

Article

Climate-Based Assessment of Radiative Cooling Potential Using Energy Simulation and Atmospheric Indicators

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Abstract

Rising global temperatures are driving an urgent need for buildings that consume less energy while maintaining comfort. Cooling demand is surging worldwide, yet conventional air-conditioning remains energy-intensive and carbon-heavy. Against this backdrop, radiative cooling materials have gained attention as a passive solution capable of reflecting incoming solar radiation while emitting thermal energy to the sky. This study aims to establish a climate-informed framework that quantitatively predicts the energy-saving potential of façade-integrated radiative-cooling materials across diverse East Asian climates. By synergizing hour-by-hour building-energy simulation with three novel atmospheric suitability indices, we provide a transferable methodology for selecting and optimizing passive cooling strategies at urban and regional scales. Three façade configurations were tested, i.e., a conventional absorptive surface, a common radiative cooling surface, and an idealized high-reflectance and high-emissivity surface. The results show that the ideal case can reduce wall surface temperatures by up to 20 °C, suppress diurnal heat flux swings by 60–80%, and cut annual cooling demand by 5–80 kWh per square meter, depending on climate conditions. To generalize these findings, three new indices—the Weather Structure Index, Diurnal Temperature Index, and Composite Climate Applicability—were proposed. Regression models with R^2 values above 0.9 confirm the Composite Climate Applicability index as a robust predictor of energy-saving potential. The outcomes demonstrate that radiative cooling is not only highly effective in hot, humid regions but also unexpectedly beneficial in clear, cold climates, offering a practical, climate-informed framework for advancing low-carbon building design.



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Keywords: radiative cooling materials; building energy simulation; wall surface temperature; energy use intensity; climate adaptability

1. Introduction

The escalating challenges of global warming and climate instability have positioned the built environment at the forefront of sustainable development discourse. Buildings account for a substantial share of global energy consumption and carbon emissions. According to the International Energy Agency (IEA), the building sector is responsible for approximately 30% of global final energy demand and 28% of energy-related CO₂ emissions, making it a critical focus of carbon-neutrality strategies [1,2]. Among various end uses, space cooling has become one of the fastest-growing sources of electricity demand, particularly in rapidly

urbanizing regions with hot climates. Driven by rising incomes and intensifying climate extremes, global demand for cooling could triple by 2050 if current trends continue [3–5].

Conventional cooling technologies, such as air-conditioning systems and mechanical ventilation, are highly energy-intensive and contribute to the urban heat island effect, grid stress, and indirect emissions [6,7]. These challenges have motivated the development of passive cooling technologies capable of reducing thermal loads without active energy input. Among them, radiative cooling (RC) stands out for its ability to operate autonomously, providing a self-sustained and low-maintenance solution for mitigating building overheating.

Radiative cooling relies on a fundamental thermodynamic principle: all objects emit thermal radiation, and if their emissivity aligns with the atmospheric transparency window in the infrared range (8–13 μm), they can dissipate heat directly into outer space, even under direct solar illumination [8–10]. The Earth's atmosphere is selectively transparent within this spectral band, allowing thermal photons to escape without absorption by greenhouse gases such as water vapor and carbon dioxide. At the same time, RC materials are designed to reflect most incoming solar radiation (0.3–2.5 μm), thereby minimizing solar heat gain—a dual mechanism often referred to as “cooling by reflection and emission” [1,11,12].

The performance of RC materials is determined by their spectral selectivity. Optimal coatings exhibit high solar reflectance (>90%) and high thermal emittance (>90%) within the atmospheric window [13,14]. Various architectures have been developed to meet these requirements, including multilayer dielectrics, polymer–metal hybrids, and porous nanocomposites [15,16]. Theoretical studies suggest that under ideal clear-sky conditions, radiative-cooling surfaces exposed to outdoor environments can achieve surface temperatures 5–15 $^{\circ}\text{C}$ lower than the outdoor ambient air temperature (typically measured at 1.5 m height), with net cooling power often exceeding 100 W/m^2 [1,17,18]. Importantly, RC can operate both during the day and at night, provided that the sky remains clear and emissivity is high in the relevant wavelength range.

Experimental investigations have confirmed these theoretical predictions under a variety of climatic conditions. Sub-ambient daytime cooling of around 5 $^{\circ}\text{C}$ has been demonstrated using multilayer photonic structures, while nanoporous polymer coatings have achieved net cooling powers approaching 100 W/m^2 under full sunlight [4,17]. Large-scale, low-cost hybrid films have also maintained stable radiative heat rejection in both arid and humid climates [19]. These results highlight the potential of RC materials not only for improving building energy efficiency but also for wider applications in thermal management, including solar panels, vehicles, and water systems.

Beyond thermal comfort, the carbon mitigation potential of RC is increasingly emphasized. By reducing the operational load on air-conditioning systems, radiative cooling contributes to peak-load reduction, lower electricity consumption, and reduced indirect emissions—especially in regions where electricity generation still depends heavily on fossil fuels [15,20]. Photovoltaic systems generate renewable electricity but often raise module temperatures, increasing building cooling loads and requiring active heat removal to sustain conversion efficiency [18]. Radiative-cooling materials, by contrast, provide passive thermal relief: they reflect solar gain and emit long-wave infrared radiation through the atmospheric window, directly reducing surface and indoor temperatures without energy input [21]. Consequently, RC aligns with climate-resilient architecture and net-zero strategies while offering long-term durability with no moving parts or refrigerants.

Nevertheless, the effectiveness of radiative cooling in practical applications is strongly influenced by local climatic conditions, including sky clearness, humidity, air temperature, and diurnal temperature range. The atmospheric window can be partially or completely obstructed under cloudy or polluted conditions, thereby limiting emissive efficiency. Al-

though the physical mechanisms of RC are well understood, its performance across different climate zones remains a key challenge for large-scale deployment. This underscores the importance of integrating climate science, material engineering, and building physics to fully realize the potential of radiative cooling as a mainstream passive cooling solution.

In response, this study develops a new climate-informed performance assessment model, the Radiative Cooling Applicability (RCA) model, to evaluate the suitability of RC materials across diverse cities. The RCA model is built upon three climate indicators: (1) the Weather Scale Index (WSI), which reflects sky clarity through the balance of clear, partly cloudy, and overcast hours; (2) the Diurnal Temperature Index (DTI), quantifying the intensity of daily temperature swings; and (3) Normalized Sunshine Hours (NSH), representing solar exposure potential. Together, these indices offer a composite view of radiative cooling potential under real atmospheric dynamics.

To validate this model, we conducted a comparative EnergyPlus V22-1-0 simulation of eleven representative cities—five from China and six from Japan—covering distinct building thermal zones and climatic typologies. Beyond material assessment, the simulation framework demonstrates how high-resolution building-energy modeling can reliably predict post-retrofit demand, rank retrofit packages, and guide climate-responsive design decisions for both new and existing stock. This positions EnergyPlus not merely as a validation tool, but as a scalable engine for cost-optimal, low-carbon renovation strategies tailored to local climate contexts [22,23].

Three types of external wall materials were modeled: a conventional absorptive wall, a moderately reflective wall, and an idealized high-reflectance/emissivity surface. Outputs included hourly surface temperature, heat flux, and annual cooling energy demand. The energy savings achieved by IRC compared to NRC reached over 50% in several high-insolation cities such as Shenzhen and Naha, confirming the practical potential of RC technologies [24,25].

By integrating physical simulation with climatological indices, the RCA model enables a location-specific evaluation of passive cooling strategies. This approach bridges the gap between material science, environmental data, and building energy modeling. The results provide actionable insights for urban planners, architects, and policymakers to prioritize radiative cooling deployment where it is most effective—supporting the global shift toward resilient and low-carbon buildings.

2. Methodology

2.1. Research and Analytical Framework

The methodological framework of this study, shown in Figure 1, establishes a structured linkage between climatic conditions, building thermal performance, and the applicability of radiative cooling materials. The process is divided into four stages, integrating meteorological datasets with building energy simulation and climate-based evaluation to derive robust insights into regional suitability. The first stage involves microclimate data acquisition and façade-level model verification. Boundary conditions—outdoor air temperature, relative humidity, solar radiation, and wind speed—were collected for eleven representative cities across the thermal climate zones of China and Japan. These data were used to calibrate and validate the simulation model by comparing simulated and measured outdoor wall-surface temperatures, with geometry and parameter settings adjusted to ensure consistency with the observed envelope thermal behavior. Indoor environmental variables and thermal-comfort indices are not included in this verification step, as the present study focuses on the external radiative-cooling performance of façade materials and their climate-dependent energy implications. This step ensures the reliability of the computational platform for subsequent assessments.

