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Publication Date

2023

DOI

10.20357/B7DK6T

Peer reviewed

P. Rajagopalan, V. Soebarto and H. Akbari (Eds.), *6th International Conference on Countermeasures to Urban Heat Islands (IC2UHI)*, pp. 1–10. ©2023, RMIT University, Melbourne, Australia.

Cool envelope benefits in future typical weather and heatwave conditions for single-family homes in Los Angeles

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ABSTRACT

Cool (solar reflective) roofs and walls can reduce solar heat gain and decrease unwanted heat flowing into indoor spaces. To explore the potential of these strategies to mitigate energy and thermal comfort challenges in Los Angeles, we conducted a study that used EnergyPlus building energy simulations. Our analysis focused on single-family homes in Los Angeles under various historical and future weather conditions, including both typical meteorological year (TMY) and heatwave weather year (HWY) scenarios, based on the COordinated Regional Downscaling EXperiment (CORDEX) framework under the Representative Concentration Pathway (RCP) 8.5. Our study evaluated the impact of cool envelope strategies on heating, ventilation, and air conditioning (HVAC) primary energy intensity savings and thermal comfort improvements. We employed three thermal comfort models: predicted mean vote (PMV), adaptive, and heat stress. Our findings indicate that in Los Angeles, a package of cool roof + walls (reflective roof and reflective walls) can reduce annual HVAC energy consumption by at least 11% for buildings equipped with mechanical cooling systems. They can reduce occupants' warm thermal discomfort (thermal-sensation-scale-unit-weighted warm exceedance hours) by at least 28% in air-conditioned buildings and by at least 16% in buildings without mechanical cooling systems. Cool envelopes can also lower daily heatwave heat stress by at least 9%.

Keywords: cool roofs, cool walls, future weather, heatwave

Introduction

Climate change and increasing extreme heat events can substantially increase building energy use and/or reduce occupant thermal comfort. The rising number of cooling degree days (CDD) in future climate scenarios will boost cooling energy consumption (Radhi & Sharples, 2013). Furthermore, intense and prolonged heatwaves pose a significant threat to occupant health, especially for vulnerable populations. Buildings without cooling systems or experiencing grid power failure during heatwave events are particularly at risk (Miller et al., 2021). High indoor temperatures can cause heat-related diseases, making resilient cooling strategies critical for buildings to provide resistance, robustness, and recoverability during power outages. There are several passive or low-energy technologies that offer these features, including cool envelope materials, solar shading, solar-controlled glazing, ventilated roofs and facades, and thermal mass, such as phase-changing materials (Zhang et al., 2021).

Our paper focuses on the benefits of cool envelope materials applied to roofs and walls, which reduce radiative heat gain at the building's opaque envelope and decrease heat flow into the conditioned space. Previous studies have shown that cool envelope materials can

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provide significant cooling load reductions and energy savings (Hernández-Pérez et al., 2014; Holzer et al., 2022, sec. 2.2; Levinson & Akbari, 2010; Rosado & Levinson, 2019). Additionally, the application of cool envelope materials can result in thermal comfort improvements by reducing the air and operative temperature in occupied spaces, which in turn reduces annual discomfort hours. The thermal comfort improvement in buildings can be achieved by temperature reduction in the occupied space, which decreases annual discomfort hours (Fabiani et al., 2020; Pisello & Cotana, 2014). This paper investigates energy savings and thermal comfort improvement from the application of cool envelope materials to a single-family home in Los Angeles, using historical, mid-term future, and long-term future weather conditions. It also assesses heat stress reduction during heatwave periods.

Historical and Future Weather Data

The benefits of cool envelope strategies can vary depending on the weather conditions. We developed historical and future weather data for Los Angeles to evaluate the performance of cool envelope strategies. The weather dataset was generated from the COordinated Regional Downscaling EXperiment (CORDEX) project database (Machard et al., 2023). We extracted climate data from the Regional Climate Model (RCM), for historical and future periods under the Representative Concentration Pathway (RCP) 8.5, which represents the most pessimistic scenario at the time of the IPCC (IPCC, 2023). This was chosen to evaluate the worst case possible in a resilience and adaptation context.

