Cool roofs can mitigate cooling energy demand for informal settlement dwellers

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Abstract

Cities are critical to meeting our sustainable energy goals. Informal settlement redevelopment programs represent an opportunity to improve living conditions and curb increasing demand for active cooling. We introduce an energy modeling framework for informal settlements to investigate how building design decisions influence the onset of heat stress and energy-intensive cooling demand. We show that occupants of tropically-located informal settlements are most vulnerable to prolonged heat stress year-round. Up to 98% of annual heat stress exposure can be mitigated by improving the building envelope. We find a universal solution (cool roofs) that reduces up to 91% of annual heat stress exposure. Finally, we show how proposed redevelopment building schemes could worsen thermal conditions of dwellers and further increase urban energy demand. Our results underscore how building design affects human well-being and highlight potential near-term and long-term pathways for reducing energy-intensive cooling demand for 800+ million informal settlement dwellers worldwide.

Highlights

- This paper introduces a generalizable energy simulation framework to evaluate heat stress exposure in informal settlements.
- We utilize our framework to explore 150,000+ design scenarios across 17 global cities.
- Our results find that building envelope materials are the most influential design factors affecting indoor heat stress.
- We find that cool roofs are can reduce up to 91% of annual heat stress exposure in tropical climates.
- Informal settlement redevelopment may introduce cooling demand inequity among building occupants.

Keywords

Heat stress, space cooling, informal settlements, energy simulation, building energy

Word count

7515 words

List of abbreviations (including units and nomenclature)

ACH	Air changes per hour

ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BEM	Building energy modeling
ECM	Energy conservation measure
HVAC	Heating, Ventilation, and Air-Conditioning
ISO	International Organization for Standardization
NGO	Non-governmental organization
PMV-PPD	Predicted Mean Vote – Predicted Percentage Dissatisfied
SDG	Sustainable Development Goal
TMY	Typical Meteorological Year
UBEM	Urban building energy model
WBGT	Wet bulb globe temperature

1 Introduction

The world is rapidly urbanizing. As cities account for over 75% of global primary energy consumption [1], this growth only exacerbates the importance of urban energy efficiency for the world's long-term energy future. Much of this growth is occurring in cities of the "Global South" (e.g., Mumbai, Nairobi, Jakarta) where it is projected that 90% of the world's urban population growth is expected to occur [2]. However, in many of these massive cities of the Global South, informal settlements, or informal settlements, represent the struggle to keep up with rapid rural-to-urban migration, large influxes of refugees, high birth rates, and globalization [3]. Nearly 1 in 8 people globally (800+ million people) live in informal settlements or "informal settlements" – characterized by poor quality of life and lacking water, sanitation, and housing infrastructure or security of tenure [3]. Another neglected aspect of informal settlement housing is increased vulnerability to heat stress and risk of mortality [4]. The UN HABITAT's New Urban Agenda [5] highlights informal settlements as a key to achieving several of the Sustainable Development Goals (SDGs) including the expansion of energy access (SDG7), the promotion of human health and well-being (SDG3) and the provision of better quality housing (SDG11). While active cooling (e.g., air conditioning) can mitigate the consequences of heat stress, it accounts for 10% of global electricity demand and is expected to sharply increase in tropical countries resulting from climate change [6–8] and growing household incomes [9]. While SDG7 accounts for rising global temperatures in how to close the energy poverty gap, the expected demand for space cooling needed to offset heat stress exceeds this estimate [10].

Global NGOs and local governments have proposed redevelopment schemes to improve informal settlement living conditions – initiatives that involve demolition and reconstruction [11]. For example, India's *Housing for All* policy is working to transform existing informal settlements into dense, high-rise social housing units by 2022 [12], and Kenya's Informal settlement Upgrading Programme (KENSUP) aims to provide existing informal settlement dwellers across the country with improved mid-rise housing and urban sanitation infrastructure by 2020 [13]. However, in surveys that reviewed the socio-economic and human health outcomes of past informal settlement upgrading projects, results have been mixed in their effectiveness to improve quality of life [14,15]. In the case of Nairobi's redeveloped Kibera settlement, while informal settlement upgrading improved housing infrastructure, many of its new occupants reported increased financial burden [16] and reduced social cohesion [17]. Previous work [11,18] has also demonstrated how proposed redevelopment designs in Mumbai may actually exacerbate thermal discomfort and related health consequences. While these works show that a lack of well-informed designs or policies can negatively affect some of the world's most vulnerable communities, they do not investigate potential low-energy solutions to overcome these challenges.

Extensive academic research has utilized physics-based building energy models (BEM) to understand how building design decisions influence cooling energy demand at both the building [19,20] and urban [21,22] scales. It is well established in academic literature that building design and the urban form heavily impact thermal comfort, well-being, and economic productivity [10,23,24]. However, because the majority of these studies have predominantly focused on developed cities and formal buildings, we lack an understanding for how similar decisions affect informal buildings in the Global South – where rising global temperatures will likely lead to the greatest increased demand for active cooling [10]. It is expected that 70% of India's 2030 building stock has yet to be constructed, and Africa is predicted to have the largest growth in its construction industry of all major geographic regions worldwide [25]. Given the magnitude of future new construction and urbanization occurring across the Global South, the energy and thermal comfort implications are enormous. The decisions being made today about informal settlement upgrading and redevelopment programs will undoubtedly shape the thermal comfort and subsequent urban energy demand for decades to come.

Here, we develop a methodology that leverages building energy modeling tools to assess how building design parameters (e.g., building materials, ventilation) contribute to active cooling demand – measured through indoor heat stress exposure. We develop building energy models that describe existing indoor thermal conditions of informal settlements in 17 cities across the Global South. We then expand these models by evaluating how their exposures to heat stress change under various in-situ retrofits and proposed redevelopment schemes. We show how cool roof retrofits can provide low-cost, short-term pathways to passively improve thermal comfort. Finally, we describe how proposed redevelopment designs can worsen indoor comfort through rising indoor temperatures that subsequently increase energy demand for space cooling. We discuss how a parameterized energy modeling framework can inform informal settlement redevelopment to curb demand for urban space cooling and direct our cities towards a sustainable energy future.

2 Background

Buildings consume energy to support the demands of their occupants. Often one of the most energy-intensive building services is balancing the thermal loads (i.e., adding or removing sensible or latent heat) required to meet indoor thermal comfort expectations. Because building energy consumption is so closely linked to indoor occupant thermal comfort, an extensive amount of research has been dedicated to studying the relationship between the two. Historically, most academic literature related to studying building energy use and thermal comfort has been focused on the developed world; however, an increasing amount of research has begun to extend its scope to the developing world.

Thermal comfort is a subjective response from building occupants that describes their perceptions about their comfort within the indoor environment (i.e., is a space too hot, too cold, or just right). Thermal comfort is the basis for how building occupants or facility managers operate HVAC systems, which can account for 30-40% of a building's total energy consumption [26]. Because it is subjective, the same indoor environment can be perceived differently between people based on both physiological factors and psychological factors [27,28].

There are two primary metrics that researchers use to evaluate thermal comfort: steady-state and adaptive comfort approaches [29]. Steady-state methods are based on the idea of achieving thermal equilibrium between a person's body and the environment in which it is located. This measure of equilibrium of often reported through the Predicted Mean Vote-Predicted Percentage Dissatisfied (PMV-PPD) model, in which its score, based on four physical parameters (air temperature, relative humidity, air velocity, mean radiant temperature) and two human parameters (clothing insulation, metabolic activity level), dictates if the indoor environment is acceptably comfortable to a specified percentage of its occupants [30]. However, it has been shown that while these results hold for air-conditioned buildings, they are less reliable in naturally ventilated ones (comfortable indoor temperatures increase in warmer climates within naturally ventilated buildings) [31]. This is a potential issue in hot and humid countries like India, in which low-income households will often rely more on ceiling fans and natural ventilation versus any other active cooling system [32].