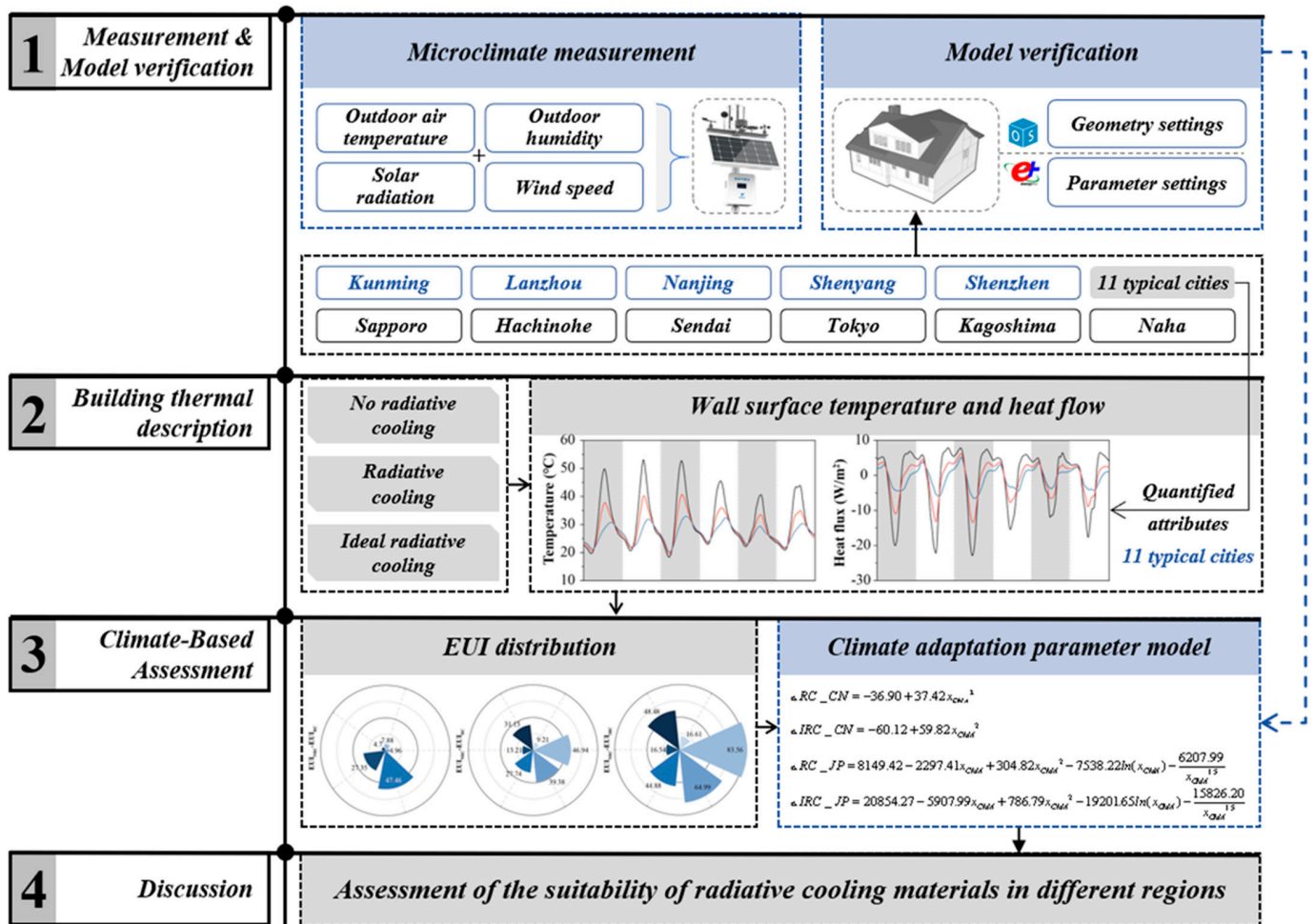


Figure 1. Framework of climate-based assessment of radiative cooling potential.

The second and third stages address the building thermal response and climate-based assessment. Three façade configurations were considered: a conventional absorptive surface without radiative cooling, a standard radiative cooling surface, and an idealized high-reflectance and high-emissivity surface. Hourly simulations of wall surface temperature and heat flux were performed to quantify thermal performance across all cities. The results were coupled with climate indicators, including the Weather Scale Index and Diurnal Temperature Index, to construct a parameter model capturing the influence of atmospheric conditions on radiative cooling effectiveness. The final stage conducts the applicability analysis, synthesizing simulation outputs and climate-model results to evaluate the regional suitability of radiative cooling strategies.

It should be noted that this study focuses on façade-level thermal and energy performance. Although building-energy simulation codes can also assess indoor comfort indices such as PMV or adaptive models, these were intentionally excluded to maintain methodological clarity and consistency across climates. The validated framework nevertheless provides a foundation for future research coupling radiative-cooling performance with indoor comfort assessment. By linking material properties with climatic variability, the framework provides a rigorous basis for identifying favorable deployment contexts and guiding energy-efficient building design in diverse environments.

2.2. City and Climate Zone Selection

A rigorous evaluation of radiative cooling technologies requires case studies that reflect the diversity of building thermal zones [21]. Both China and Japan employ standardized

climatic classifications that link outdoor meteorological conditions to indoor heating and cooling demands, providing a robust framework for selecting representative cities, as shown in Figure 2.

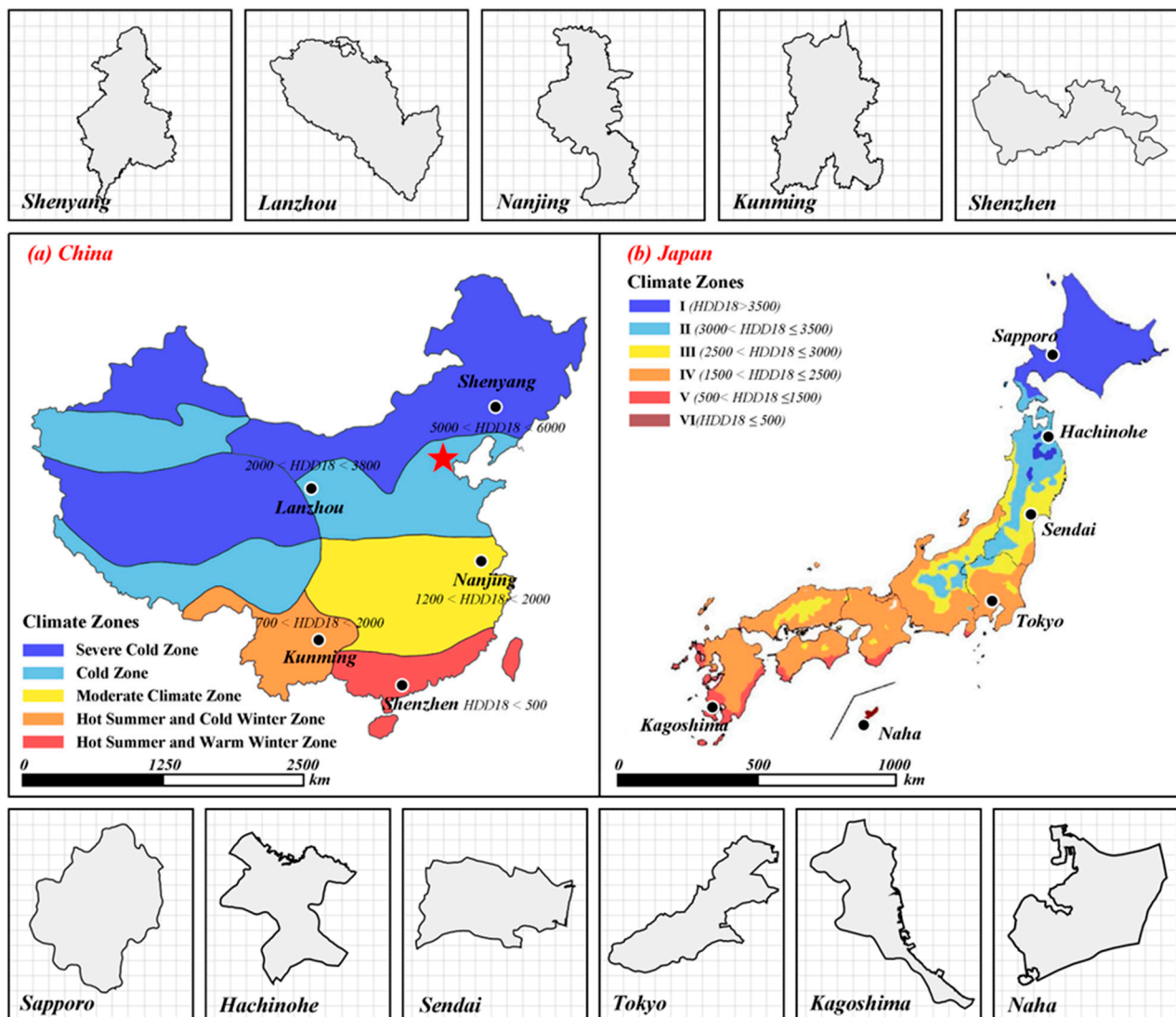


Figure 2. Climate zones and selected representative cities in China and Japan.

Figure 2 presents the thermal climate zoning and the spatial distribution of the study sites in China and Japan. In China, the national building energy standard defines five thermal climate zones: the severe cold zone, the cold zone, the hot-summer and cold-winter zone, the hot-summer and warm-winter zone, and the moderate climate zone. To capture these categories, five representative cities were selected: Shenyang for the severe cold zone, Lanzhou for the cold zone, Nanjing for the hot-summer and cold-winter zone, Kunming for the moderate climate zone, and Shenzhen for the hot-summer and warm-winter zone. These cities were chosen because they are widely recognized benchmark locations in thermal zoning studies and typify the heating-dominated climates of the north as well as the cooling-dominated climates of the south.

In Japan, thermal zoning is based primarily on heating degree days, resulting in six distinct regions ranging from cold in the north to tropical in the south. To ensure comprehensive climatic coverage, six cities were selected: Sapporo in the northern cold region, Hachinohe and Sendai in intermediate temperate regions, Tokyo representing a densely populated warm-humid metropolitan climate, Kagoshima in the subtropical zone,

and Naha in the tropical zone. This selection reflects both the strong heating demand of northern Japan and the significant cooling demand of its southern regions.

Taken together, these eleven cities span the full spectrum of thermal zones in East Asia. Their systematic selection based on national zoning frameworks ensures that the subsequent assessment of radiative cooling potential is grounded in scientifically defined climatic contexts and is representative of both heating- and cooling-dominated environments.

