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# ViBA Rad: Visualization and basic analysis tools for radiative cooling

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ABSTRACT

Radiative cooling (RC) is an emerging technology that can lower the temperature without external energy consumption via thermal radiation. To evaluate RC materials, there is a growing interest in considering not only the calculation of basic cooling flux but also external weather and regional characteristics. However, tools that can increase the convenience of dynamic analysis and visualization of radiative cooling have not yet been investigated. Here, we report ViBA Rad, a free and open software. This tool allows the user to perform (1) basic cooling flux calculation of RC, (2) time-domain outdoor simulation with external climate, and (3) representation of global cooling flux map.

Code metadata

| | |
|---|---|
| Current code version | *V1.0* |
| Permanent link to code/repository used for this code version | https://github.com/ElsevierSoftwareX/SOFTX-D-23-00341 |
| Code Ocean compute capsule | https://codeocean.com/capsule/4102935/tree |
| Legal Code License | LGPL-2.1 license |
| Code versioning system used | git |
| Software code languages, tools, and services used | *Python* |
| Compilation requirements, operating environments & dependencies | none |
| If available Link to developer documentation/manual | none |
| Support email for questions | dasol@yonsei.ac.kr, m.kim@gist.ac.kr |

## 1. Motivation and significance

Throughout history, cooling technologies have played a significant role, leading to the development of various innovative techniques. However, given the growing apprehensions about global warming, there is a focus on discovering environmentally friendly and energy-efficient approaches to cool down objects. Radiative cooling (RC) is a recently spotlighted technology that lowers temperature without external energy consumption [1–3]. Unlike other cooling methods that transfer heat to different areas on Earth [4,5], RC stands out by releasing heat directly to the universe. RC utilizes the natural coldness of the universe to dissipate excess heat from terrestrial objects into space via thermal radiation. Notably, the atmosphere is transparent in a specific range of wavelengths (8–13 μm), known as the atmospheric window (AW), which overlaps with the wavelength range emitted by objects at approximately 300 K on cloud-free days. This transparency allows thermal radiation from these objects to escape into space without being absorbed by the atmosphere. The RC can even cool down an object under direct sunlight by reflecting solar irradiance simultaneously [6–13].

A cooling flux has been widely used as a measure to quantitatively evaluate the cooling effect. The cooling flux includes four factors: heat release by blackbody radiation and heat gain from solar irradiance, the surrounding atmospheric radiation, and nonradiative heat exchange channels, namely, conduction and convention. That is, to accurately evaluate the RC effect, calculations must include not only optical characteristics (either simulated or measured optical spectrum) but also various surrounding conditions such as climate. Therefore, a tool that can predict the cooling fluxes from the given optical spectrum will be beneficial in assessing the RC effect and designing RC materials and consequently, significantly lower the barrier for researchers in wide fields. To fulfill such demands, web-enabled simulation tools and Python packages have been reported recently. While these tools support the evaluation of RC effect on thermophotovoltaic systems and multilayer nanostructures [14,15], respectively, current papers about

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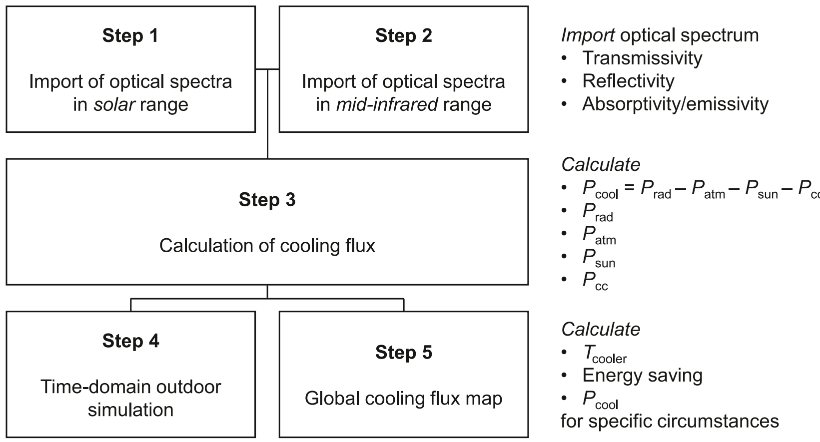


**Fig. 1.** Illustration of ViBA Rad architecture.

RC are trending towards more comprehensive calculations, such as time-domain simulation under dynamic weather conditions [16,17] and the evaluation of cooling flux at the global level [18,19].