Adaptive comfort models are derived from field studies that determine the actual acceptance of the thermal environment based on the dynamic interaction between people and the built environment

[33].Thermal adaptation is unique to a region as it is often influenced by both the seasonal climate as well as other cultural norms (e.g., types of indoor activities, clothing choices) [34,35]. For example, while ASHRAE-55 standards [36] and ISO 7730 [37] dictate acceptable indoor operative temperature ranges of 20-26˚C during the year, previous work exploring apartment buildings [38] and offices [39] in a temperate region of India found that actual comfort ranges were instead 26-32˚C. Similarly, an adaptive comfort study done in Chongqing, China, with a warm, temperate climate, found that its actual ranges of thermal comfort were typically broader than those defined by ASHRAE-55 but narrower in extreme temperatures [40]. These discrepancies are largely the result of thermal adaptation measures (e.g., window operation) that make building occupants more comfortable [41,42]. While adaptive comfort models can capture thermal comfort in a more localized manner, they are not generalizable to other cities or countries. For example, while several studies by Indrigranti [38,41] all take place in the Indian context, they each only encompass one out of five of the country's climate zones. This has since motivated the development of a single adaptive comfort model for every Indian climate zone based on local climatic adaptations [43]. Overall, while there is an extensive body of literature describing methods to measure indoor thermal comfort, they are limited in how they can be generalized across demographics, climate zones, and building types.

While the steady-state and adaptive comfort methods rely on subjective measurements of how people perceive indoor environmental conditions, other methods of measuring thermal comfort are based on human health and safety considerations. For example, heat stress has been shown to negatively affect human health (e.g., exhaustion, heat stroke) when people are consistently exposed to a wet bulb globe temperature (WBGT) above 35˚C for at least 4-6 hours [4]. Heat index, or apparent temperature, is the measure of a "feels like" temperature to the human body and is based on a combination of relative humidity and air temperature [44]. While it is less often used to evaluate building-related thermal comfort, this measure is used as the basis for indoor occupational safety limits [45].

There are two primary methods in which designers and engineers can evaluate thermal comfort and cooling energy demand in buildings: data-driven, statistical models and physics-based building energy models (BEM). The global deployment of sensing technologies, combined with the rapid development of new machine learning models has allowed for more computational approaches to understanding hidden patterns of building performance. As a result, these emerging data-driven prediction models have been able to achieve high degrees of accuracy in the prediction of PMV-PPD scores utilizing wearable technologies and high frequency indoor environmental data [46] and deep artificial neural networks [47]. Other works have instead focused on forecasting indoor air temperature or relative humidity given the local weather conditions outside the building of study. For example, utilizing data on outdoor temperature, solar insolation, and window operating patterns, Moon et al. trained an ANN to predict indoor dry bulb temperature and relative humidity [48]. This type of deep learning-based modeling has been replicated in other contexts including Turkey [49], Canada [50], and Cameroon [51] – all with the broader objective of forecasting indoor thermal performance. And, by drawing from data describing building design characteristics, outdoor weather, and historical energy demand, data-driven models have also been previously used to predict building cooling energy demand [52]. Despite their high accuracy, data-driven models predict future building conditions based on prior mathematical patterns in their training datasets and therefore largely have no grounding in physical or thermodynamic theory. Because of this, these types of models are unable to inform decision-making on how to improve thermal comfort or lower cooling demand through physical changes to a building (i.e., retrofits).

Building energy models (BEM) simulate the underlying energy-consuming thermodynamic processes in a building by abstracting building geometries to a series of interconnected nodes. These nodes are then used to solve heat balance equations based on a set of assumed non-geometric building characteristics (e.g., building materials, occupancy schedules, HVAC types). These tools are based on a series of deterministic inputs and modeling assumptions, which, if incorrectly defined, can result in unreliable predictions of building performance – especially in low-energy buildings [53,54]. Models developed to estimate thermal comfort in simulation software tools such as EnergyPlus [55] are capable of outputting predictions of thermal conditions such as dry bulb temperature, relative humidity, and cooling energy demand on granular scale. Because the outputs from building energy models rely on the building-related inputs given to them, their results emphasize how thermal comfort and cooling energy demand are influenced by the physical and operational characteristics of a building. This concept has subsequently been used to demonstrate the importance of design factors such as fan speed [56], wall insulation [57], overhang projection [58], and building height [59] on thermal comfort. Using a building energy model of a multi-family residential building, an analysis by Yıldız et al. [60] found that window performance (e.g., window-to-wall ratio, U-value, and solar heat gain coefficient) was the most significant factor affecting cooling demand in hot and humid climates. Overall, while these physics-driven models provide an interpretable way of understanding how various building design characteristics affect thermal comfort, their results can be challenging to validate, especially when ground-truth data is not available [61].

In addition to predicting the thermal comfort and cooling demand of existing buildings, building energy models have also been previously used in two aspects of early-stage design: sensitivity of building performance to design parameters and optimization of their values with respect to a pre-defined objective. Sensitivity analyses allow designers to evaluate a critical set of design parameters to understand their individual effects on building performance. For example, previous work applying parametric analyses found that window-to-wall ratio and building morphology were most influential in affecting indoor operative temperature and relative humidity in low-income housing in Mumbai [18]. A similar cross-city analysis done in India found that active cooling equipment, building typology, and construction materials all heavily affected cooling energy demand [62]. And a previous work employing parametric energy simulations with an exhaustive search optimization algorithm found that building performance indicators including energy use intensity and energy resilience were most sensitive to modifications in wall constructions and window sizing [22]. While parametric analyses tend to take a more brute-force approach (i.e., modeling all possible design combinations based on selected design parameters), optimization-based approaches to early-stage design aim to utilize more computationally efficient workflows and advanced algorithms to satisfy one or multiple design objectives [63]. Multi-objective genetic algorithms have been used to optimize building design based on tradeoffs between life cycle cost and annual thermal discomfort hours [64] and energy consumption and thermal comfort [65,66].

While initially designed for building performance estimation on a single building scale, the building energy modeling research domain has since evolved to focus on larger models that assess larger neighborhoods or urban areas. While the magnitude of data inputs required to model hundreds, if not thousands, of buildings across a city often requires the urban simulation to be simplified through resistance-capacitance (RC) models [67] or representative archetypes [21,68], these urban building energy models (UBEMs) can provide detailed depictions of building energy and thermal performance on a larger geographic scale. For example, it is well established that urban building energy performance is significantly influenced by a building’s urban context – factors that may include surrounding buildings [69], microclimatic effects [70], or the broader urban form [71,72]. UBEMs, especially when combined with urban climate models such as urban canopy models or computational fluid dynamics, have been able to predict outdoor thermal comfort and assess the effects of urban heat island and radiation exchange on building energy demand [73,74]. Because they excel in building energy performance prediction on larger spatial scales, these tools have also been used extensively to evaluate district heating and cooling demand [75–78]. However, because of the steep data and computational requirements, most UBEM research has been applied to American and European contexts [79]. Few UBEMs have been developed for cities in low or middle-income countries, and aside from [18], no UBEMs have been developed for informal settlements.

Given the data limitations and lack of digital infrastructure in informal settlements, similar studies in these contexts have largely focused on their electrification [80] and provision of energy access [81]. However, recent work has begun to focus on localized case studies to predict the impact of various building materials and vernacular architectural design on thermal comfort. For example, a building energy model was developed to assess 35 combinations of wall and roof material options for informal settlements in

Nairobi and New Delhi [82]. Vernacular design – where buildings are constructed based on the environmental, historical, and cultural backgrounds of a local region [83] – has been highlighted as an effective strategy to improve thermal comfort through high ceiling heights in India [84] and self-shading building layouts in Brazil [85]. Others have explored the effects of building typology [86] and alternative brick materials [87] on energy consumption. Because of the limited information on energy consumption and/or existing indoor environmental conditions, it remains a challenge to validate these sorts of models to have reliable insights on early-stage design or future retrofit performance.