2.3. Building Model Configuration and Validation

The building energy simulation model was developed in EnergyPlus to investigate the thermal performance of radiative cooling materials under representative climatic conditions. The simulation framework follows the dynamic heat-balance methodology consistent with ISO 13790 for calculating space cooling and heating loads, while the normalization of energy-use results and the derivation of energy-use intensity indicators are based on the principles defined in EN 50016 [26,27]. These alignments ensure that the modeling process and results are comparable with internationally recognized energy-performance standards, while the proposed CMA framework further extends their applicability to cross-climatic evaluation of radiative-cooling façades.

Dynamic results correspond to a representative clear-sky week in mid-summer (15–20 July) for each city, when cooling demand and solar irradiance reach their seasonal maximum. This selection enables a consistent comparison of façade-level thermal behavior across different climates.

Three types of façade surfaces were considered to capture different radiative cooling capabilities. In all configurations, the radiative-cooling treatment was applied only to the external opaque wall surfaces of the perimeter zone, while internal partitions, floors, ceilings, and the roof were kept unchanged. The first represents a conventional absorptive wall with low solar reflectivity and high infrared emissivity, corresponding to the non-radiative cooling case. The second is a typical reflective coating material with moderately high solar reflectivity and stable emissivity, representing the common radiative cooling case. The third is an idealized configuration with near-unity reflectance and emissivity, used to explore the upper limit of cooling potential. The optical parameters of these materials are summarized in Table 1, which provided the fundamental input for assessing the impact of surface spectral properties on building thermal response [2,7].

Table 1. Material properties of non-radiative, radiative, and ideal radiative cooling surfaces.

Material Type	Solar Reflectivity (α)	Infrared Emissivity (ϵ)	Description
NRC (Non-RC)	0.3	0.9	Conventional absorptive wall surface
RC (Common RC)	0.8	0.9	Typical reflective coating material
IRC (Ideal RC)	0.99	0.97	Idealized high-reflectance/emissivity RC surface

To ensure the reliability of the simulations, the model was validated against experimental outdoor wall-surface temperature measurements across four representative seasons. As illustrated in Figure 3, the simulated temperature profiles reproduce both the diurnal variation and the peak–valley amplitudes observed in the measurements, indicating strong consistency between prediction and observation. This validation therefore confirms the accuracy of the façade-level thermal response, while indoor microclimatic conditions and comfort indices are intentionally left outside the scope of the present analysis. To further quantify this agreement, two statistical indicators were employed: the Root Mean Square

Error (RMSE), which measures the average deviation between simulated and measured values, and the Coefficient of Variation of RMSE (CV), which normalizes the error relative to the mean of the measured data. They are defined as follows:

$$RMSE = \sqrt{\frac{1}{n} \sum_{t=1}^n (M_t - S_t)^2} \quad (1)$$

$$CV_{(RMSE)} = \frac{RMSE}{\bar{M}_t} \times 100\% \quad (2)$$

where M_t is the measured value at time step t , S_t is the simulated value, and n is the total number of time steps.

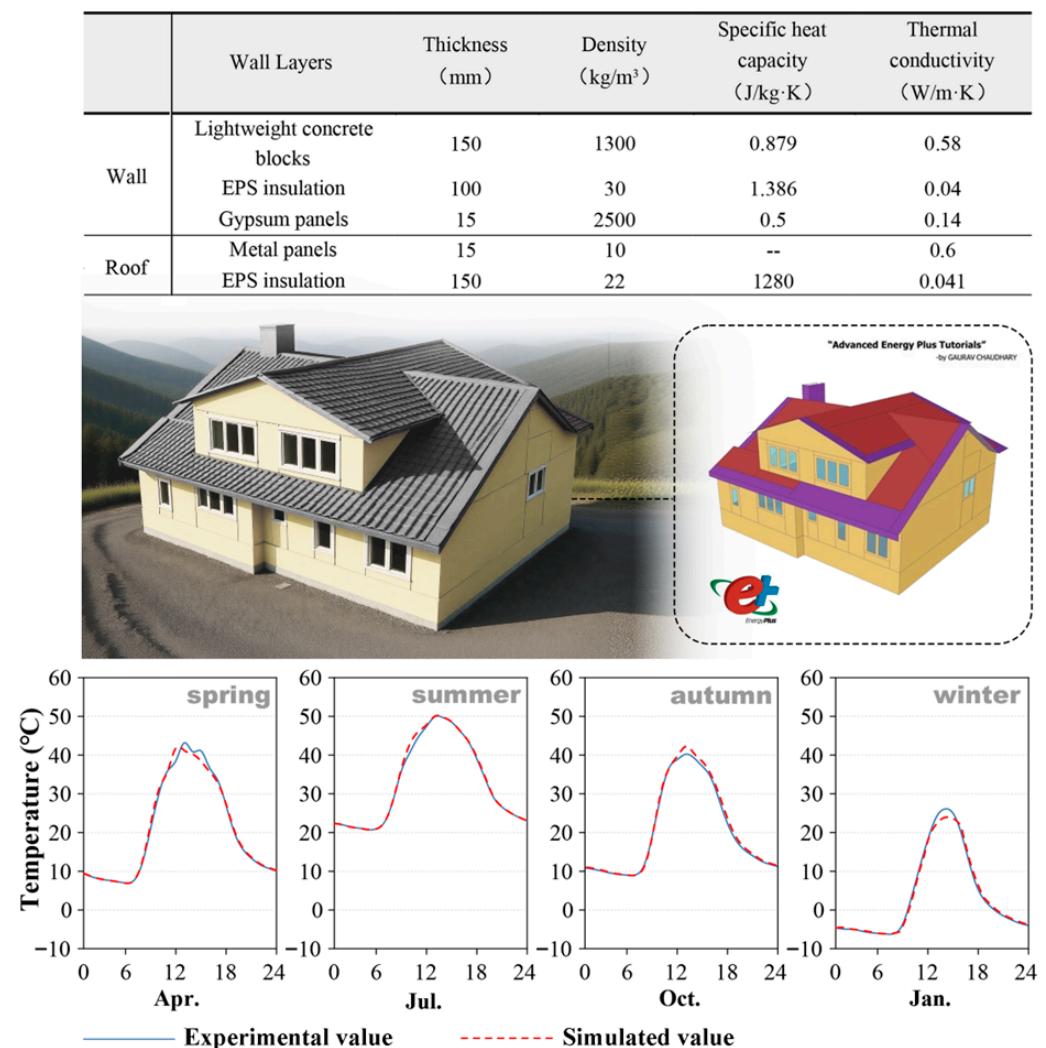


Figure 3. Building model configuration and validation of simulated thermal performance.

Validation indicates that the RMSE varied seasonally from 1.1 °C (summer) to 2.4 °C (winter), while the Coefficient of Variation, calculated as RMSE divided by the mean measured surface temperature in °C, remained between 3% and 7%. The slightly higher summer RMSE is attributed to intense solar irradiance and rapid surface-temperature transients, whereas the lower winter RMSE reflects more stable boundary conditions. Both metrics fall well within the acceptance limits for whole-building energy-simulation studies, lending confidence that the model faithfully reproduces envelope thermal dynamics and can therefore be used to evaluate radiative-cooling performance across climates.

Furthermore, the calibrated EnergyPlus model satisfies the ASHRAE Guideline 14 validation criteria for hourly calibration data, where $CV \leq 30\%$ and $NMBE \leq 10\%$. The obtained CV values of 3–7% and RMSE values of 1.1–2.4 °C confirm that the model demonstrates strong agreement between simulated and measured results, ensuring high reliability and accuracy for subsequent analyses.

3. Simulation Results

3.1. Variation in Wall Temperature

The hourly variation in outdoor wall-surface temperature under different radiative cooling configurations was simulated for eleven representative cities in China and Japan. The results are presented in Figure 4 for the five Chinese cities and in Figure 5 for the six Japanese cities, with detailed temperature ranges summarized in Table 2.