The weather datasets were generated for Los Angeles international airport (weather station 722950). The typical metrological year (TMY) data were generated from bias correction for 20 years of regional climate data based on the ISO 19527-4 methodology (ISO, 2005b). The historical and future Los Angeles TMYs were generated to represent weather of the historical period (CORDEX 2010 for 2001-2020), mid-term future period (CODEX 2050 for 2041-2060), and long-term future period (CORDEX 2090 for 2081-2100). The CORDEX 2010 historical period covers years between 2001 and 2020. For more comprehensive historical weather data coverage, we also used the historical TMY3 weather data representing twelve typical meteorological months (January through December) between 1991 and 2005 (Wilcox & Marion, 2008). The heatwave weather year (HWY) dataset was developed for each CORDEX historical and mid- and long-term future period. Table 1 provides the summary of TMY weather datasets. The heatwaves were detected by calculating duration and severity expressed in degree days over the temperature thresholds (Ouzeau et al., 2016), and characterized by three criteria: most severe, most intense, and longest (Machard et al., 2023). For the resilience assessments, we selected the most severe heatwave weather data. Table 2 shows the summary of heatwave weather data during the heatwave period. These TMY and HWY data were converted to the EnergyPlus weather (EPW) format for use in building energy simulations.

Cool Envelope Performance Evaluation Method

Prototype buildings and simulation environments

We used the whole-building energy simulation tool EnergyPlus version 9.6 (DOE, 2023a) to model prototype buildings before and after application of cool envelope strategies. The single-family home prototype model was used to evaluate the energy and thermal comfort under the TMY3, CORDEX historical, and CORDEX future weather scenarios. The single-family home is based on a U.S. Department of Energy (DOE) residential prototype building model used to evaluate performance under the International Energy Conservation Code (IECC) (DOE, 2023b). Figure 1 shows the single-family home EnergyPlus model screen captured from Sketchup software (NREL, 2023).

The model represents pre-1980 construction. The total conditioned floor area is 223 m² and the window-to-wall ratio (WWR) is 0.15 for each orientation. Each floor in this two-story home is modeled as a separate 112 m² thermal zone. The home has gas-furnace space heating and direct-expansion (DX) space cooling. The HVAC system was sized for pre-1980 vintage single-family home construction but the study assumed cooling and heating efficiencies compliant with the 2019 California Title 24, Part 6 building energy standards—i.e., a cooling system coefficient of performance (COP) of 3.43 and a heating system efficiency of 0.80 for all weather conditions (CEC, 2018). The heating setpoint is 21.0 °C and the cooling setpoint is 24.9 °C in each hour of the year.

Table 1. TMY weather data summary for Los Angeles TMY3 and CORDEX historical and mid- and long-term future periods

Los Angeles TMY weather dataset	Years	Annual average temp. (°C)	Peak temp. (°C)	Annual cooling degree days base 18 °C (°C·day)	Annual heating degree days base 18 °C (°C·day)	Annual average global horiz. radiation (W/m²)	Annual average direct normal radiation (W/m²)	Annual average diffuse horiz. radiation (W/m²)
TMY3	1991-2005	16.8	26.7	326	751	208	201	80
CORDEX 2010	2001-2020	16.6	29.1	395	910	220	210	85
CORDEX 2050	2041-2060	17.8	32.6	618	705	214	201	86
CORDEX 2090	2081-2100	19.4	31.2	894	392	203	187	85

Table 2. HWY weather data summary for Los Angeles CORDEX historical and mid- and long-term future periods

Los Angeles HWY weather dataset	Heatwave start	Heatwave end	Heat-wave dur-ation (days)	Heatwave period average temp. (°C)	Heatwave period max temp. (°C)	Heatwave period cooling degrees base 18 °C (°C)	Heatwave period average global horiz. radiation (W/m²)	Heatwave period average direct normal radiation (W/m²)	Heatwave period average diffuse horiz. radiation (W/m²)
Historical most severe	2019-08-03	2019-08-07	5	24.1	32.7	6.1	314	319	86
Mid-term future most severe	2051-08-21	2051-09-10	21	24.8	39.4	6.8	259	251	87
Long-term future most severe	2086-08-06	2086-09-25	51	24.2	37.8	6.2	250	227	93