Overall, informal settlements, which include hard-to-reach communities of people with limited access to energy, are largely underrepresented in the energy research literature. While many of the studies highlighted here present novel approaches to predicting thermal comfort and cooling energy demand or evaluating retrofit pathways to improve building performance, their data (and associated financial) requirements are massive [88]. These studies largely require a combination of data describing indoor environmental conditions, building design information, and human reviews of thermal comfort, and because informal settlements typically lack this type granular and localized data, it would be a challenge to replicate these works in this sort of built environment. By leaving this significant portion of the urban environment out of energy planning and management, cities may struggle to allocate clean and reliable energy to these communities – a central tenant SDG7. As a result, this paper introduces a generalizable framework that, given limited observational and sensor data, leverages urban-scale building energy modeling tools and parametric analysis to evaluate the exposure of heat stress in informal settlements. Using these insights, we demonstrate how simple interventions of existing informal settlements can reduce the need for a blanketed, energy-intensive active cooling solution to achieve adequate thermal comfort.

3 Methods

In this section, we describe our computational energy modeling framework used to study the thermal comfort and cooling energy requirements of informal settlements, as shown in Figure 1. Buildings rely on space cooling to help balance thermal loads to achieve desired thermal comfort conditions for its occupants. As the amount of time occupants are exposed to indoor heat stress increases, the amount of energy required to sufficiently cool an indoor environment also rises. Because so many informal settlement dwellers do not have access to reliable electricity and mechanically driven space cooling [89], we instead use heat stress exposure as a proxy to evaluate the required energy demand for providing adequate active space cooling. To measure the risk of heat stress exposure, we develop physics-based building energy models in EnergyPlus [55] to determine the indoor thermal conditions of buildings representative of existing informal settlements. To demonstrate how this energy modeling framework can be broadly applied to cities of varying geographies, climates, and levels of urbanization, we performed our assessment of heat stress exposure and space cooling energy demand on five geographically diverse countries and major cities containing large populations of informal settlement dwellers within them. However, because each informal settlement is inherently unique from all others, we apply an exhaustive search method (i.e., simulate all combinations of possible design choices from a discrete search space) to an urban building energy model in EnergyPlus – a physics-based building energy modeling tool. By doing so, we can explore how the design of informal settlements influences heat stress exposure and the correlated demand for space cooling. While the exhaustive search method is computationally intensive than other optimization-based approaches, it provides a modeler with the full solution space of how design decisions affect building energy performance. Overall, this method was developed to strike a balance between the real-world constraints of collecting detailed building information in low-income communities while still accurately characterizing the impact of potential retrofits and redevelopment plans. The following subsections describe each of the steps in this framework as well as the method to calculate heat stress exposure in additional detail.

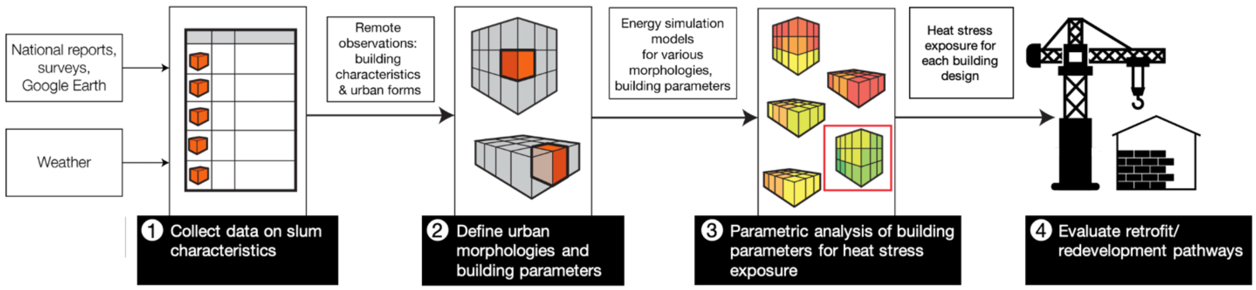

Figure 1. Schematic of generalizable building energy modeling approach. First, typical weather information and data from national reports, surveys, and building codes, as well as local news articles and peer-reviewed journal articles, are collected for information on the existing conditions of informal settlements. Next, the observational data is used to develop a set of urban morphologies and building design parameters in a physics-based building energy modeling (BEM) platform called EnergyPlus. We then simulate each combination of possible design parameters for a selected location to generate a database of indoor environmental comfort. These results are then assessed to understand how different combinations of building parameters impact heat stress exposure and subsequent space cooling needs in different parts of the world. Finally, using these insights, modifications to the existing informal settlement models can be made to understand how incremental retrofits would impact the thermal comfort of its residents.

3.1 Data collection

One of the primary challenges associated with modeling urban built environments of cities in the Global South is the lack of data available to describe them. Previous work [11,18] leveraged observational and in-situ sensor data to develop and validate energy models to characterize informal settlements in Dharavi, Mumbai, India. However, because this work is a cross-city study of many informal settlements, we also rely on observational data from peer-reviewed journal articles, national surveys and building codes, Google Earth, and local news articles. These observational sources are used to create a representative database of typical materials and construction practices used to build informal settlements in each city studied as part of this work. In addition to collecting data on how informal settlements are constructed (which we refer to as "Baseline" materials), we also collect data on materials commonly found in residential buildings constructed in compliance with their national building code (defined as "Building Code" materials). A summary of this database can be found in Table 1.

Table 1. Data table of building materials and construction practices used in informal settlements, organized by country. For the roof, floor, wall, and window constructions, material information is collected for both existing informal settlements ("Baseline" materials) as well as residential buildings constructed in compliance with their national building code ("Building Code" materials).

Parameter Name	**India** *Mumbai, Jodhpur, Allahabad, Bangalore, Dehradun*	**Brazil** *Bélem, Curitiba, Rio de Janeiro, São Paulo*	**South Africa** *Cape Town, Durban, Johannesburg*	**Kenya** *Nairobi, Mombasa*	**Indonesia** *Jakarta, Palembang, Surabaya*
Weather	Local weather data for specific city				
Morphology	Low-rise Morphology A, Low-rise Morphology B, Redevelopment Option A, Redevelopment Option B				
Orientation	0˚, 90˚, 180˚, 270˚				
Urban Context/ Urban Shading	None, single-story shade, multi-story shade				
Ventilation	***Baseline***: 0.43 ACH, 1.89 ACH, 3.90 ACH (operates when indoor air temperature > 26˚C) ***Retrofit:*** 6.00 ACH (operated when air temperature is > 26˚C)				