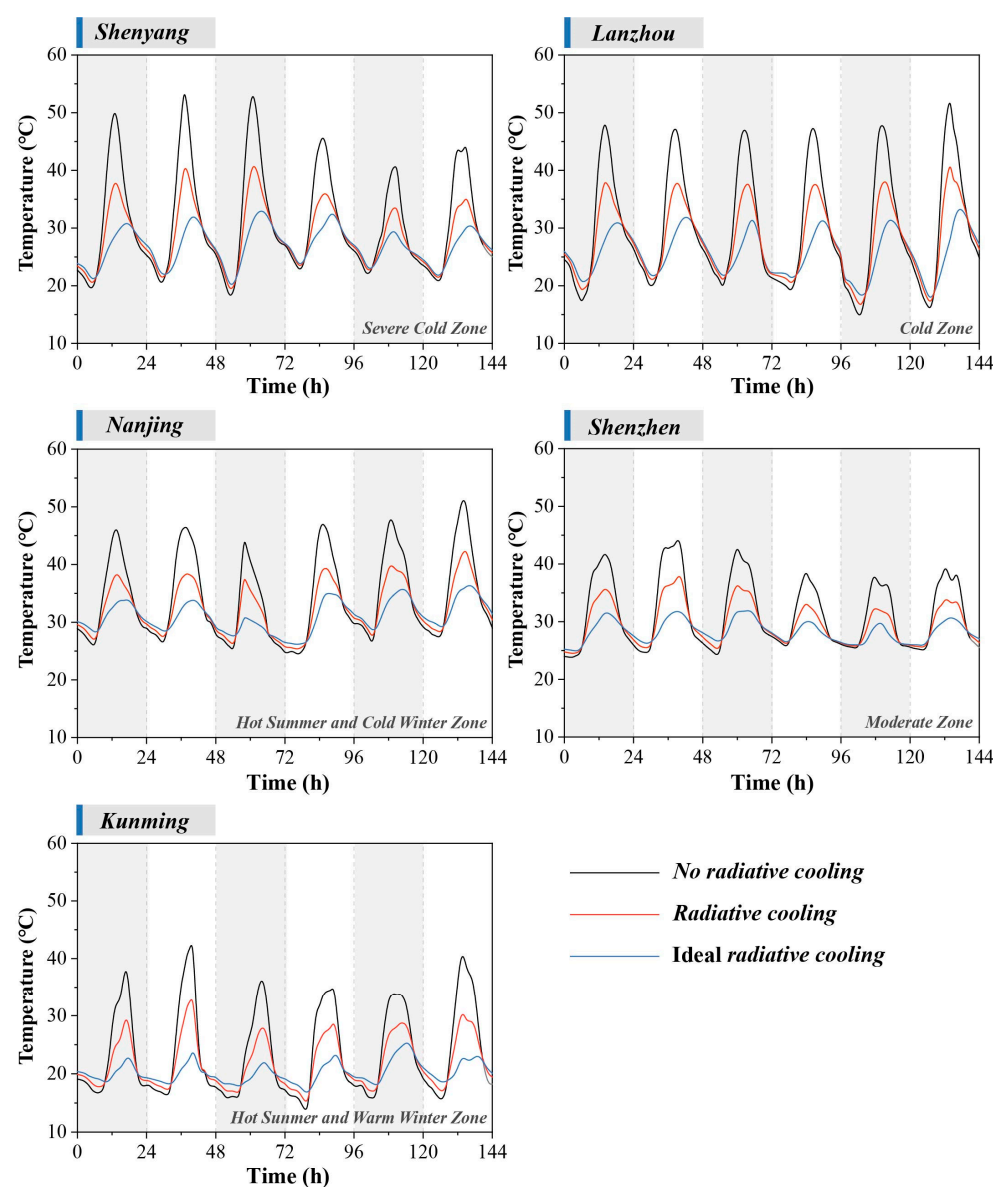


Figure 4. Hourly variation in outdoor wall-surface temperature under different radiative cooling configurations in five representative Chinese cities.

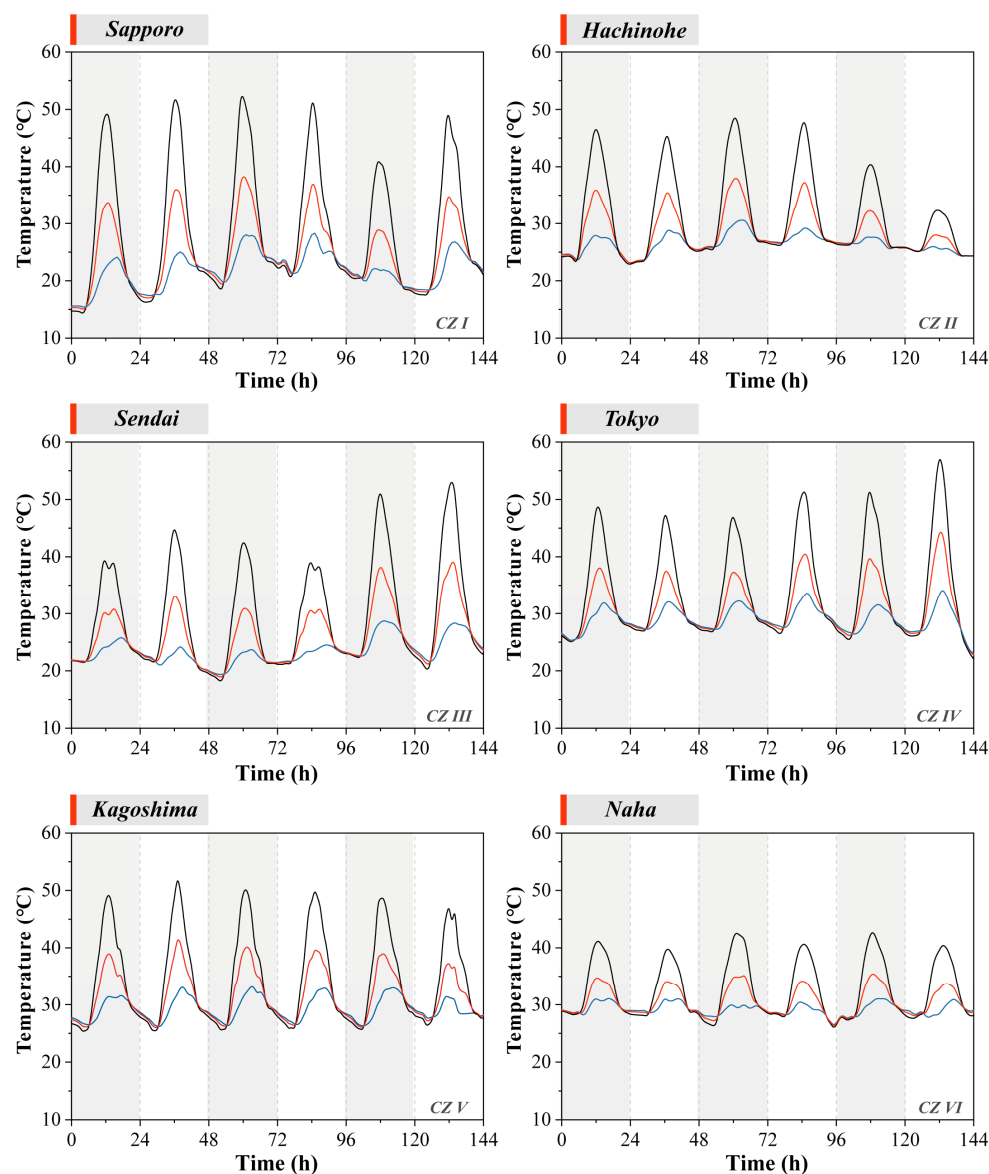


Figure 5. Hourly variation in outdoor wall-surface temperature under different radiative cooling configurations in six representative Japanese cities.

Table 2. Statistical range of simulated outdoor wall-surface temperature under NRC, RC, and IRC configurations.

City	Peak Temperature Range (°C)			Average Temperature Range (°C)		
	NRC	RC	IRC	NRC	RC	IRC
Shenyang	43.2~53.3	34.4~40.7	29.5~32.9	28.5~32.3	27.0~29.4	26.4~28.1
Lanzhou	43.6~52.5	32.9~41.4	28.3~33.3	27.9~30.8	25.7~28.8	23.7~26.8
Nanjing	46.5~53.1	38.3~43.1	33.1~36.6	31.1~36.3	29.8~35.7	28~5~28.8
Shenzhen	38.4~46.0	32.4~38.9	29.9~37.8	30.1~33.2	28.2~31.1	27.0~29.2
Kunming	34.2~44.2	27.9~33.8	22.0~25.3	22.6~25.3	20.8~22.8	19.4~21.4
Sapporo	45.2~57.0	32.2~40.8	27.2~28.4	27.8~29.5	24.3~25.1	22.0~21.6
Hachinohe	42.9~50.8	35.9~39.5	29.3~30.8	30.9~31.4	28.2~28.6	26.3~26.5
Sendai	45.2~54.3	35.5~39.8	28.1~28.8	28.6~30.1	25.8~26.4	23.3~23.5
Tokyo	15.2~57.8	37.5~44.4	31.5~34.1	33.2~34.7	30.7~31.3	28.9~29.1
Kagoshima	42.9~52.6	37.0~41.7	32.3~33.3	33.9~34.9	31.3~31.9	29.2~29.4
Naha	40.5~43.0	34.4~35.7	30.9~31.0	32.2~33.0	30.3~30.8	29.1~29.4

Across all locations, a consistent trend is observed, i.e., conventional absorptive surfaces exhibit the highest surface temperatures, common radiative cooling surfaces provide moderate reductions, and ideal radiative cooling surfaces achieve the most significant cooling benefits. Since wall surface temperature directly influences both the conductive heat flux into indoor spaces and the overall cooling energy demand of buildings, these results provide a critical basis for assessing the effectiveness of radiative cooling strategies. Furthermore, by comparing performance across distinct thermal climate zones, the analysis enables a deeper understanding of how material spectral properties interact with local atmospheric conditions to shape building thermal behavior.

For the Chinese cases (Figure 4), the cooling effect is evident in all climate zones, but its intensity varies with climatic conditions. In Shenyang and Lanzhou (severe cold and cold zones), surface temperature reductions are noticeable yet limited, with maximum reductions of approximately 10–12 °C under IRC. This is attributed to lower solar gains and larger diurnal swings, which constrain daytime overheating. In contrast, in Nanjing, Shenzhen, and Kunming (hot-summer and cold-winter, hot-summer and warm-winter, and moderate climate zones), the benefits are more substantial. For instance, in Shenzhen, the NRC wall surface temperature peaked near 46 °C, while the IRC surface remained below 38 °C, representing a reduction of nearly 20%. These results highlight that radiative cooling is particularly effective in climates where high solar radiation coincides with prolonged cooling demand.

For the Japanese cases (Figure 5), a similar climate dependence is observed. In northern cities such as Sapporo and Hachinohe, reductions are modest due to cooler ambient conditions and lower solar radiation intensity. However, in central and southern regions, including Tokyo, Kagoshima, and Naha, the advantages of radiative cooling are pronounced. In Tokyo, the peak surface temperature decreased from above 57 °C for NRC to around 34 °C for IRC, a reduction exceeding 20 °C. In Naha, the southernmost city, average surface temperatures dropped by nearly 4 °C, with peak reductions exceeding 12 °C. These results confirm that the potential of radiative cooling increases significantly in warm and humid climates with high insolation.