To address these challenges and facilitate comprehensive simulations of RC, we propose the Python-based software: Visualization and Basic Analysis tools for radiative cooling (ViBA Rad). ViBA Rad not only includes the cooling flux calculation but also computes the time-evolution of the cooler's temperature under dynamic outdoor weather and evaluates cooling flux at the global scale across terrestrial regions. Furthermore, ViBA Rad is equipped with a user-friendly graphic user interface (GUI) to enhance accessibility. We aim to empower researchers and engineers in the field of RC to easily and efficiently analyze system performance and make informed design decisions.

## 2. Software description

### 2.1. Software architecture

The software consists of five steps as depicted in Fig. 1: steps 1 and 2 for the data import, step 3 for the cooling flux calculation, and steps 4 and 5 for the cooling effect evaluation under specific circumstances. First of all, steps 1 and 2 import the optical spectra of the given RC in the solar spectrum range ($0.3 < \lambda < 2.5$ μm) and mid-infrared (MIR) range ($2.5 < \lambda < 15$ μm), respectively. Users can import either the emissivity spectrum of the RC in both steps or the complete optical spectra including transmissivity, reflectivity, and emissivity in step 1 to assess the color appearance of the RC material. Additionally, ViBA Rad allows users to specify or import other environmental optical factors such as the solar spectrum and atmospheric transmittance in steps 1 and 2, respectively. In step 1, the type of solar spectrum can be selected among AM1.5 Direct, AM1.5 Global, and AM0 [20] or imported by the user. Meanwhile, in step 2, the atmospheric transmittance data can be selected as AM1.5 PW 1 mm [6,21] or imported by the user. The imported data is then used to calculate four cooling fluxes $P_{rad}$, $P_{atm}$, $P_{sun}$, $P_{cc}$ individually and the resultant cooling flux $P_{cool} = P_{rad} - P_{atm} - P_{sun} - P_{cc}$ in step 3.

Whereas steps 1 and 2 are indispensable for calculating the cooling flux in step 3, steps 4 and 5 are optional and independent of each other. Step 4 uses the optical spectra imported in steps 1 and 2 and the cooling fluxes calculated in step 3 to conduct a time-domain simulation under outdoor conditions. This step evaluates the time evolution of the RC temperature and the amount of energy saved. On the other hand, step 5 calculates the global cooling flux by incorporating global climate data, including the ambient temperature and solar irradiance. The calculation process in step 5 is similar to that in step 3 except that $P_{cool}$ is computed for the given RC temperature value at every spatial point.

### 2.2. Software functionalities

#### 2.2.1. General

ViBA Rad is composed of five components: the step panel, direction panel, status panel, toolbar, and main panel. The step panel includes five buttons, from which users can select each step of the process. The direction panel provides specific instructions and information for each step, assisting them in navigating the process and predicting the expected outcomes. The status panel displays users' actions. The toolbar contains eight buttons. *Info.* displays general information about ViBA Rad and its developers, *Load* enables the users to load previous inputs and settings, *Save* allows the users to save current inputs and settings to a text file for future use, *Import* opens a small window that connects to a file dialog to import data, *Plot* visualizes the results, *Clear* removes plots and inputs from the current step, *Clear all* clears plots and inputs from all steps, and *Exit* terminates ViBA Rad. Finally, the main panel includes input channels and display items where users can enter simulation parameters and settings and view the generated results. The detailed appearance of ViBA Rad and its functionalities for each part can be found in the user guide.

The functionalities of our software are explained in detail for each step below.

#### 2.2.2. Step 1

Step 1 contains two display items. *Spectrum in solar range* visualizes the optical spectra of the RC material, along with the spectrum of external sunlight (shaded). The optical spectra can either be emissivity or a combination of transmissivity, reflectivity, and emissivity.

The second display item, located in the bottom right corner next to the label "Color:", visualizes the color of the RC material under the given light source, allowing users to predict its appearance. The displayed color is that of the reflected light by obtaining reflectivity by subtracting the emissivity from unity if only emissivity is provided and is that of transmitted light if all three optical spectra are provided. Additionally, a pop-up window displaying the $(x, y)$ coordinates of the color in the CIE 1931 chromaticity diagram appears. Details of the representation of a color from spectral data can be found in [22,23].