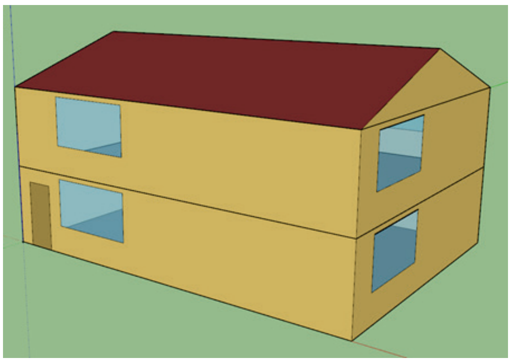

Figure 1. Single-family home EnergyPlus model 3D view screen captured from Sketchup software

Cool envelope strategy

A cool roof reduces solar heat gain at the roof by increasing roof solar reflectance. The prototype baseline single-family home is assumed to have a high-slope (4:12) roof deck with conventional asphalt roofing shingles of long-term (aged) solar reflectance 0.10. The cool roof strategy uses a bright-white asphalt shingle with long-term solar reflectance 0.60. The cool-wall strategy reduces solar heat gain by increasing the solar reflectances of all four walls. Each baseline wall is assigned long-term solar reflectance 0.25 (medium-brightness colored paint), while each cool wall is assumed to have a dull-white or off-white painted surface with long-term solar reflectance 0.60. The cool roof + walls package combines the cool walls and cool roof. The cool roof, cool walls, and cool roof + walls package are modeled in the prototype single-family home and simulated to assess energy savings and thermal comfort improvements.

Key performance indicators (KPIs)

Energy metric

The metric of annual heating, ventilation, and air conditioning (HVAC) system total primary energy use intensity per unit conditioned floor area (MJ/m²) is compared between strategies with historical (TMY3 and CORDEX 2010) and future (CORDEX 2050 and CORDEX 2090) TMY weather data. Consumption of primary energy—energy that has not been subjected to any conversion or transformation process—is calculated by multiplying the electricity and natural gas used at the building site by the regional primary energy factors for each energy carrier (ISO, 2017b). We used the California state average primary energy factor of 1.88 for electricity and 1.09 for natural gas based on the Emissions & Generation Resource Integrated Database (eGRID) California State database. California has many renewable and hydropower sources for electricity generation, yielding an electricity primary energy factor lower than the U.S. average of 2.66 (GTI Energy, 2023).

Thermal comfort metrics

International Energy Agency Annex 80 – Resilient Cooling of Buildings aims to support solutions for low energy and overheating issues in buildings (IEA, 2023). Annex 80 provides a guideline for thermal comfort evaluation depending on the building's mechanical cooling operation conditions and for heat stress evaluation for the heatwave period (Zhang et al., 2023). ISO Standard 17772-1 introduces thermal comfort evaluation methods using Predicted Mean Vote (PMV) – Predicted Percentage of Dissatisfied (PPD) model and adaptive model (ISO, 2017a). Predicted Mean Vote (PMV) is an index that predicts the mean value of the votes of a large group of persons on a thermal sensation scale ranging from -3 (cold) to +3 (hot) (ASHRAE, 2017). The PMV-PPD model is used to evaluate thermal comfort for buildings with mechanical cooling systems while the adaptive model is used for buildings without mechanical cooling systems (ISO, 2005a).

- Warm discomfort evaluation based on PMV-PPD model

For homes with mechanical cooling systems, the PMV-PPD model-based thermal comfort evaluation is used. PMV greater than +0.7 should be considered uncomfortably warm during the summer season according to ISO 17772-1:2017 Annex H.1 Category III (ISO, 2017a). PPD-weighted exceedance hours are used to evaluate the PMV-based warm discomfort. We sum PPD-weighted warm discomfort exceedance hours when PMV exceeds +0.7. The weighting factor ($PPD_{actualPMV}$ / $PPD_{PMV=+0.7}$) is a function of the PPD as defined in Annex H, Method C of ISO 17772-2:2018 (ISO, 2018).

- Warm discomfort evaluation based on adaptive model

The adaptive comfort model applies to "free-running" homes without mechanical cooling. It assumes that the occupants are mostly sedentary and that thermal conditions are regulated primarily by occupants opening and closing windows. This method applies to homes in which occupants have easy access to operable windows and can freely adapt their clothing to the indoor and outdoor conditions. The adaptive model uses operative temperature for the thermal comfort evaluation, where operative temperature is approximated as the average of air temperature and the mean radiant temperature. If the operative temperature is greater than the allowable indoor operative temperature upper limit as defined in the ISO 17772-1:2017 Annex H.2 Category III, then it is evaluated as warm discomfort by the adaptive model using the upper operative temperature limit derived from the running mean outdoor temperature (ISO, 2017a). We report adaptive-model based operative temperature degree-weighted warm exceedance hours (°C·h), the sum of positive values of (operative temperature minus upper limit) during the occupied hours.