Household Size	4, 6, 8 people				
Lighting and Electric Power Density	1.5 W/m^2, 3.0 W/m^2				
Roof Construction *(and associated U-value)*	***Baseline:*** Concrete (U = 2.62) Corrugated metal (U = 3.83) ***Building Code:*** Concrete/clay tile (U = 0.30)	***Baseline:*** Concrete (U = 2.62) Corrugated metal (U = 3.83) ***Building Code:*** Concrete/clay tile (U = 0.30)	***Baseline:*** Corrugated metal (U = 3.83) ***Building Code:*** Concrete/clay tile (U = 0.30)	***Baseline:*** Corrugated metal (U = 3.83) ***Building Code:*** Concrete/clay tile (U = 0.30)	***Baseline:*** Concrete (U = 2.62) Wood (U = 3.04) Corrugated metal (U = 3.83) ***Building Code:*** Concrete/clay tile (U = 0.30)
Floor Construction *(and associated U-value)*	***Baseline:*** Concrete (U = 2.07) Dirt (U = 2.17) ***Building Code:*** Concrete (U = 1.34)	***Baseline:*** Concrete (U = 2.07) ***Building Code:*** Concrete (U = 1.34)	***Baseline:*** Concrete (U = 2.07) Dirt (U = 2.17) ***Building Code:*** Concrete (U = 1.34)	***Baseline:*** Dirt (U = 2.17) Soil-stabilized bricks (SSB) (U = 2.37) ***Building Code:*** Concrete (U = 1.34) Coral stone (U = 1.45)	***Baseline:*** Wood (U = 2.67) ***Building Code:*** Concrete (U = 1.34)
Wall Construction *(and associated U-value)*	***Baseline:*** Brick (U = 1.65) Concrete (U = 2.62) Rammed earth (U = 1.76) ***Building Code:*** Brick (U = 0.29) Concrete (U = 0.30) Rammed earth (U = 0.33)	***Baseline:*** Brick (U = 1.65) Concrete (U = 2.62) ***Building Code:*** Brick (U = 0.29) Concrete (U = 0.30)	***Baseline:*** Brick (U = 1.65) Wood (U = 1.87) ***Building Code:*** Brick (U = 0.29) Concrete (U = 0.30)	***Baseline:*** Coral stone (U = 3.43) Soil-stabilized bricks (SSB) (U = 1.76) ***Building Code:*** Coral stone (U = 0.31) Brick (U = 0.29) Soil-stabilized bricks (SSB) (U = 0.33)	***Baseline:*** Brick (U = 1.65) Wood (U = 1.87) ***Building Code:*** Brick (U = 0.29) Concrete (U = 0.30)
Window Construction *(and associated U-value)*	***Baseline:*** Single pane (U-value = 4.99) ***Building Code:*** Double pane (U-value = 2.36)				

3.2 Defining urban morphologies and building parameters

Building energy models rely on inputs describing the local weather, geometric information (e.g., footprint, height, number of floors), and the various local materials and operational patterns (i.e., electricity consumption, occupancy) to produce hourly predictions of indoor environmental conditions. To contextualize a building energy model within a specific city or region, Typical Meteorological Year (TMY) weather data is used to describe the local climatic characteristics (e.g., dry bulb temperature, relative humidity, wind speed and direction) on an hourly time scale. While these TMY files are more representative of rural landscapes than dense city centers [90], they are easily accessible, open datasets available for thousands of global cities. However, if the appropriate data was available, this modeling framework would also work with historical weather files and weather files that project anticipated regional climate change.

To define the building geometry, we model individual informal settlement dwellings based on a validated 23 m^2 energy model developed for Dharavi, Mumbai, India [12]. Specifically, the energy model was calibrated against measured sensor data of indoor temperature and relative humidity in Dharavi's existing dwellings. The dwelling model received an hourly MBE of 1.07% and CV(RMSE) or 2.26% – acceptable error rates according to ASHRAE Guideline 14 standards [91].

Using the individual dwelling model, we can build up larger urban morphologies to better represent an informal settlement. To describe the various urban morphologies that make up informal settlements, we developed two low-rise informal settlement morphologies (Figure 2): one with dwellings tightly packed together and one with dwellings more spaced out.

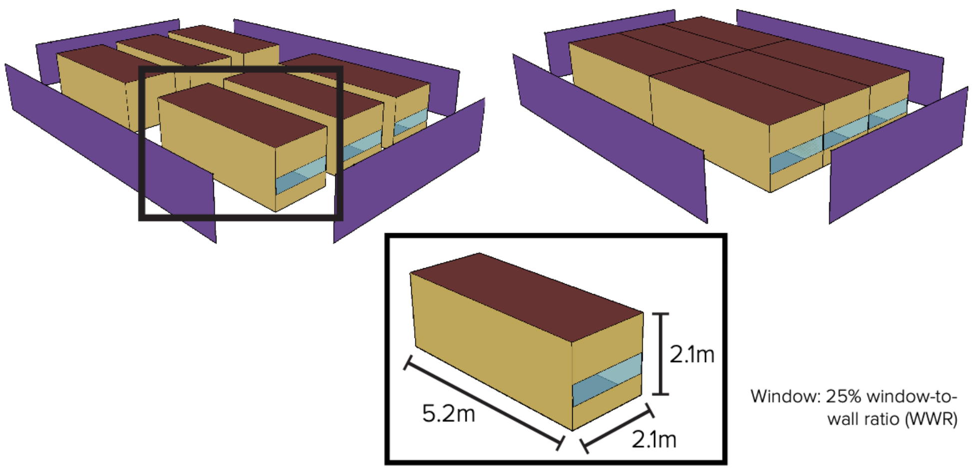

Figure 2. Informal settlement morphologies. The top two, low-rise morphologies represent a tightly-packed informal settlement – characteristic of dense cities – and a more sprawling informal settlement located further towards the city's outskirts. The boxed diagram is a schematic of a single informal settlement dwelling. Each dwelling is 23 m^2 and is based on a validated model by Nutkiewicz, Jain, and Bardhan [18]. The purple structures surrounding these models represent urban shading structures and capture the impacts of how surrounding buildings might shade these buildings throughout the year.

Finally, we define the non-geometric characteristics based on the observational data collected for each city, as described in Section 3.1. While previous work has distilled informal settlements from around the world into a distinct set of urban typologies [92], we found that they are characterized broadly by differences in three parameters: orientation relative to the sun, urban shade caused by surrounding buildings, and ventilation based on the local terrain, measured in air changes per hour (ACH). These three urban-scale characteristics are assigned a set of discrete values that become inputs to the urban building energy model. To determine the building-scale characteristics that will be parameterized in the model, we select 8 factors that are most likely to influence changes in heat stress exposure (e.g., building envelope materials, household size, electricity and plug loads). Each of these 8 characteristics are also assigned a discrete set of values that will be inputs for the urban building energy model. While some of these discrete inputs are agnostic to the location of a particular informal settlement (e.g., household size), others are specific to the city or country they are in (e.g., Brazil and India use different materials to construct buildings). To compare the performance of how informal settlements are currently built to the performance of residential buildings constructed in compliance with local building codes, we simulate our energy models under both "Baseline" and "Building Code" materials described in Section 3.1. We note that we specifically omit HVAC equipment from our model as these systems are not present in informal settlement dwellings and are unlikely to ever get them due to their high operating costs.

In total, the building energy model takes in an 11-dimensional search space for its parametric analysis where each city has a unique set of input values based on the local construction practices and occupancy patterns. A parameter tree representative of the input space for informal settlements in India can be found in Figure 3.