#### 2.2.3. Step 2

Step 2 contains two display items. First, *Emissivity spectrum in MIR range* displays the user-imported emissivity spectrum of the RC material, along with the atmospheric transmittance (shaded). Meanwhile, *Directional emissivity* displays the average emissivity at $8 < \lambda < 13$ μm for various incident angles. This plot is available only when emissivity under angled incidence is received, i.e., when *emissivity data type* in *Import window (step 2)* is selected as *Angled incidence*. Note that while ViBA Rad accepts the emissivity spectrum under normal incidence, import of the angular emissivity spectrum is recommended to achieve accurate results (see Eqs. (1)–(3)).

#### 2.2.4. Step 3

Step 3 contains one display item and one setting box for data input. *Cooling flux* displays the cooling fluxes $P_{\text{cool}}$, $P_{\text{rad}}$, $P_{\text{atm}}$, $P_{\text{sun}}$, $P_{\text{cc}}$ calculated using the following equations:

$$P_{\text{rad}} = 2\pi \iint \sin\theta \cos\theta I_{\text{BB}}(T, \lambda)\epsilon(\lambda, \theta)\, d\lambda\, d\theta \tag{1}$$

$$P_{\text{atm}} = 2\pi \iint \sin\theta \cos\theta I_{\text{BB}}(T_{\text{amb}}, \lambda)\epsilon_{\text{amb}}(\lambda, \theta)\epsilon(\lambda, \theta)\, d\lambda\, d\theta \tag{2}$$

$$P_{\text{sun}} = \int I_{\text{AM}}(\lambda)\epsilon(\lambda, \theta_{\text{sun}})\, d\lambda \tag{3}$$

$$P_{\text{cc}} = h_{\text{cc}}(T_{\text{amb}} - T) \tag{4}$$

where $\theta$ indicates the incident angle, $T$ is the temperature of the RC material, $T_{\text{amb}}$ is the ambient temperature, $\epsilon$ is the emissivity of the RC material, $\epsilon_{\text{amb}} = 1 - t(\lambda)^{1/\cos\theta}$ is the emissivity of ambient, $t(\lambda)$ is the atmospheric transmittance spectrum, and $I_{\text{BB}}$ is the spectral irradiance of a black body. Evaluation of the cooling power under various climate or outdoor conditions is allowed by importing the atmospheric transmittance of the specific circumstances or by adjusting $h_{\text{cc}}$ [24]. To compute the cooling fluxes from the given discretized data, the summation is used instead of the integral as follows:

$$\int d\lambda \rightarrow \sum_{i=1}^{i=N-1} (\lambda_{i+1} - \lambda_i), \tag{5}$$

$$\int d\theta \rightarrow \sum_{i=1}^{i=N-1} (\theta_{i+1} - \theta_i), \tag{6}$$

and the summation with respect to $\lambda$ and $\theta$ runs from the given wavelength and angular range, respectively. If the emissivity spectrum is only provided under normal incidence, $\theta$ is discretized from 0° to 90° with 10° step and $\epsilon(\lambda, 0°)$ is used as $\epsilon(\lambda, \theta)$ for all $\theta$ values. The parameters required for the cooling flux calculations, such as the RC temperature range, ambient temperature, and the coefficient of heat conduction and convection, are received in the setting box in step 3.

#### 2.2.5. Step 4

Step 4 contains two display items and two setting boxes for each display item. First, *Time-domain simulation* displays the user-imported solar irradiance (shaded) and ambient temperature, along with the calculated RC temperature. The nonzero $P_{\text{cool}}$ from step 3 implies that the RC material is not in thermal equilibrium and undergoes dynamic temperature changes. In addition, the solar irradiance used in Eq. (3) is an instantaneous value, generally obtained under direct sunlight, but the actual solar irradiance varies over time. Therefore, by considering the time-varying solar irradiance and ambient temperature, the time evolution of the RC temperature can be computed by

$$T_{i+1} = T_i - \frac{P_{\text{cool}}}{C}(t_{i+1} - t_i) \tag{7}$$

where $t$ denotes time, the subscript $i$ is the index of each time step, and $C$ is the heat capacitance. To conduct this simulation, the setting box receives the time range for which the time-domain simulation is conducted and the heat capacitance of the RC material or that of the system that includes the RC material and the object to be cooled. For user convenience, the software provides access to solar irradiance and ambient temperature data measured by the Korea Meteorological Administration in Seoul from July to August of either 2021 or 2022 [25]. Users can select *Seoul (2021 Jul–Aug)* or *Seoul (2022 Jul–Aug)*, in *Outdoor weather*. Alternatively, the solar irradiance and ambient temperature data from other regions and times can be imported by users using a text file. The initial temperature of the RC material can also be entered in the same setting box.