- Heat stress evaluation for heatwave period

During heatwaves, occupants of free-running buildings or those in mechanically cooled buildings experiencing a grid power outage may face health risks or even life-threatening consequences. Therefore, the threshold for the indoor thermal environment should be selected by considering the impact on occupant health. Annex 80 recommends using the standard effective temperature (SET) adopted in ASHRAE 55-2017 (ASHRAE, 2017) to evaluate human response to heat stress in this study (Zhang et al., 2023). SET is defined as the equivalent dry bulb temperature of an isothermal environment at 50% relative humidity in which a subject, while wearing clothing standardized for the activity concerned, would have the same heat stress (skin temperature) and thermoregulatory strain (skin wetness) as in the actual test environment. A SET threshold of 30 °C for free-running buildings or mechanically cooled buildings without grid power outage is used to calculate the heat stress exceedance hours during a heatwave (Sun et al., 2021). We calculate SET degree-weighted hot exceedance hours (°C·h), the sum of positive values of (SET minus 30 °C) during occupied hours. Since heatwave durations vary by year (Table 2), heatwave-total SET degree-weighted hot exceedance hours may not be the ideal metric. We normalized it to heatwave duration (°C·h/day) to compare outcomes from heatwaves of varying length.

Results and Analysis

We evaluated the energy and thermal comfort performance changes from cool envelope strategies application under the historical and future weather scenarios. Buildings with mechanical cooling systems were evaluated for annual HVAC primary energy intensity savings and reduction in PPD-weighted warm discomfort exceedance hours for TMY weather data. For buildings without mechanical cooling systems, adaptive-model-based operative temperature degree-weighted warm discomfort exceedance hours were used for thermal comfort evaluation.

Figure 2 details the HVAC primary energy use intensity and energy savings intensity for a mechanically cooled home. Panel A shows the baseline annual HVAC primary energy use intensity and panel B shows absolute and fractional HVAC primary energy intensity savings for each strategy and weather dataset. The baseline in panel A shows more HVAC energy in the future years due to the increased cooling energy consumption in the future. However, the decreased heating energy consumption in mid- and long-term future makes the HVAC energy consumption less than the CORDEX 2010. Cool walls save more energy than the cool roof, and the cool roof + walls package (cool roof plus cool walls) shows the greatest savings. Panel B shows more absolute savings in the future years. However, fractional reductions are smaller in the future years as the baseline energy use increases more than the absolute savings. For example, the cool roof + walls package provides 4 MJ/m^2 more absolute savings intensity under CORDEX 2010 than under TMY3, but the baseline HVAC energy use intensity is 59 MJ/m^2 higher. Overall, the cool roof + walls package can reduce annual HVAC primary energy use intensity by about 12% for TMY3 historical weather, 11% for CORDEX

2010 historical weather, 12% for CORDEX 2050 mid-term future, and 13% for CORDEX 2090 long-term future weather.