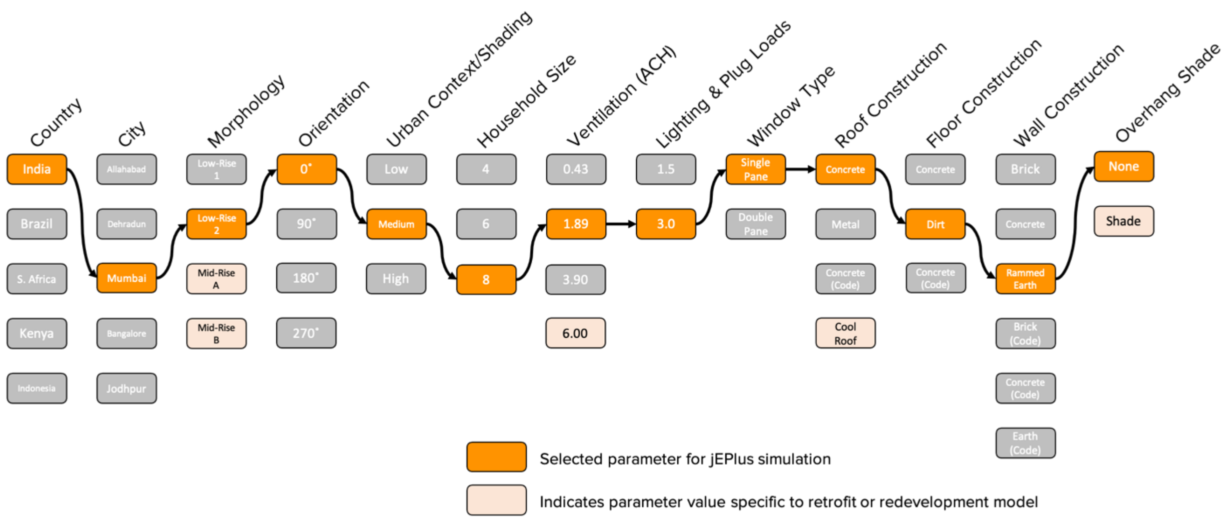

Figure 3. Example of an energy modeling parameter tree representing simulation scenarios for informal settlements in India. For each energy simulation, the model takes a unique combination of each column of parameter values. Each country's parameter tree may differ from one another based on its localized set of building materials.

3.3 Parameterized simulation of informal settlement models

Using the eleven-dimensional search space defined for each city, we simulate every combination of model inputs using a combination of EnergyPlus and jEPlus. EnergyPlus [55] is an open-source, physics-based energy simulation software that calculates energy consumption and indoor thermal performance of a particular building based on the physical and operational characteristics of its design. It is used as a plug-in to jEPlus [93] – a simulation tool used to conduct parametric analyses of building energy model inputs. jEPlus takes in a parameterized energy modeling file that contains a model's information about its weather, geometric, and non-geometric inputs and runs the model with every combination of design parameters (i.e., one value from each column in a parameter tree like the one diagrammed in Figure 4). For every run of the model, jEPlus creates a csv file with hourly predictions of indoor dry bulb temperature, relative humidity, and mean radiant temperature. For each city analyzed as part of this work, jEPlus runs between 10,368 and 23,328 simulations. These results are then assessed to understand how different combinations of building parameters impact heat stress exposure and subsequent cooling needs in each city of this work.

3.4 Calculating heat stress exposure from energy simulation outputs

After simulating all combinations of possible informal settlement designs for each city, we use the outputs from each model to calculate the level of indoor heat stress exposure for its occupants. Given typical values for resting human metabolic rate, previous work has shown that wet bulb globe temperatures (WBGT) of 35˚C can result in irreversible heat trauma in people within 4-6 hours of exposure [4]. While other indicators exist to assess thermal comfort, we selected WBGT as it is considered the ISO standard used to measure the physiological impacts of heat stress[94]. Whereas many thermal comfort indicators provide ranges of acceptable indoor temperatures based on varying demographics and adaptive strategies[95,96], using a threshold value of WBGT to indicate heat stress more inclusively measures relative comfort across diverse populations. We calculate WBGT using the outputs from jEPlus and EnergyPlus.

To evaluate the impact of building design characteristics on heat stress, we define the indicator "Heat Stress Incidents" based on the number of times annually at least one informal settlement dwelling experiences an hourly WBGT greater than 35°C for more than 4 hours. Additionally, we evaluate sensitivity of each simulation parameter most critical to heat stress through a sensitivity equation based on[18,22]:

$$SI_p = \frac{\frac{\tilde{x}_{worst}}{8760} - \frac{\tilde{x}_{best}}{8760}}{\frac{\tilde{x}_{worst}}{8760}}$$

Sensitivity Index (SI_p) is the sensitivity of the average number of heat stress incidents across all dwellings to the design parameter p. $\tilde{x}_{best}$ is the fraction during the year in which an informal settlement experiences heat stress (total number of hours in heat stress divided by 8,760 hours during the year). $\tilde{x}_{best}$ represents the median fraction of annual heat stress exposure out of all design combinations that include the best performing value of the parameter p, and $\tilde{x}_{worst}$ is the median fraction of annual heat stress exposure of all design combinations that include the worst performing value of the parameter.

3.5 Evaluating retrofit and redevelopment scenario designs

To improve the thermal conditions of existing informal settlements, these *Baseline* buildings can either undergo full redevelopment schemes, the more common option, or retrofitting. We compared how each of these pathways would affect heat stress and subsequent space cooling energy demand by assessing two proposed designs for redevelopment and three types of low-cost, in-situ retrofits: cool roofs, increased air ventilation, and shaded overhangs.

As many urbanizing cities in the Global South are looking for solutions to improve the poor living conditions of informal settlement housing, some city planning agencies are proposing mid-rise redevelopment schemes to replace the existing informal settlement morphologies. Therefore, in addition to defining these two low-rise urban morphologies, we also developed two mid-rise morphologies modeled based on schemes proposed by Mumbai's Informal settlement Redevelopment Authority [97] (Figure 4). While these designs were specifically modeled for a redevelopment project in Mumbai, they are similar to building forms used in the redevelopment of Kibera, Nairobi, Kenya [98]. They are exclusively modeled using the building characteristics that comply with local building codes ("Building Code" materials, described in Table 1).

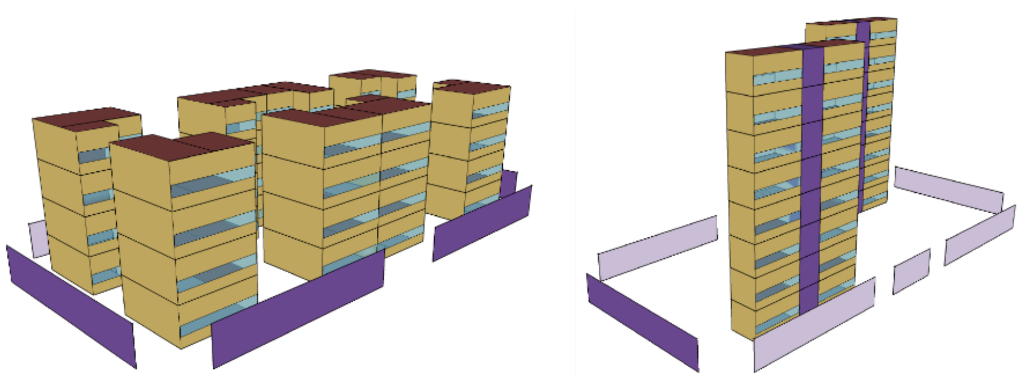

Figure 4. Mid-rise redevelopment morphologies. These building geometries are modeled after designs from [12]. Like Figure 2, the purple structures surrounding these models also represent urban shading that capture the impacts of how surrounding buildings may affect the informal settlements year-round.

Cool roofs – typically created by adding a layer of white paint with high solar reflectance properties – are common low-cost solutions for energy efficiency and thermal comfort in low-income houses in tropical climates [99] or regions or the world with abundant solar insolation [100]. The typical "Baseline" roof materials have a low amount of thermal storage, thus much of the solar insolation given off by the sun that hits the roof will be radiated into the indoor space below it. By adding a layer of reflective paint to the metal roof, more solar insolation can be reflected during the day, minimizing the amount of additional indoor heat gain and subsequent negative thermal comfort effects on the building's occupants. To model this retrofit in EnergyPlus, we add an additional paint layer with a decreased solar absorptance to each type of "Baseline" roof. Increased fan ventilation is modeled by increasing the dwelling's overall air changes per hour when the indoor air temperature increased to above 26˚C, which can mimic how an occupant may open or close windows to regulate indoor temperature, for example. Finally, to assess whether shading the building from direct sun would improve thermal performance, we use EnergyPlus to simulate overhangs over each window in the model.