If the RC temperature is lower than the ambient temperature, it indicates that energy that would have been used to cool down the RC material has been saved. The surplus cooling flux is plotted in *Energy saving* and its time integral, i.e., the surplus cooling energy per unit area, over the given time range is displayed as a text below *Energy saving*.

#### 2.2.6. Step 5

Step 5 contains three display items and one setting box. Because the cooling power of a given RC material is highly dependent on the local climate and weather conditions, the cooling effect may differ in various terrestrial regions. To address this issue, ViBA Rad provides the cooling flux calculation on a global scale. Two display items entitled *Temperature* and *Solar irradiance* visualize the spatial distribution of those quantities imported by users. Below these two colormaps is a setting box that receives the RC temperature. Then the third display item *Global cooling flux* shows the calculated cooling flux at each spatial point and provides insights into the cooling effect of the RC material across different regions, considering the local climate and weather conditions. In this computation, parameters such as $T_{\text{amb}}$ and $h_{\text{cc}}$ are set to the same values as those received in step 3.

## 3. Illustrative examples

### 3.1. Cooling effect prediction

To demonstrate the computational capabilities of ViBA Rad, the spectrum of an ideal cooler that exhibits unity reflection in the solar spectral region and unity emissivity at any incident angle in the AW is used. In step 1, We import the complete optical spectra (transmissivity, reflectivity, and emissivity) of the cooler (Fig. 2a) and select the type of solar spectrum as AM1.5 Global. The transmitted color of the cooler under the selected source can be visualized. In step 2, the averaged emissivity spectrum in the MIR region and the directional emissivity (averaged in the range of 8–13 μm) are visualized as shown in Fig. 2b.

In step 3, to evaluate the cooling effect, we set RC temperature range from 298 K to 328 K with a step size: 1 K, ambient temperature as 303 K, and conduction/convection coefficient as 6 W/m$^2$. The total cooling flux ($P_{\text{cool}}$) and individual terms ($P_{\text{rad}}$, $P_{\text{atm}}$, $P_{\text{sun}}$, $P_{\text{cc}}$) of the ideal cooler are then computed (Fig. 3a). In addition, the total cooling flux is compared with that of a broadband emitter (Fig. 3b). The cooling flux of broadband and selective emitters, with nonradiative heat transfers ignored ($h_{\text{cc}}$ = 0 W/m$^2$K) and included ($h_{\text{cc}}$ = 6 W/m$^2$K), agree well with the previously reported tendency: selective emitters generally provide a higher cooling flux below ambient, while broadband emitters are more favorable at or above ambient temperature [1,26].

### 3.2. Dynamic analysis of cooling effect by surrounding climate

To simulate the time-evolution of the cooler's temperature, we set the time cycle from 0 h to 24 h with a step size of 0.5 h, the heat capacitance as $10^5$ JK$^{-1}$, and the initial temperature of RC to be equal to the ambient temperature. The built-in outdoor weather data of Seoul (15th Jul, 2022) is selected. The imported data and the calculated RC temperature are plotted in Fig. 3c. Fig. 3d shows the surplus cooling energy per area under the imported weather conditions over time when the target temperature for energy saving calculation is set to ambient.

### 3.3. Visualization of global cooling flux map

To evaluate the cooling effect on a global scale, the database of Earth skin temperature and solar irradiance at each spatial point in July are acquired from the NASA Langley Research Center (LaRC) Power project and imported in ViBA Rad. For demonstration, the target temperature is set as the ambient temperature, i.e., Earth skin temperature. The global cooling flux is then computed at each location (Fig. 4).

Considering that the Earth skin temperature and solar irradiance are the average values over the entire month of July including both day and night, the global cooling flux is also an averaged value and may differ from that at a specific time. Global energy saving of the month can be estimated from this global cooling flux by multiplying it with the corresponding time quantities, for example, $\frac{60\times60\times24s}{1\text{ day}} \times \frac{31\text{ days}}{1\text{ month}}$ at July.