Quantitative analysis in Table 2 reinforces these findings. Peak surface temperatures for NRC conditions generally exceeded 50 °C in hot-summer regions (e.g., Nanjing, Tokyo, Kagoshima), while IRC surfaces consistently maintained peak values below 37 °C. Average surface temperatures followed the same trend, with reductions of 2–5 °C across most cities when shifting from NRC to IRC. The magnitude of improvement is strongly correlated with solar radiation intensity and atmospheric transparency, indicating that radiative cooling materials not only mitigate extreme peaks but also stabilize average thermal loads on building envelopes.

Overall, the combined results demonstrate that radiative cooling materials substantially lower wall surface temperatures across diverse climatic contexts, with the strongest benefits in high-insolation, cooling-dominated zones. The comparison between Chinese and Japanese cities further illustrates that climatic drivers—including solar radiation, ambient air temperature, and diurnal variability—govern the extent of achievable cooling. These insights highlight the necessity of climate-based evaluation for optimizing the deployment of radiative cooling strategies, and they underscore the critical role of material spectral design in enhancing building resilience under future warming scenarios.

3.2. Variation in Wall Heat Flow

The diurnal variation in outdoor wall-surface heat flux under different façade configurations is shown in Figure 6 for eleven representative cities. In general, NRC surfaces exhibited the largest fluctuations, with daytime gains typically exceeding 10 W/m² and

nighttime losses dropping below -20 W/m^2 . Such wide swings reflect the strong solar absorption of conventional façades during the day and the subsequent rapid release of stored heat at night. When RC surfaces were applied, both peaks and valleys were markedly reduced, while IRC surfaces further stabilized the flux, keeping most values within -4.9 W m^{-2} and $+5.1 \text{ W m}^{-2}$ (mean $\pm 1.96 \sigma$, $n = 8760 \text{ h}$), corresponding to a relative variation of $\pm 4\%$ with respect to the annual mean flux. This narrowing of the diurnal heat-flux band suggests that radiative cooling not only limits solar heat penetration but also moderates the envelope's radiative exchanges with the atmosphere.

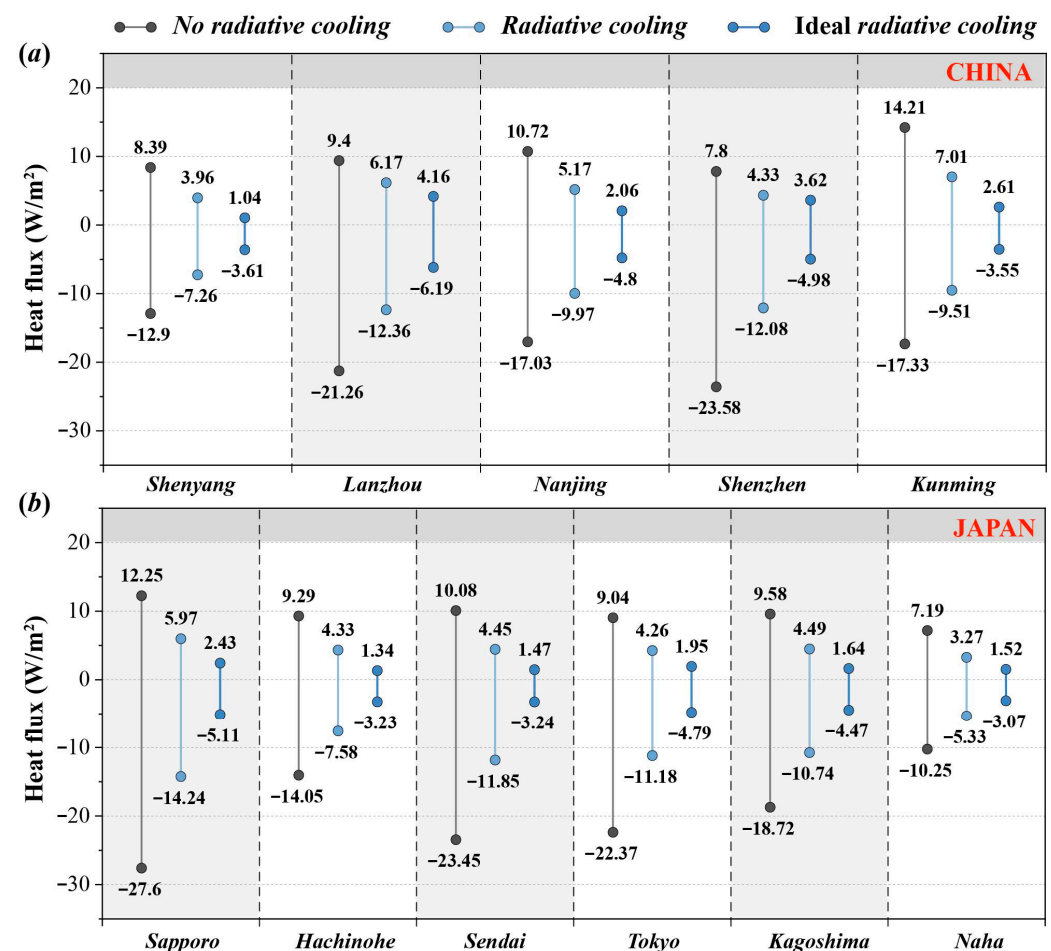


Figure 6. Diurnal variation of wall-surface heat flux under different façade configurations: (a) five cities in China; (b) six cities in Japan.

In Chinese cities, the benefits of radiative cooling were most prominent in hot-summer climates. In Nanjing, the daytime peak decreased from 10.7 W/m^2 to 2.1 W/m^2 , and the nocturnal minimum improved from -17.0 W/m^2 to -4.8 W/m^2 , indicating more than 70% suppression of diurnal extremes. Similarly, in Shenzhen, which combines strong solar radiation with high humidity, the peak gain was reduced from 7.8 W/m^2 to 3.6 W/m^2 , while nighttime heat loss declined from -23.6 W/m^2 to -5.0 W/m^2 . By contrast, in northern cold zones such as Shenyang and Lanzhou, the absolute values of heat flux were smaller, but IRC still reduced both daytime peaks and nighttime valleys by more than half, demonstrating the robustness of radiative cooling even in heating-dominated regions.

In Japanese cities, the results highlight how climate modulates the role of radiative cooling. In Sapporo, NRC façades showed extreme nighttime losses of -27.6 W/m^2 , whereas IRC limited the minimum to -5.1 W/m^2 , an 80% reduction that mitigates excessive envelope cooling in clear, cold conditions. In Tokyo, where high insolation and dense

urban morphology exacerbate overheating, the daytime flux dropped from 9.0 W/m^2 to 2.0 W/m^2 , while the nocturnal loss improved from -22.4 W/m^2 to -4.8 W/m^2 . In the subtropical city of Naha, the positive peak decreased from 7.2 W/m^2 to 1.5 W/m^2 , while the minimum improved from -10.3 W/m^2 to -3.1 W/m^2 . These results suggest that radiative cooling contributes differently across climates: in warm and humid regions it primarily reduces solar heat gain, while in cold clear-sky regions it moderates excessive nighttime radiative losses.

Taken together, these findings demonstrate that radiative cooling narrows the diurnal heat-flux amplitude by approximately 60–80% across diverse climates. Beyond the numerical reduction, the qualitative effect is equally important: radiative cooling flattens the diurnal flux profile, delays the occurrence of midday peaks, and reduces the sharp gradients driving conductive heat transfer. This leads to more stable wall thermal behavior, reduced HVAC cycling, and improved thermal comfort at the building perimeter. The results underscore that the advantage of radiative cooling lies not only in lowering absolute heat flux values but also in stabilizing the thermal interaction between building envelopes and their climatic context, thereby enhancing the resilience of buildings under both hot and cold conditions.

3.3. Annual Energy Consumption

To evaluate the operational impact of different RCM configurations, this section compares the annual cooling EUI across selected cities. The analysis focuses on how façade-integrated RC and IRC affect cooling loads under varying climate conditions. These results provide a quantitative perspective on RCM performance in real-world settings and validate the effectiveness of passive cooling strategies at regional scales.

Figure 7 presents annual cooling EUI in kWh/m^2 across eleven cities under three façade conditions: NRC, RC, and IRC. Figure 7a shows results for Chinese cities, while Figure 7b presents those for Japanese cities. Each city is represented by a cluster of bars corresponding to the three conditions, with red arrows denoting the energy reduction from NRC to RC, and black arrows showing the additional savings from RC to IRC.

In Chinese cities, the application of RC surfaces leads to modest but consistent reductions, ranging from 4.7 kWh/m^2 in Lanzhou to 47.5 kWh/m^2 in Shenzhen. Under the IRC scenario, the benefits are significantly amplified, particularly in warm and humid climates. In Shenzhen and Kunming, savings reach 84.3 and 57.0 kWh/m^2 , respectively. Even in moderate or heating-dominated climates such as Shenyang and Lanzhou, both RC and IRC configurations still deliver measurable improvements, highlighting the universal applicability of radiative cooling, though with smaller absolute reductions.

In Japanese cities, the savings are generally more pronounced. For example, Hachinohe, Tokyo, and Kagoshima achieve reductions of 48.5 , 44.9 , and 66.0 kWh/m^2 under IRC, reflecting the combined effect of high diurnal temperature variation and relatively favorable sky conditions. The highest reduction occurs in Naha, where IRC reduces the cooling EUI by 83.6 kWh/m^2 compared with NRC. Interestingly, even colder regions such as Sapporo and Sendai also exhibit substantial energy savings, demonstrating that radiative cooling is effective not only in warm climates but also in clear, dry conditions that enhance longwave radiative losses.

Taken together, these results highlight three important insights. First, radiative cooling benefits scale with climatic stress: the warmer and sunnier the environment, the greater the potential energy savings. Second, IRC represents a theoretical upper bound, but even the common RC configuration delivers meaningful reductions in both hot and temperate climates. Third, the positive results from cold, clear-sky cities confirm that radiative cooling is not exclusively a hot-climate solution but a broadly applicable passive strategy.