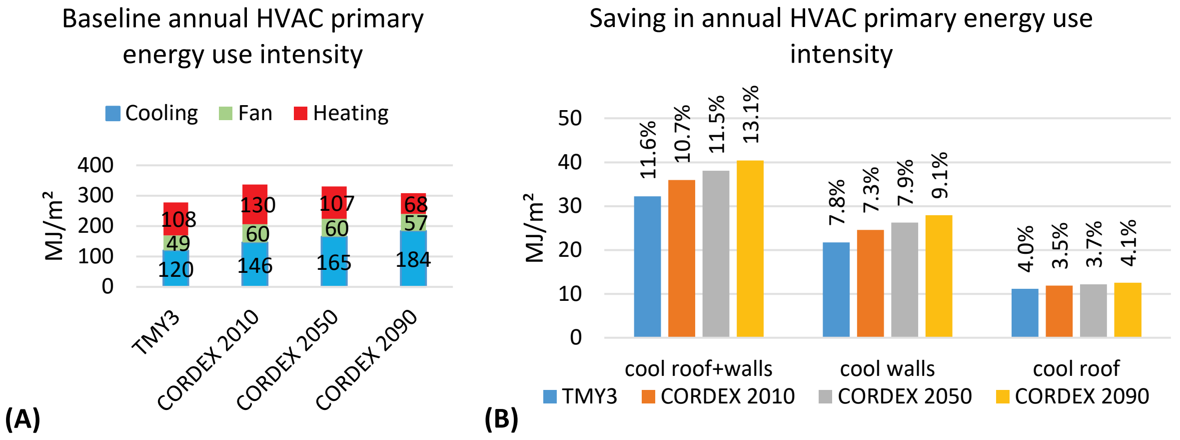

Figure 2. (A) Baseline annual HVAC primary energy use intensity for a single-family home in Los Angeles with typical historical (TMY3 and CORDEX 2010), mid-term future (CORDEX 2050) and long-term future (CORDEX 2090) weather data. (B) HVAC primary energy use intensity absolute savings and fractional savings

Figure 3A shows the baseline annual PPD-weighted warm discomfort exceedance hours. The home experiences many PPD-weighted warm discomfort exceedance hours in Los Angeles because the size of its cooling system is based on that pre-1980 construction for all weather conditions. This results in more PPD-weighted warm discomfort exceedance hours in the future as the cooling system has more hours not meeting the increased cooling load. The cool roof + walls package shows the greatest improvement. Figure 3B shows greater absolute reductions in PPD-weighted warm discomfort exceedance hours in the future years. However, fractional reductions are smaller in the future years as the baseline PPD-weighted warm discomfort exceedance hours increase faster than the absolute reductions. The cool roof alone contributes to about 9 – 13% discomfort reduction, and cool walls alone 20 – 27% reduction, and cool roof + walls package can reduce discomfort by about 28 – 37% depending on the weather data years.

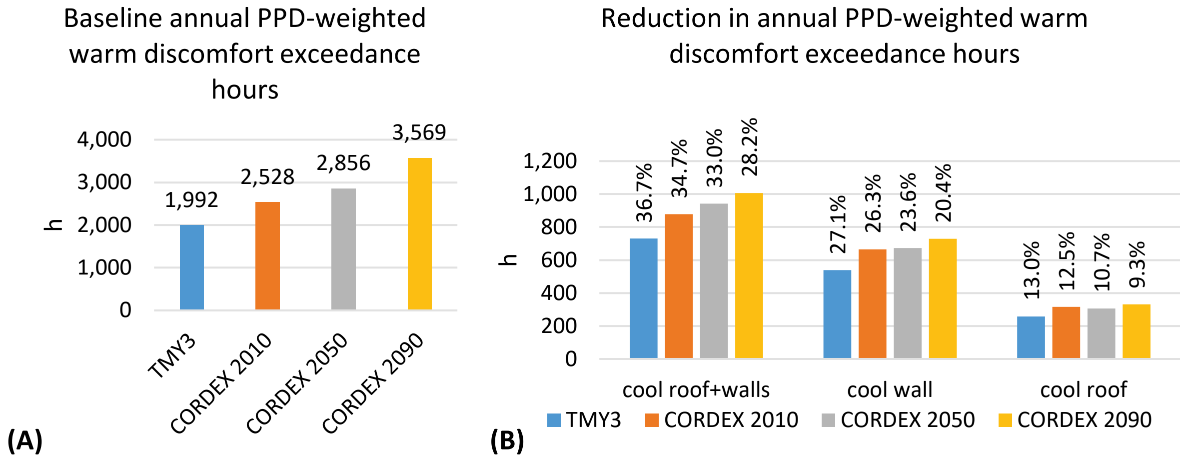

Figure 3. (A) Baseline annual PPD-weighted warm discomfort exceedance hours for a mechanically cooled single-family home in Los Angeles with typical historical weather (TMY3 and CORDEX 2010), mid-term future weather (CORDEX 2050), and long-term future weather (CORDEX 2090). (B) Absolute and fractional reductions in this metric.

For a home without mechanical cooling, thermal comfort evaluation uses the adaptive model. Figure 4A illustrates the baseline annual operative temperature degree-weighted warm discomfort exceedance hours when operative temperatures exceed the allowable upper limit.