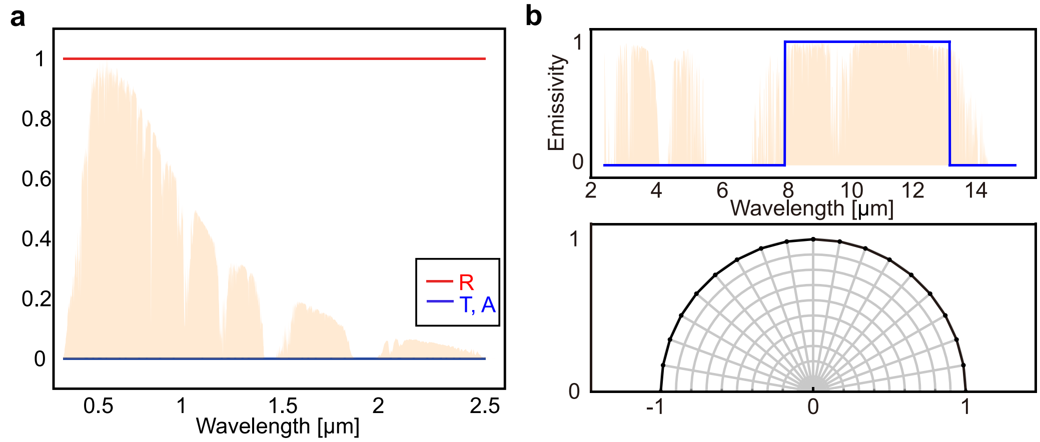


**Fig. 2.** (a) User-imported transmissivity, reflectivity, and emissivity spectra of the ideal cooler in the solar spectrum range. (b) The averaged emissivity of the ideal cooler in the MIR region and directional emissivity.