By reducing annual cooling demand by 5–80 kWh/m² depending on location, radiative cooling has the potential to make a significant contribution to building energy efficiency and to the long-term goal of carbon mitigation in diverse urban contexts.

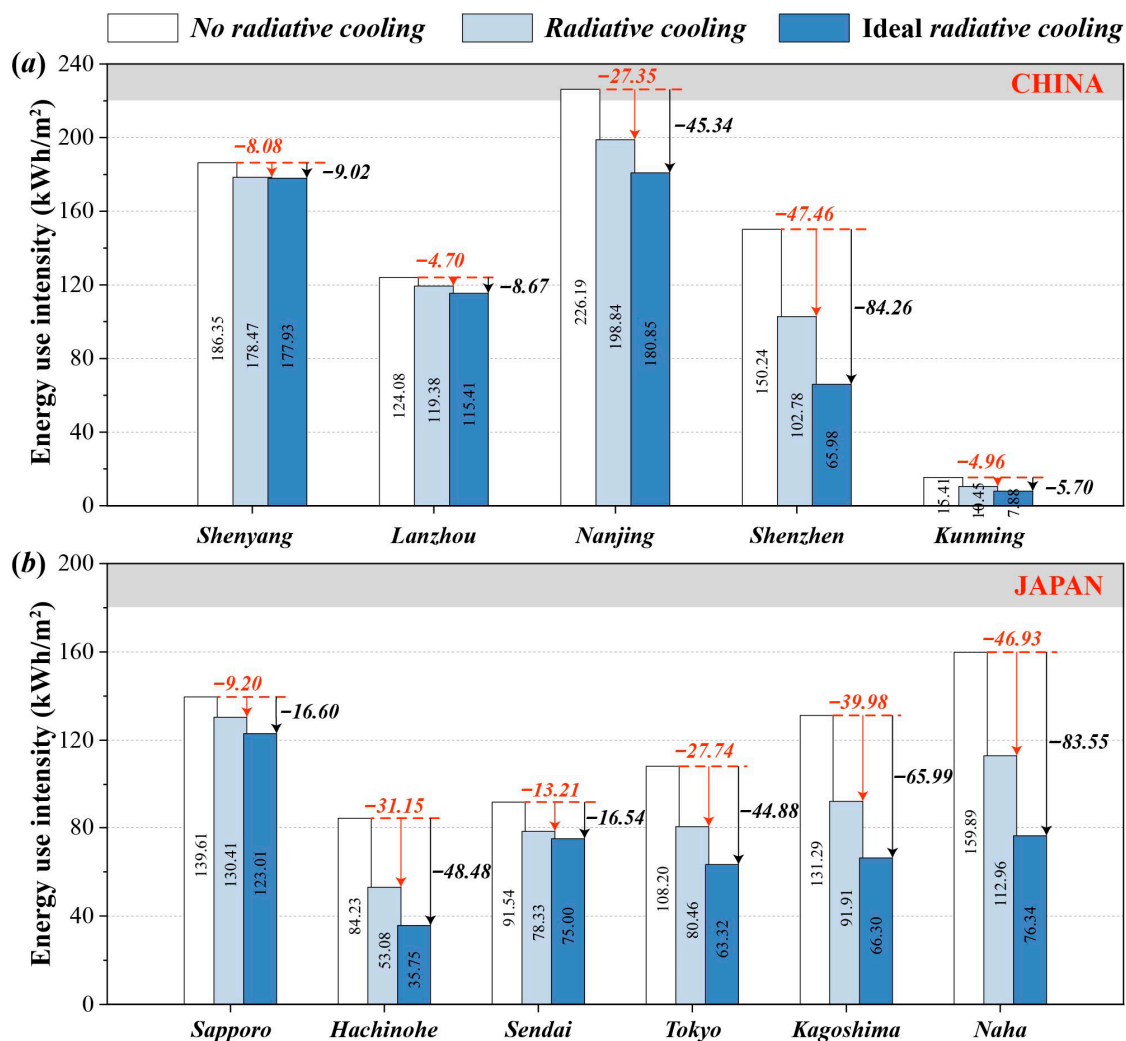


Figure 7. Annual energy use intensity under different façade configurations: (a) five cities in China; (b) six cities in Japan.

Figure 8 illustrates the energy savings achieved by different cities using Radiative Cooling and Ideal Radiative Cooling, as expressed by the difference between EUI under no radiative cooling (EUI_NRC) and that under RC and IRC configurations. Each city is represented by two radial bars: the lighter bar denotes the energy saved by RC (EUI_NRC–EUI_RC), and the darker bar represents the additional saving achieved by IRC (EUI_NRC–EUI_IRC).

Figure 8a shows the results for five cities in China. Shenzhen and Kunming exhibit the highest IRC-related energy savings of 84.2 and 5.7 kWh/m², respectively. While Lanzhou and Shenyang show only minor savings under RC, the shift to IRC yields a moderate gain. Nanjing presents a balanced performance with 27.3 kWh/m² savings under RC and 47.4 kWh/m² under IRC. Figure 8b presents data for six Japanese cities. Naha achieves the highest savings across all cases, with 83.5 kWh/m² under IRC. Tokyo and Kagoshima also show notable reductions of over 40 kWh/m². In contrast, cities like Sapporo and Hachinohe exhibit more moderate benefits from both RC and IRC, reflecting differences in climatic suitability.

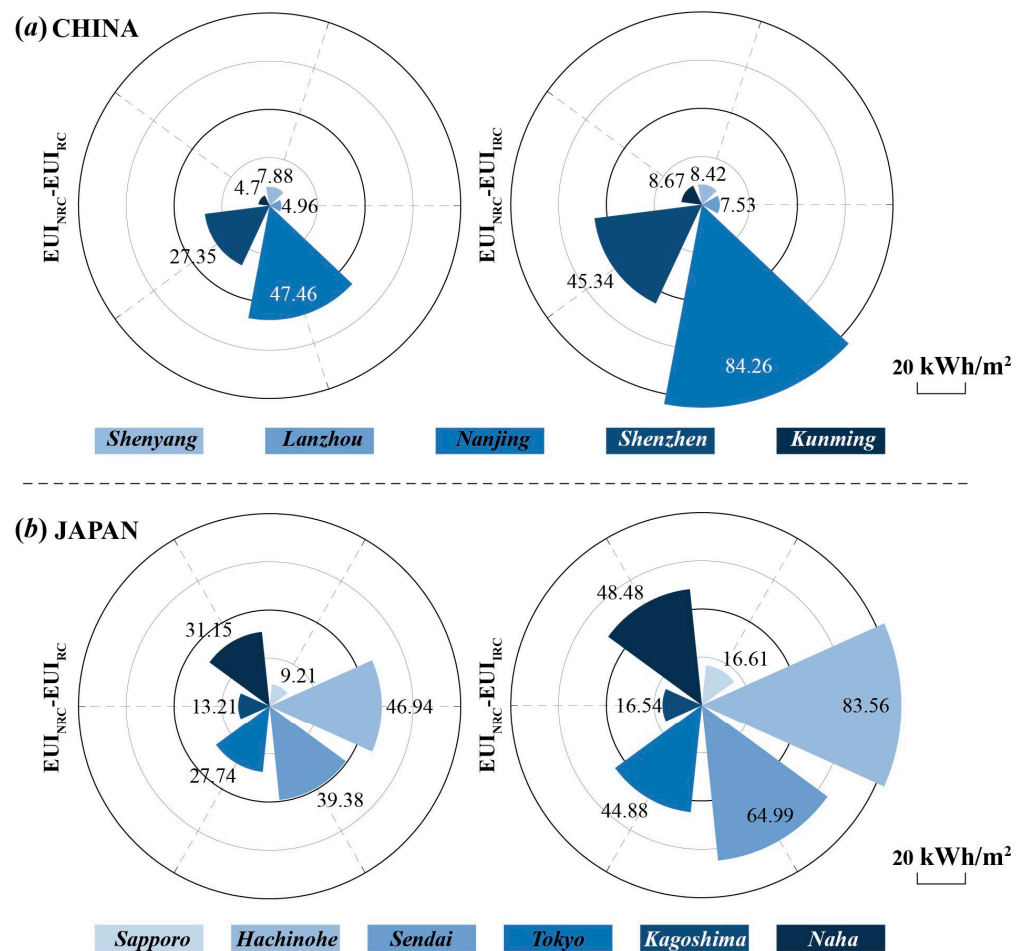


Figure 8. Energy savings achieved by different cities using RC and IRC.

4. Assessment of the Suitability of Radiative Cooling Materials in Different Regions

4.1. Regional Solar Resource and Climate Suitability Assessment for Radiative Cooling Materials

As the global demand for energy-efficient and climate-adaptive technologies intensifies, radiative cooling materials are gaining attention for their ability to passively reduce surface temperatures without the need for energy input. While substantial progress has been made in understanding their spectral design, material performance, and cooling potential under idealized conditions, there remains a lack of comprehensive frameworks to evaluate how local climates affect their real-world applicability.

Given that radiative cooling is inherently sensitive to environmental conditions—particularly sky clarity, temperature fluctuations, and atmospheric transparency—it becomes essential to quantify how these variables differ regionally and how they influence RCM effectiveness. To construct this assessment framework, we identify three core climate indicators: the Weather Structure Index, the Diurnal Temperature Index, and the Composite Climate Matching Applicability index. These metrics are derived from high-resolution hourly meteorological datasets and serve to quantify sky clarity, thermal variation, and their combined effect on RCM performance.