The annual operative temperature degree-weighted warm discomfort exceedance hours are greater in the future-year weather datasets. Table 1 shows that CORDEX 2050 weather data has the highest peak outdoor air temperature of 32.6 °C among the future weather dataset; this yields the most operative temperature degree-weighted warm discomfort exceedance hours. Figure 4B shows absolute and fractional reductions in operative temperature degree-weighted warm discomfort exceedance hours. The implementation of cool envelope strategies in the future decreases indoor operative temperature during the summer season, which contributes to the operative-temperature weighted warm discomfort hours reduction. For example, the simulation results show that the cool roof + walls package can reduce the average operative temperature by about 1.3 °C in the Los Angeles prototype home during the summer months of June, July, and August for all weather datasets. The adaptive warm thermal comfort is directly affected by the indoor allowable operative temperature upper limit during the summer season. As the future weather datasets exhibit increased outdoor air temperatures, the adaptive operative temperature upper limit is also increased. This upward adjustment expands the comfort boundary, resulting in reduced discomfort for occupants as they adapt to higher temperatures in the future. Values of CDD18°C during the summer months (June, July, and August) are 155 °C·day for TMY3, 182 °C·day for CORDEX 2010, 277 °C·day for CORDEX 2050, and 310 °C·day for CORDEX 2090. Figure 4B demonstrates smaller discomfort reductions in the future caused by the increased upper limit. Cool envelope strategies will be less effective for buildings without cooling systems in the future *when evaluated with the adaptive method*. For example, the cool roof + walls package could improve the adaptive thermal comfort for free-running buildings by about 22% with TMY3 weather data, but only 16% with the future long-term CORDEX 2090 weather data.

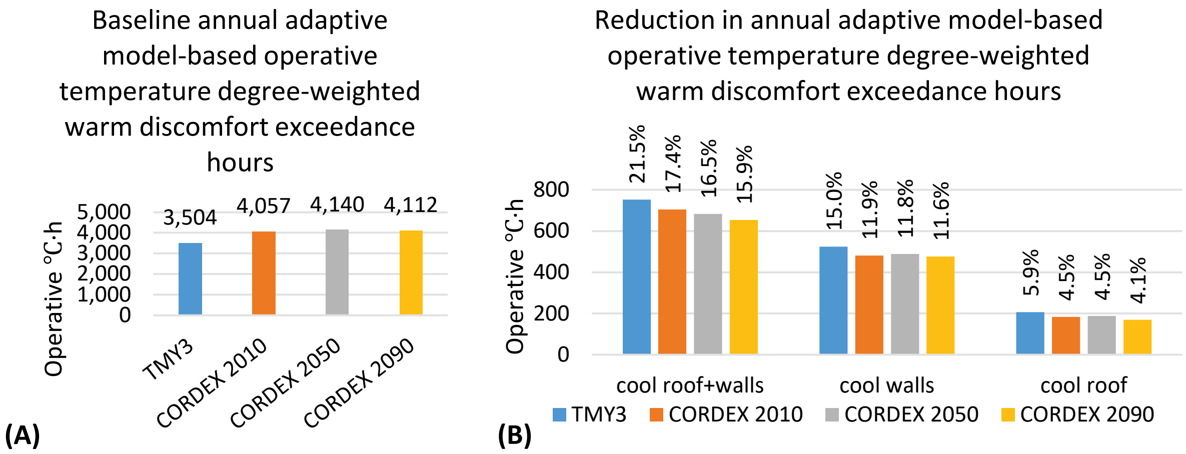

Figure 4. (A) Baseline annual adaptive model-based operative temperature degree-weighted warm discomfort exceedance hours for single-family home without mechanical cooling in Los Angeles with typical historical (TMY3 and CORDEX 2010), mid-term future (CORDEX 2050) and long-term future (CORDEX 2090) weather data. (B) Absolute and fractional reductions in this metric.

Occupants can be endangered from heat stress under the heatwave events if a home does not have mechanical cooling systems. For the heatwave event, heat stress can be evaluated using the HWY weather data for the heatwave period.

Figure 5A shows the baseline daily SET degree-weighted hot discomfort exceedance hours based on the heat stress model assuming there is no mechanical cooling system. The heat stress evaluation finds that the baseline daily heat stress is about 19 °C·h in each heatwave event. Figure 5B shows the heat stress reduction for each strategy and weather dataset compared to the baseline. The greatest heat stress reduction is realized in the historical heatwave (year 2019). In Table 2, it can be observed that heatwave period in 2019 has the shortest duration days and the highest average solar radiation among the three heatwave events analyzed, contributing to greatest heat stress reductions. On the other hand, the long-term future heatwave of 2086 exhibits the longest duration of 51 days with lowest average solar radiation during the heatwave period, resulting in the lowest heat stress reduction. For both energy savings and discomfort reduction, the benefit of (cool roof + walls) was within 7% of the cool-walls benefit plus the cool-roof benefit.