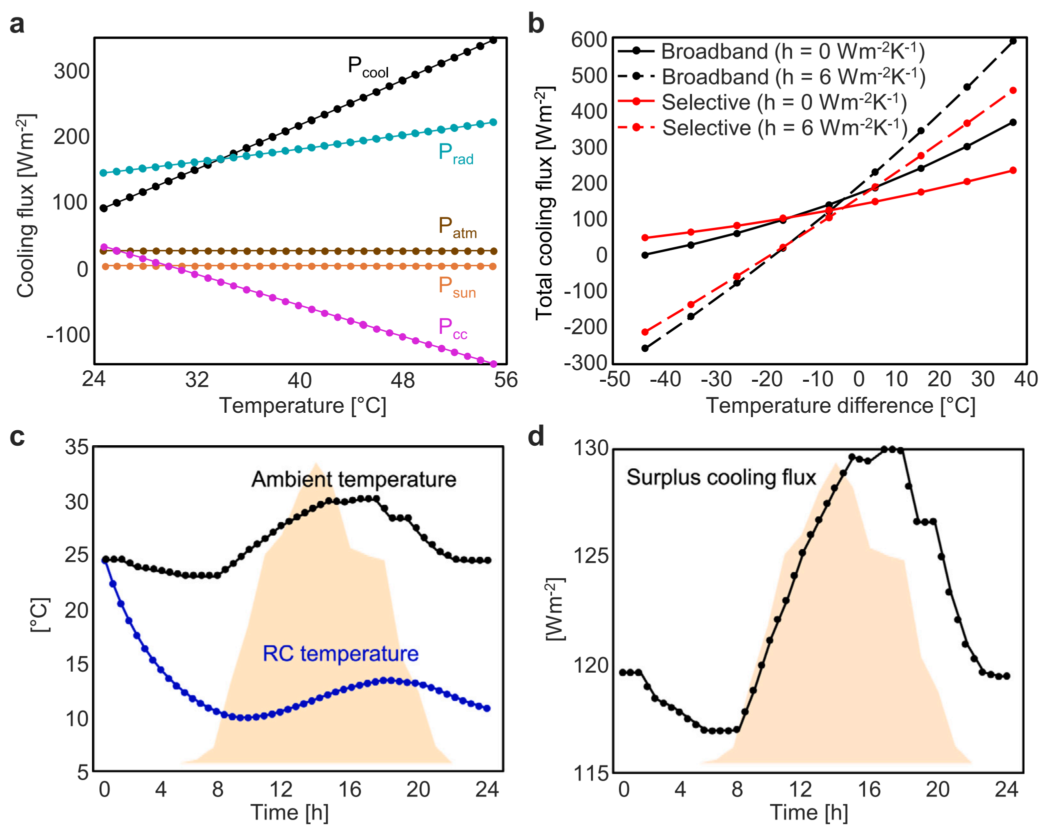


**Fig. 3.** (a) Calculated cooling flux. (b) The cooling flux of selective (red) and broadband (black) emitters with nonradiative heat transfers ignored (solid) and included (dashed). (c) User-imported data and (d) surplus cooling flux in the time domain. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

## 4. Impact

We present ViBA Rad, a free and user-friendly software that evaluates the cooling effect of RC materials. Given the interdisciplinary nature of RC studies spanning material science, thermal physics, chemistry, and optics (Eqs. (1)–(4) and (7)), predicting RC effects can be challenging for researchers from diverse fields. ViBA Rad aims to bridge this gap by converting the optical spectra to cooling fluxes, simulating time-domain behavior under dynamic outdoor conditions, and mapping the global cooling effects in different terrestrial regions. With its extensive coverage of computations and intuitive GUI, ViBA Rad serves as a powerful tool, facilitating RC research collaboration among material, chemistry, environmental researchers, and those without extensive programming experience.

## 5. Conclusions

ViBA Rad is a free and open-source software written in Python for evaluating the cooling effect of RC. Users can easily calculate cooling flux, simulate time-domain outdoor scenarios, and evaluate the global cooling effect by simply importing their simulated or measured optical spectra of RC materials. This software assists researchers in designing and testing RC candidates before conducting experiments

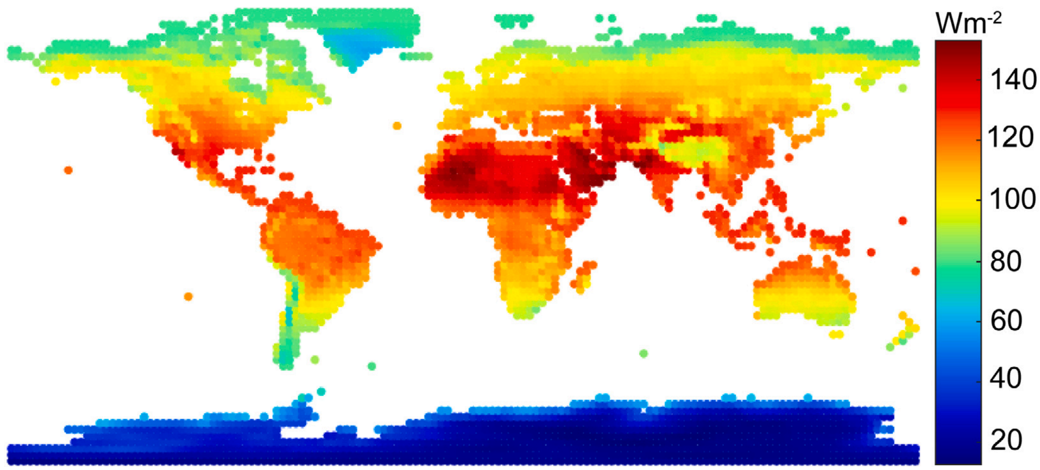


**Fig. 4.** Global cooling flux map generated by ViBA Rad.

and also provides theoretical support for experimentally confirmed RC effects. A major advantage of ViBA Rad is the user convenience ensured by GUI and the wide coverage of computations to address various conditions. To demonstrate its capabilities, we provide an example usage of ViBA Rad by reproducing the cooling effect of an ideal RC material that perfectly reflects the solar spectrum and emits in the AW. Besides the ideal RC, a case study of a practical RC that is visibly transparent and emissive in the AW is included in the user guide. While this software does not encompass every detail of outdoor experiments due to their time-varying nature, it offers a simplified model that intuitively explains the cooling effect of the RC material. We expect our software to be a widely adopted tool for evaluating RC effects, supporting fellow researchers, and contributing to the progress of the RC field. Furthermore, incorporating theoretical approaches, such as effective medium theory or rigorous coupled-wave analysis, to compute the optical spectra of RC using this software would also be promising.

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## 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.

## Data availability

We have shared our data in the public repository.

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