The Weather Structure Index captures the frequency and quality of sky conditions over the course of a year. It is defined as follows:

$$WSI = \frac{D_{pc} + D_{clear} - D_{cloudy}}{D_{tsh}} \quad (3)$$

Higher WSI values indicate a greater share of clear-sky conditions, which facilitate longwave radiation transfer from the surface to outer space. Conversely, lower or negative values reflect more frequent cloud cover, which impedes RCM efficiency by blocking the radiative window.

Complementing WSI is the Diurnal Temperature Index, which reflects the magnitude of temperature swings between day and night. This temperature difference is essential for enabling radiative heat loss during nighttime. The DTI is calculated as follows:

$$DTI = \frac{N(T > \bar{T})}{N(T < \bar{T})} \quad (4)$$

where

$\bar{T}$ is the average daily temperature range (difference between daily max and min);

$N(T > \bar{T})$ and $N(T < \bar{T})$ represent the number of days with greater or lesser temperature fluctuation than the annual mean, respectively.

Finally, to capture the interaction between these two critical dimensions of climatic suitability, we introduce the Composite Climate Matching Applicability index, calculated as follows:

$$CMA = |WSI \times DTI| \quad (5)$$

This product-based formulation emphasizes that both clear-sky availability and strong diurnal thermal gradients are necessary for efficient RCM operation. A deficiency in either dimension leads to reduced net cooling performance. To test this framework, we applied the indicators to 11 representative cities in China and Japan: Shenyang, Lanzhou, Nanjing, Shenzhen, Kunming, Sapporo, Hachinohe, Sendai, Tokyo, Kagoshima, and Naha. These cities were selected to cover a range of climates—from dry inland plateaus to humid coastal zones, and from subtropical to subarctic regions.

According to the results shown in Figure 9, it presents the climatic characteristics of 11 cities in China and Japan, including the number of cloudy, sunny, and overcast hours throughout the year, along with the calculated values of WSI, DTI, and CMA. These indicators jointly reflect the local atmospheric and thermal conditions that govern the applicability of radiative cooling materials.

Among the Chinese cities, Kunming stands out with a balanced combination of favorable metrics. It has 995 h of cloudy skies and 1127 h of sunshine, leading to a WSI of -1.19 . Coupled with a high DTI of 0.80 , it achieves a CMA of 0.95 , suggesting excellent overall climatic suitability. Lanzhou records a slightly lower WSI of -1.52 and a DTI of 0.49 , resulting in a CMA of 0.75 . Shenzhen, despite having a relatively high number of cloudy hours (991), benefits from 1266 sunny hours and a DTI of 0.59 , giving it a CMA of 0.67 . Shenyang's moderate conditions yield a CMA of 0.59 . Nanjing is the least favorable among Chinese cities, with a CMA of only 0.45 due to a low DTI of 0.34 .

Japanese cities show a broader and more contrasting distribution. Sapporo, despite having fewer overcast hours (7284), exhibits the lowest DTI at 0.20 , resulting in a CMA of just 0.31 . In contrast, Sendai demonstrates the highest overall suitability, with a DTI of 1.23 and a CMA of 2.61 , despite its low WSI of -2.12 . Hachinohe and Tokyo also have high CMA values— 1.32 and 1.66 , respectively—due to their relatively strong DTI values (0.67 and 0.54), although both cities experience frequent overcast conditions and low WSI. Naha presents a moderate case, with a WSI of -1.89 , DTI of 0.55 , and a CMA of 1.05 . Kagoshima reports the highest number of overcast hours (7740), a low DTI of 0.32 , and a resulting CMA of 0.52 .

This comparative matrix reveals several patterns. First, most Chinese cities maintain a relatively balanced sky condition with moderate to strong diurnal variation, supporting con-

sistent RCM performance. Second, some Japanese cities with high DTI values—particularly Sendai and Tokyo—achieve high CMA scores despite low WSI, underscoring the importance of thermal dynamics in compensating for limited daytime radiative cooling potential. Third, low CMA values typically arise from the simultaneous presence of poor sky clarity and weak temperature fluctuation, as seen in Sapporo and Nanjing.

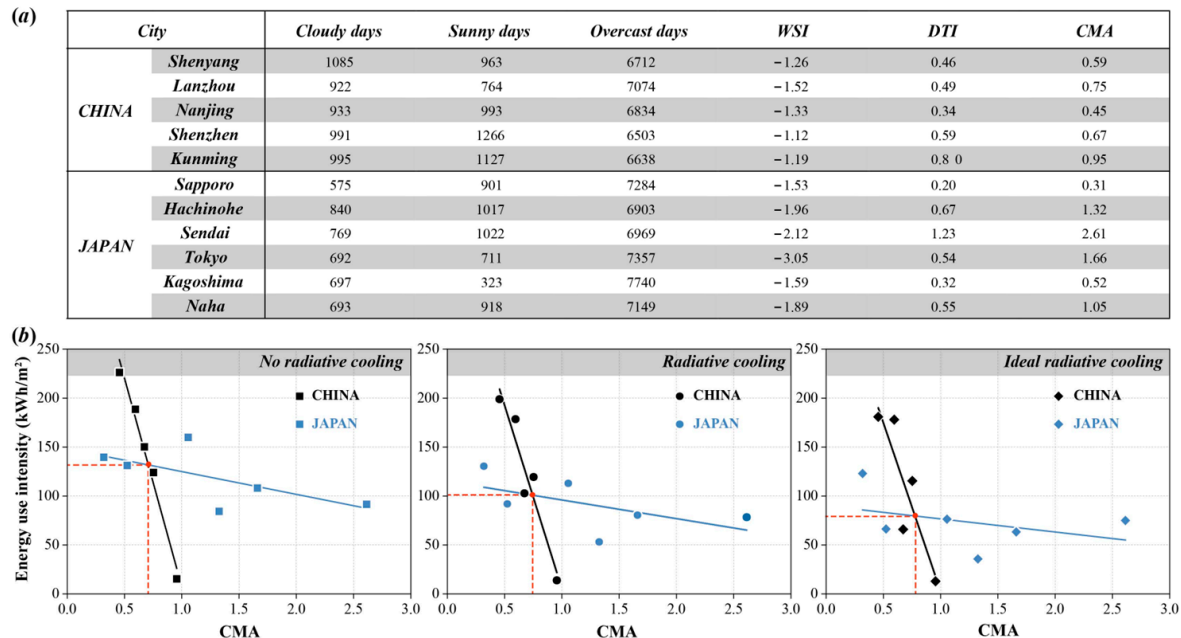


Figure 9. Climatic indicators and relationships between EUI and CMA: (a) climatic data of eleven cities; (b) EUI–CMA correlations under different radiative cooling configurations.

Figure 9a highlights the need for joint consideration of sky availability and thermal gradient when evaluating the deployment potential of radiative cooling technologies. The CMA index, as a product of WSI and DTI, provides a concise yet robust metric to synthesize these two critical dimensions.

This relationship also reflects the underlying physical mechanisms governing radiative-cooling performance. The Weather Structure Index represents sky transparency and thus the openness of the 8–13 μm atmospheric window that enables long-wave radiation to escape to space. The Diurnal Temperature Index quantifies the thermal gradient between day and night, which controls the rate of nocturnal heat release. Their product therefore encapsulates both radiative and thermodynamic drivers of passive cooling.

Cities such as Shenzhen, Tokyo, and Sendai, which exhibit moderate cloud cover, high insolation, and large diurnal temperature variations, achieve the greatest reductions in cooling energy demand ($\approx 60\text{--}80\text{ kWh m}^{-2}$) because clear-sky conditions coincide with sustained thermal gradients. Conversely, Nanjing and Sapporo experience diminished effectiveness due to high relative humidity and frequent overcast skies that attenuate the infrared emissivity of the atmosphere, reducing net radiative exchange. Kunming and Lanzhou show strong agreement between high CMA and significant energy savings, confirming that dry, clear-sky climates favor more efficient radiative cooling.

It should also be noted that urban surface albedo and morphological complexity can locally alter effective emissivity and multiple-reflection pathways, which may partially account for deviations between simulated results and CMA-based predictions. Such differences highlight that, although CMA provides a robust first-order predictor, real-world performance also depends on mesoscale radiative interactions and built-form characteristics. These additions provide a clearer linkage between climatic indicators and the physical

mechanisms underlying the observed performance differences, thereby strengthening the interpretative depth of the discussion.

To support decision making for material deployment, we propose classifying cities into three suitability tiers based on CMA values:

- High suitability: (e.g., Sendai, Tokyo);
- Moderate suitability: (e.g., Kunming, Lanzhou);
- Low suitability: (e.g., Sapporo, Nanjing).

This classification helps guide which regions may benefit most from conventional RCMs, and where more advanced spectrally selective or hybrid solutions may be necessary.

Figure 9b further validates the correlation between CMA and the energy-saving potential of RCMs from an energy efficiency perspective. The three figures show the relationship between the energy use intensity per unit area and CMA under three cooling conditions: no radiative cooling, normal radiative cooling, and ideal radiative cooling. It is evident that in all three cooling scenarios, as CMA increases, EUI decreases overall, indicating that regions with higher CMA respond better to RCMs and achieve more significant cooling effects.

Under “no radiative cooling” conditions, Chinese cities generally have higher EUI values than Japanese cities, with CMA values mostly below 1, forming a steep negative correlation regression curve, indicating a strong coupling effect between CMA and passive cooling potential. Japanese cities, however, are distributed across a wider CMA range, with less pronounced EUI variations compared to Chinese cities. In the “radiative cooling” and “ideal radiative cooling” scenarios, the overall EUI levels decrease significantly, and the differences between cities gradually widen. Chinese cities reach near-minimum EUI levels when CMA approaches 1, indicating that once a certain CMA threshold is reached, the energy-saving performance of RCMs can be fully realized; however, in Japanese cities such as Sendai and Tokyo, despite higher CMA values, EUI remains relatively high, suggesting they are still influenced by other climatic or architectural factors.