4 Results and discussion

4.1 Tropical climates increase space cooling energy demand

Throughout the year, cities with the higher median WBGT (up to 25.9˚C in Jakarta, as written in Figure 5) also tend to experience more annual heat stress incidents (up to 76% of the year in Jakarta). These cities are classified as "tropical" climates according to Köppen Climate Classification system and are characterized as having simultaneously high outdoor air temperature and relative humidity [101]. For a city such as Jakarta, where the median dry bulb temperature and relative humidity are 28.8˚C and 74.3% [102], respectively, the high humidity typical of tropical cities means that the human body is less effective in cooling itself and therefore suffers from high exposure to indoor heat stress.

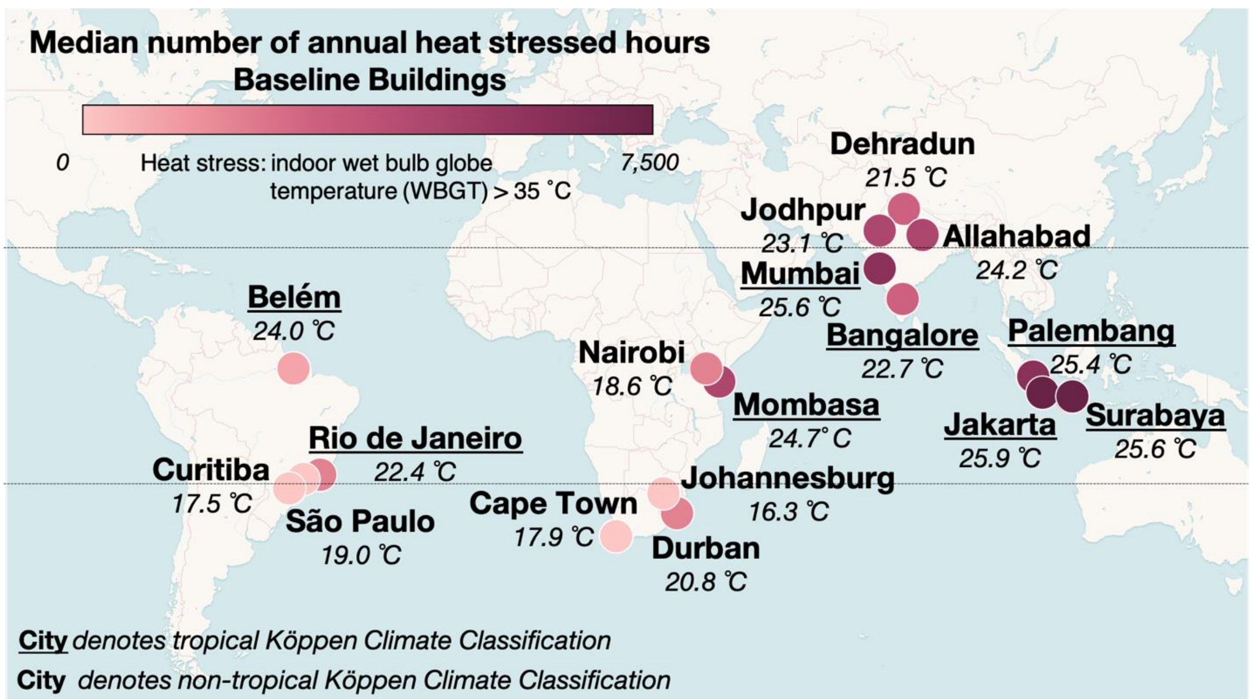

Figure 5. Annual heat stress exposure for all *Baseline* informal settlements (ones built according to current materials and constructions) for each city for a typical year (i.e., no extreme weather events). Each city is annotated with its median hourly indoor wet bulb globe temperature (WBGT). Underlined cities represent those that are classified as having tropical climates.

Through both the map of annual heat stress incidents as well as the heat maps describing heat stress incidents disaggregated at the monthly and hourly scales (Figure 6), we can explore the combined effects of outdoor weather and building design practices on indoor heat stress exposure. For example, while informal settlements in Mombasa and Nairobi are modeled as having the same construction materials and similar operational patterns to one another, the weather in Mombasa increases its residents' vulnerability to heat stress, especially during the summer months (November – April) of the year. But when comparing heat stress exposure in Belém and Palembang, which are both classified as "tropical rainforest" climate zones, we find that the typical building materials in Belém lend themselves to mitigating the onset of heat stress more effectively than Palembang (Palembang experiences indoor heat stress conditions ~66% of the year while Belém experiences ~3%). Tropical cities such as Palembang tend to experience heat stress most often during the summer months and during the second half of the day. Because the construction materials in these *Baseline* informal settlements have low thermal mass (e.g., metal roofs, single-layer brick walls), they are much more prone to changes in outdoor weather conditions. As sun exposure increases throughout the day, heat is more likely to accumulate and cause heat stress in its occupants, thus requiring more cooling energy to maintain comfortable indoor temperatures.

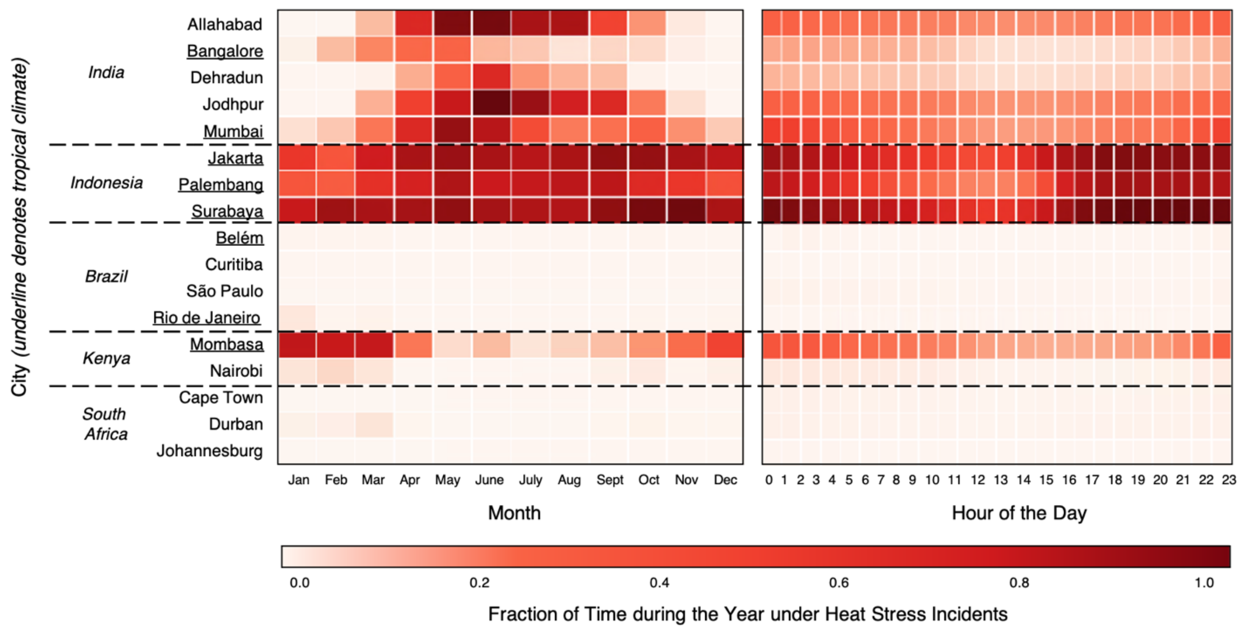

Figure 6. Average number of hours during the month (left) and hours of the day (right) of heat stress across all design combinations for each city. Heat stress incidents are defined as having a WBGT greater than 35˚C for more than 4 hours.