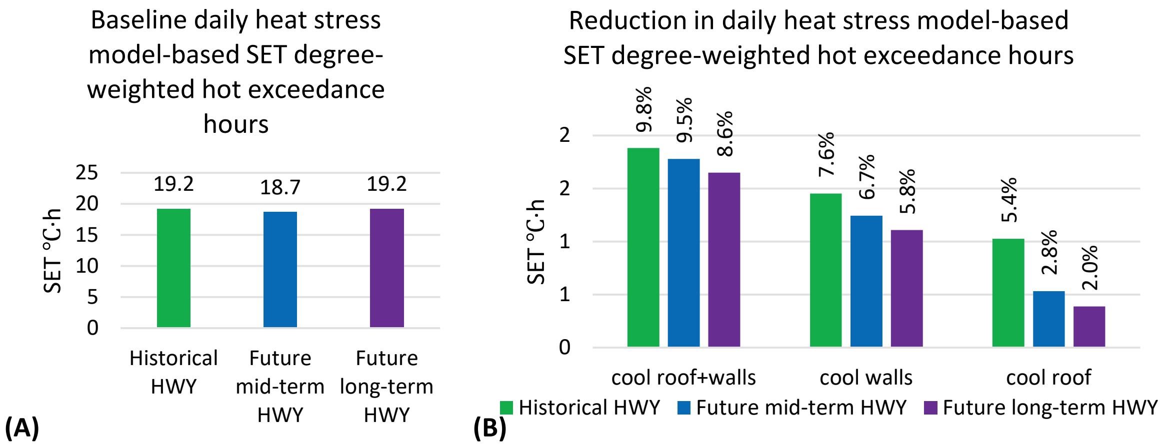

Figure 5. (A) Baseline daily heat stress model-based SET degree-weighted hot exceedance hours for single-family home without mechanical cooling in Los Angeles with historical, mid-term future, and long-term future heatwave weather data. (B) Absolute and fractional reductions in this metric.

Summary

This paper investigates how a cool roof, cool walls, and the cool roof + walls package (cool roof plus cool walls) can mitigate energy and thermal comfort challenges in a single-family home in Los Angeles under various historical and mid- and long-term future weather conditions. To assess the effectiveness of these strategies, we used EnergyPlus simulations of single-family home prototype energy models with and without mechanical cooling. We developed historical, mid-term future, and long-term future weather data based on the TMY3 and IPCC's RCP 8.5 scenario and used them for building energy simulations. Our study evaluated the impact of cool envelope strategies on HVAC primary energy intensity and thermal comfort changes compared to a baseline model.

Our findings show that annual HVAC energy consumption increases when the building is simulated with future weather data. For all weather datasets, cool walls offer about 2 times greater advantages than a cool roof in terms of HVAC energy use intensity savings, while the cool roof + walls package demonstrates about the same savings of the sum of the individual savings from the cool roof and the cool walls. Although absolute savings are higher in future years, fractional savings are lower because baseline energy usages is greater in the future. Occupants of homes with mechanical cooling systems will experience more warm discomfort exceedance hours in the future. However, cool envelope strategies help reduce warm discomfort exceedance hours. In the future, the cool roof + walls package can reduce warm discomfort by at least 28% in single-family homes with mechanical cooling systems. For homes without mechanical cooling, the cool roof + walls package can reduce warm discomfort operative temperature weighted hours by at least 16%. However, its effectiveness is reduced when evaluating adaptive thermal comfort in the future because outdoor air temperatures are rising. We also evaluated occupant heat stress during heatwave events for homes without mechanical cooling. We used the HWY weather data to evaluate SET degree-weighted hot exceedance hours for the heatwave period, finding that the cool roof + walls package can reduce heat stress by about 9% during heatwave events.

Acknowledgments

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Office, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. The authors wish to recognize Marc LaFrance and Sven Mumme, Technology Managers of the Building Technologies Office of the US Department of Energy for their support and assistance in this work. We also thank IEA Annex 80 colleagues Chen Zhang and Ongun Berk Kazanci for their leadership of the simulation efforts, and Annex 80 operating agent Peter Holzer for leading development of KPIs.

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