4.2. Statistical Modeling Framework for RCM Climate Suitability

To further explore the impact of climate adaptability indicators on the actual energy-saving performance of radiative cooling materials, this section establishes a regression modeling system based on the relationship between annual energy consumption intensity and CMA. The modeling targets encompass three categories of typical exterior wall materials: traditional constructions without radiative cooling functionality, conventional materials with basic radiative cooling characteristics, and ideal materials with high-selectivity spectral performance. The models were constructed using urban samples from China and Japan to reflect the application trends and performance boundaries of RCMs under different climatic conditions.

As shown in Table 3, in Chinese cities, there is a relatively stable nonlinear response relationship between the EUI of RCMs and CMA. In all regression analyses, the annual cooling energy use intensity (EUI, kWh/m²) is taken as the dependent variable, and the Composite Climate Applicability index is used as the sole explanatory variable; no additional climatic or building variables enter the regression directly. We used a unified quadratic regression model to fit NRC_CN, RC_CN, and IRC_CN, with the model form shown in Equation (6). The results show that this form effectively characterizes the energy-saving behavior of materials at different levels of climate adaptability, with determination coefficients R^2 of 0.99, 0.92, and 0.88 for the three configurations, respectively, demonstrating strong explanatory power. In the Japanese urban sample, considering the complexity of RCMs' energy-saving responses, an extended regression structure was further introduced to construct a polynomial model as shown in Equation (7). In this case, CMA remains the independent climatic variable, while additional linear, quadratic, logarithmic, and

fractional-power terms of CMA are introduced to better represent the nonlinear response of EUI to climate adaptability. This model comprehensively considers linear terms, quadratic terms, logarithmic terms, and fractional power functions, thereby more fully expressing the nonlinear regulatory effect of CMA on material performance.

Table 3. Regression correlation between composite climate applicability (CMA) and annual cooling energy use intensity (EUI) for three façade configurations (NRC, RC, and IRC).

(a) CHINA

$y_{EUI} = a_i + b_i x_{CMA}^2$ (6)			
Model	R ²	a_i	b_i
NRC_CN	0.99	290.55	−299.96
RC_CN	0.92	253.65	−262.54
IRC_CN	0.88	230.43	−240.14

(b) JAPAN

$y_{EUI} = a_i + b_i x_{CMA} + c_i x_{CMA}^2 + d_i \ln(x_{CMA}) + e_i \frac{1}{x_{CMA}^{1.5}}$ (7)						
Model	R ²	a_i	b_i	c_i	d_i	e_i
NRC_JP	0.99	−58,301.02	16,641.45	−2218.38	53,383.93	44,062.69
RC_JP	0.95	−50,151.60	14,344.04	−1913.56	45,845.71	37,854.70
IRC_JP	0.99	−37,446.75	10,733.46	−1431.59	34,182.28	28,236.49

Based on this, we further established a material energy-saving difference model by subtracting the RC and NRC models and the IRC and NRC models, respectively, to obtain the energy-saving improvement values corresponding to the CMA response relationship, as shown in Formulas (8)–(11). These models quantify the energy-saving improvement potential of RC and IRC materials relative to traditional construction and clarify the nonlinear amplification effect of their energy-saving response as CMA strengthens. Taking the Chinese model as an example, the RC–NRC difference model shows a steady increasing trend, while the IRC–NRC gain is more significant, indicating that in high-adaptability regions, using materials with better performance can yield higher energy-saving returns.

This modeling framework has multiple practical implications. First, it provides a tool for quickly predicting the energy-saving benefits of RCMs based on climate adaptability, enabling the prioritization of material deployment at the urban scale. Second, the energy-saving difference model identifies the “critical points” at which different materials release their benefits, providing quantitative basis for material selection and cost control. Third, the model reveals the marginal energy-saving gains from upgrading from RC to IRC, suggesting that high-end materials are only worthwhile under specific CMA conditions, thereby optimizing resource allocation. Finally, the model structure has good scalability, allowing for the introduction of additional factors such as air humidity and atmospheric transmittance for multi-dimensional fitting, thereby supporting regional energy consumption simulation and building climate response design.

$$\Delta RC_CN = -36.90 + 37.42x_{CMA}^2 \quad (R^2 = 0.94) \quad (8)$$

$$\Delta IRC_CN = -60.12 + 59.82x_{CMA}^2 \quad (R^2 = 0.95) \quad (9)$$

$$\Delta RC_JP = 8149.42 - 2297.41x_{CMA} + 304.82x_{CMA}^2 - 7538.22\ln(x_{CMA}) - \frac{6207.99}{x_{CMA}^{1.5}} \quad (R^2 = 0.94) \quad (10)$$

$$\Delta IRC_JP = 20854.27 - 5907.99x_{CMA} + 786.79x_{CMA}^2 - 19201.65\ln(x_{CMA}) - \frac{15826.20}{x_{CMA}^{1.5}} \quad (R^2 = 0.97) \quad (11)$$

In summary, the indicator-based modeling framework—centered on the Weather Structure Index, Diurnal Temperature Index, and the composite Climate Applicability

Index—not only demonstrates CMA’s effectiveness as a key climatic indicator for evaluating radiative-cooling suitability, but also establishes a robust theoretical and data-driven foundation for the cross-regional deployment of RCMs. By linking localized climate characteristics with material performance expectations, this approach enables informed decisions in design, technology selection, and policy development.

Furthermore, although the present analysis successfully establishes a climate–energy correlation framework based on CMA, it is recognized that Figures 6 and 7 mainly illustrate comparative performance among three façade configurations—NRC, RC, and IRC—each characterized by fixed solar reflectivity and infrared emissivity values. Because these optical parameters were defined as discrete material properties rather than continuous variables, the figures show categorical differences in energy use intensity and heat flux, rather than a direct quantitative correlation between emissivity and energy performance. The climate–energy correlation has therefore been captured through the CMA-based regression framework, which integrates solar radiation availability and diurnal temperature variation to describe the climatic influence on radiative-cooling performance. Future extensions of this framework will involve a parametric analysis in which solar reflectivity and emissivity are continuously varied to construct X–Y relationships linking thermophysical material parameters with annual energy intensity and façade heat flux. This will enable a more explicit understanding of the coupling between material optical properties and local climatic drivers such as solar irradiance, humidity, and atmospheric transmittance.

In parallel, the multi-group EUI regression models and energy-saving difference equations derived from CMA provide quantitative tools for evaluating material performance under diverse environmental conditions. Subsequent model enhancements will incorporate additional climatic variables—including atmospheric emissivity, water vapor concentration, and seasonal cloud dynamics—to further improve predictive capability and adaptability across climatic zones.

It should also be noted that this study focuses exclusively on the outdoor radiative-cooling potential and façade-level energy performance of RC materials. A detailed indoor comfort assessment—accounting for operative temperature, mean radiant temperature, air velocity, and humidity—will be undertaken in following research once coupled building–HVAC system models are established.

5. Conclusions

This study performed a climate-based evaluation of radiative cooling materials across eleven representative cities in China and Japan by integrating building energy simulation with climate indicators. The main conclusions are as follows:

- (1) By conducting comparative simulations across eleven representative cities in China and Japan, this study systematically revealed the climate-dependent adaptability of radiative cooling materials, demonstrating their effectiveness in both reducing daytime overheating in high-insolation regions and mitigating excessive nocturnal cooling in cold, dry climates.
- (2) Through a comprehensive assessment of wall surface temperature, heat flux, and annual energy use intensity, this study quantified the differentiated performance of NRC, RC, and IRC façades. Results show that IRC reduces diurnal heat-flux amplitude by 60–80% and annual cooling energy demand by 5–80 kWh/m².
- (3) An assessment framework was developed based on the Weather Structure Index, Diurnal Temperature Index, and Composite Climate Applicability. Regression models confirmed that CMA serves as a robust predictor for evaluating the regional applicability of RCMs.

- (4) The findings verify the high energy-saving potential of RCMs in warm-humid regions and reveal their unexpected adaptability in cold-dry climates, challenging the conventional perception that RCMs are only suitable for hot areas. This provides methodological support for cross-regional deployment of climate-sensitive materials and low-carbon building design.

In summary, radiative cooling materials constitute an effective passive strategy for reducing building cooling demand across multiple climate zones. By lowering peak envelope temperatures, stabilizing diurnal heat flux, and decreasing annual energy consumption, these materials contribute significantly to energy efficiency and carbon mitigation objectives. The integration of climate indicators with building energy simulation enables targeted deployment strategies, ensuring that radiative cooling materials are applied where their benefits are maximized.

Future research should expand this framework by incorporating additional atmospheric parameters such as humidity, emissivity, and cloud dynamics, and by coupling radiative cooling with other passive or hybrid technologies to enhance building resilience under future climate conditions.

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Abbreviations

Symbol	Description	Unit
α	Solar reflectivity (albedo)	–
ϵ	Infrared emissivity	–
T	Temperature	°C
q	Heat flux	W·m ^{−2}
λ	Wavelength	μm
σ	Stefan–Boltzmann constant (5.67×10^{-8})	W·m ^{−2} ·K ^{−4}
Abbreviation	Description	
RC	Radiative Cooling	
NRC	Non-Radiative Cooling	
IRC	Ideal Radiative Cooling	
RCM	Radiative Cooling Material	
HVAC	Heating, Ventilation, and Air Conditioning	
EUI	Energy Use Intensity	
WSI	Weather Structure Index	
DTI	Diurnal Temperature Index	
CMA	Composite Climate Applicability	

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