4.2 Heat stress is most sensitive to building envelope materials

Using the *Baseline* models for each city, we further explore the impacts of how varied construction materials, occupancy, and electricity use patterns affect changes in indoor heat stress exposure (Figure 7a) and the subsequent demand for space cooling energy. In addition to modeling the various material options used in informal settlements, we also compare their performance to how these buildings would perform if they were constructed according to their country-specific building codes. The methodology through which we calculate this change in heat stress exposure based on varying building design choices is described in Section 3.4.

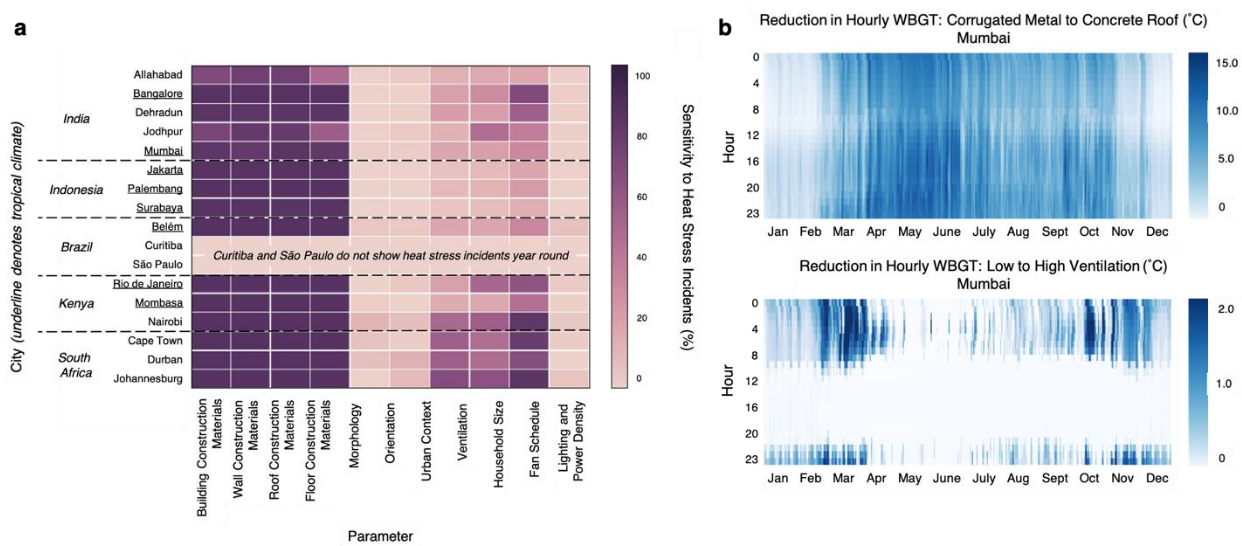

Figure 7. (a) Sensitivity to annual changes in heat stress exposure by urban and building-level design parameters. (b) Reduction in hourly WBGT in Mumbai, India when modifying a single design parameter in the *Baseline* model: metal to concrete roof (top) and low to high ventilation levels (bottom).

The materials used in the building envelope (e.g., roof, floor, walls) of each informal settlement are the most influential of all design parameters to affect indoor heat stress (Figure 7a). The materials compliant with each country's national building code have increased insulation and thermal mass, which reduces the amount of heat that enters each dwelling and therefore makes these buildings less prone to changes in outdoor weather conditions. Passive design methods often rely on improving insulation within the building envelope to decrease the amount of heating or cooling a building requires year-round[60]. These impacts are well illustrated in Mumbai, India, for example, whereby changing the model's roof construction from its worst performing design, corrugated metal, to one with increased insulation that abides by the National Building Code of India [103], an insulated reinforced concrete roof, the number of heat stress incidents drops by ~98%. Furthermore, by switching roofing materials in Mumbai, heat stress exposure is mitigated consistently throughout the year but most often between April and June and October (Figure 3b, top) – the months that surround Mumbai's monsoon season. These are also the months in which Mumbai experiences the most heat stress incidents, according to Figure 6.

In many cities in our study set, including ones with temperate climate zones (e.g., Cape Town, Nairobi), increased ventilation, measured in air changes per hour (ACH), is also a key driver for changes in indoor heat stress exposure. The change in ventilation mimics an increase in outdoor air flow in and out of a space (e.g., opening and closing windows) and takes place when the indoor air temperature exceeds 26˚C. Using Mumbai as an example, by increasing ventilation from 0.43 ACH to 3.90 ACH, heat stress exposure can decrease as much as 39%, especially during the early and later hours of the day in the months that surround local monsoon season (Figure 7b, bottom) – the time of year when heat stress exposure is highest. Here, increased ventilation plays a moderate role in improving indoor thermal performance for the remainder of the day. While there are minimal improvements during the afternoon hours of each day resulting from higher ventilation, building policies should emphasize passive or low-energy approaches to night flushing, which, depending on the climate zone, may range from increasing thermal mass to providing additional ventilation through fans. As a result, these isolated design changes should reduce the number of annual heat stress incidents.

Insufficient living area space – a typical characteristic of informal settlements – can also affect indoor comfort conditions. By increasing the household size of each informal settlement, indoor heat stress exposure can increase by up to 75% in Johannesburg. Urban context (i.e., how much shading is provided by surrounding buildings) can also influence indoor heat stress exposure, where increased shade can help reduce the influx of solar insolation that enters a space.

Overall, heat stress can mostly strongly be mitigated without increasing demand for active cooling energy by integrating passive design principles (i.e., improving the insulation of building materials) or increasing the use of ventilation. These two design changes are both decisions typically made on a building scale rather than at a scale required at early stage, urban-scale planning. Therefore, there remain pathways to reduce indoor heat stress exposure through the careful implementation of building retrofits.

4.3 Comparing retrofit and redevelopment cooling energy pathways

As previously introduced, global NGOs and governments are working to improve housing quality of informal settlements through full demolition and reconstruction of these buildings – often referred to as redevelopment. However, because proposed designs for redeveloped buildings do not typically account for their energy or thermal implications, we explore how our modeling framework could also be used to evaluate the possible heat stress conditions of these proposed mid-rise redevelopments. Using four of the most heat stress prone cities, we model these redevelopments based on designs put forward through Mumbai's Informal settlement Redevelopment Authority [97]. Each of the *Redevelopment* models are constructed with a larger floor area ratio using materials compliant with local building codes. Because full-scale redevelopment projects have been previously criticized for causing unintended social and financial burdens on its occupants, we also evaluate the results of these redevelopment schemes against informal settlements in these cities instead retrofitted with low-cost, in-situ updates that would not require full demolition and rebuilding efforts. These *Retrofit* models include the following changes: increased ventilation, overhang shading, and cool roofs. The retrofits are described in detail in Section 3.5. While these measures would not eliminate other characteristic informal settlement deprivations (e.g., adequate living space, security of tenure, improved sanitation), they would serve as a low-cost, short-term intervention to mitigate heat stress and improve human health and well-being in informal settlements.

We find that the most significant reductions in annual heat stress incidents (between 22–91%) occur when implementing any of the three retrofits. The cool roof tends to perform the best across each city (Figure 8). Mumbai and Jakarta, two of the cities that had the highest annual heat stress incidents based on their existing *Baseline* model results, also were found to mitigate the greatest number of heat stress incidents through cool roof retrofits (2,861 annual hours in Mumbai and 3,470 hours in Jakarta). Cool roofs – which involve painting a white, reflective coating on an existing roof material – help reduce heat stress by reducing the amount of solar insolation that can penetrate a roof's surface to reach the indoor environment and are therefore most effective in reducing indoor WBGT during the daytime (Figure 9). Furthermore, because the building envelope is the most influential building design component to effect change in indoor temperature (Figure 7a), incremental improvements to the roof, for example, result in major improvements to the indoor environment.

