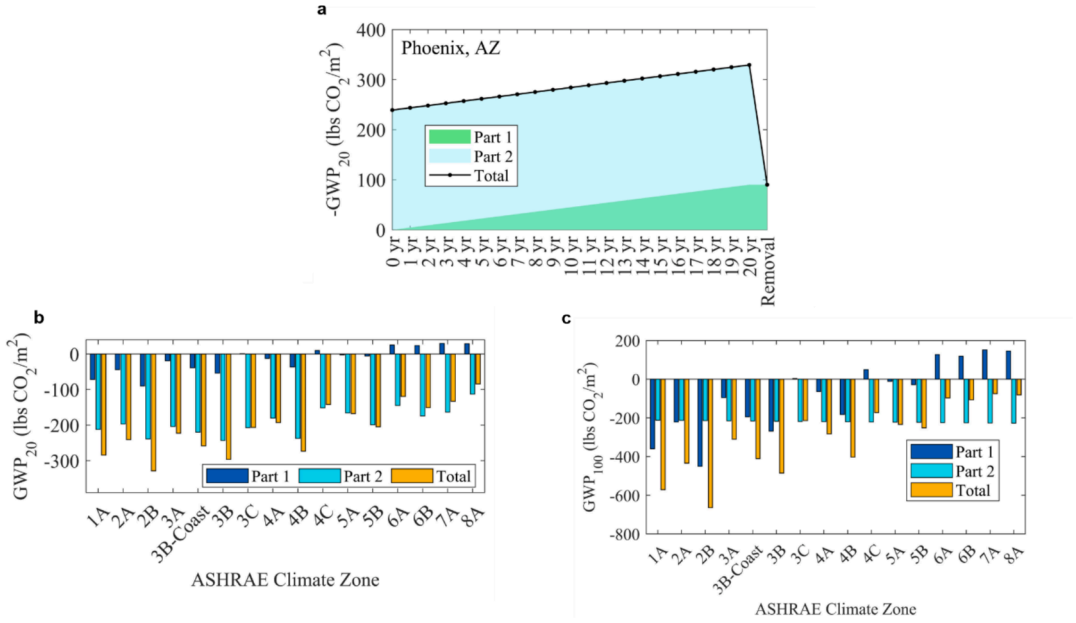


**Fig. 4.** The total results for the two parts, shown in two ways. (a): the effect of each of the mechanisms over 20 years of application. (b) and (c): $GWP_{20}$ and $GWP_{100}$ of each part as well as their total.

relative and total performance at reducing the heat on the earth system through GWP. Overall, it was observed that RC paints had a negative GWP, leaving a positive impact on the climate, for all US climate zones, with larger impacts in warm, dry areas, and a maximum of 665 lbs $CO_{2eq}$ removed per $m^2$ of paint applied, as shown in climate Zone 2B. Exact data for Fig. 4b-c are shown in Table S3 for reference.

## 4. Conclusion

A comprehensive analysis of the potential impact of $CaCO_3$ radiative cooling paints on climate change was provided, by considering two distinct mechanisms: reducing $CO_2$ emission at power plants due to HVAC energy savings in buildings painted with RC paints, and directly cooling our planet by sending heat into deep space. Ultimately the combination of the parts was found to have a positive impact on global climate, regardless of location within the US. Depending on the climate

**Table 2**
Summary of the different properties for Parts 1 and 2.

| | Effect on $CO_2$ or $CO_{2eq}$ Removal | | | |
|---|---|---|---|---|
| | Real or Equivalent $CO_2$ | Power of Action of $CO_2$ or $CO_{2eq}$ Removal | Effect of $CO_2$ or $CO_{2eq}$ Removal After Paint is Removed | Cooling Effect of the Earth Associated with $CO_2$ or $CO_{2eq}$ Removal |
| Part 1 – Reduced HVAC Loads | Real $CO_2$ | Cumulative over lifespan | Permanent | Cumulative, forever |
| Part 2 – Direct Cooling | $CO_{2eq}$ | Instant at paint installment | Vanish | Consistent, over the lifespan |

and building insulation, the impact of the paints was equivalent to the removal of up to 665 lbs $CO_{2eq}$ (considering $GWP_{100}$) from the atmosphere per $m^2$ of applied paint. The paints are most effective in hot/warm/mild and dry climates, and if used in these areas, less than 1 % coverage of the paint on the earth's surface would stop the global warming trend.

## CRediT authorship contribution statement

**Emily Barber Ruan:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Navdeep Vansal:** Data curation. **Ziqi Fang:** Methodology, Investigation, Data curation. **Yu-Wei Hung:** Conceptualization. **Joseph Peoples:** Validation, Methodology, Investigation, Conceptualization. **Rebecca Ciez:** Methodology. **Travis Horton:** Supervision, Project administration, Methodology. **Xiulin Ruan:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2025.115458.

## Data availability

All data and original codes mentioned in this study will be made available upon request from the research community.

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