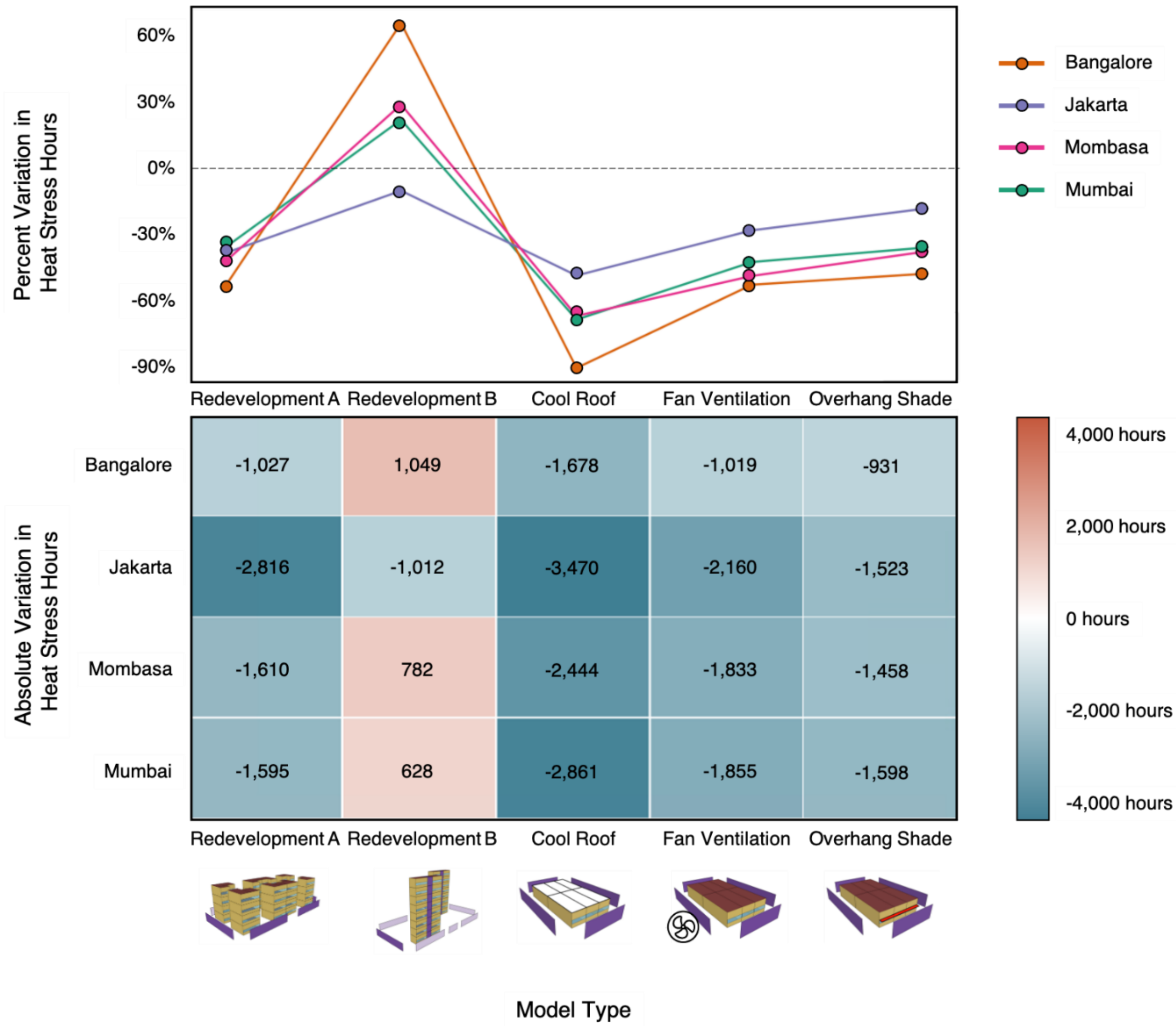

Figure 8. Variation (percentage reduction, top; absolute reduction bottom) of annual heat stress incidents (hours during the year when wet bulb globe temperature (WBGT) is less than 35°C for at least 4 hours) of each retrofit/redevelopment type when compared to *Baseline* model conditions.

Similarly, while increased air ventilation and overhang shade retrofits are also effective in reducing heat stress exposure, because we found that indoor heat stress is less impacted by changes in ventilation and urban context/shading, we would also expect that these impacts on indoor heat stress would be lower than modifications made to a component of the building façade. Increased ventilation is most effective during the earlier and later hours of the day (Figure 9), similar to the improvements found in Figure 7b. Because the objective of an overhang shading device is to limit the amount of solar insolation entering the indoors during the day, it is mostly effective only during the daytime rather than the hours of the day not impacted by the sun (i.e., night-time) and therefore cannot help shed night-time heat gain that is a common source of heat stress in hot and humid climates [4].

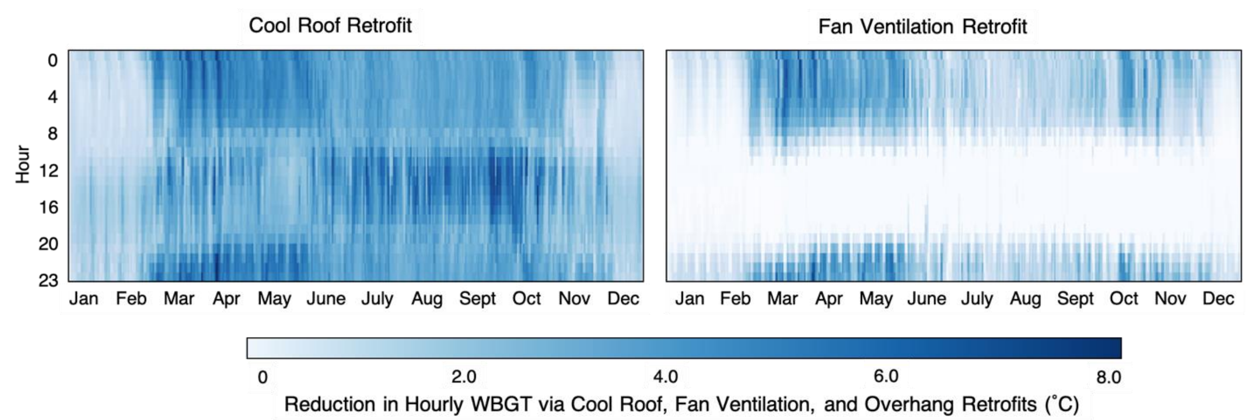

Figure 9. Reduction in hourly wet bulb globe temperature (WBGT) in Mumbai, India when retrofitting *Baseline* models to cool roofs (left) and increased ventilation (right). Details on retrofit modeling assumptions are described in Section 3.5.

Between the two Redevelopment scenarios, Redevelopment Option A significantly outperforms Option B as Option B can actually increase the number of annual heat stress incidents occupants experience. Option A is a shorter (four-story) building whose dwellings are distributed among more buildings and thus benefits from the mutual shade provided between them. Similar to earlier studies [18], there are significant differences in indoor thermal performance depending on the floor a dwelling is situated (Figure 10). While there is little difference in indoor thermal conditions between each building in a particular morphology, for both Redevelopment buildings, as the floor number increases, the WBGT also increases. This is likely because lower floors in naturally ventilated vertical apartments have lower average temperatures due to thermodynamic impacts (i.e., heat rises and settles in higher floors) [38]. Because most *Baseline* buildings are single-story, there is less variation in thermal performance and subsequent exposure to annual heat stress incidents. Finally, despite being modeled using materials that comply with their local building codes, there are increased heat stress equity issues that emerge for occupants located on higher floors.

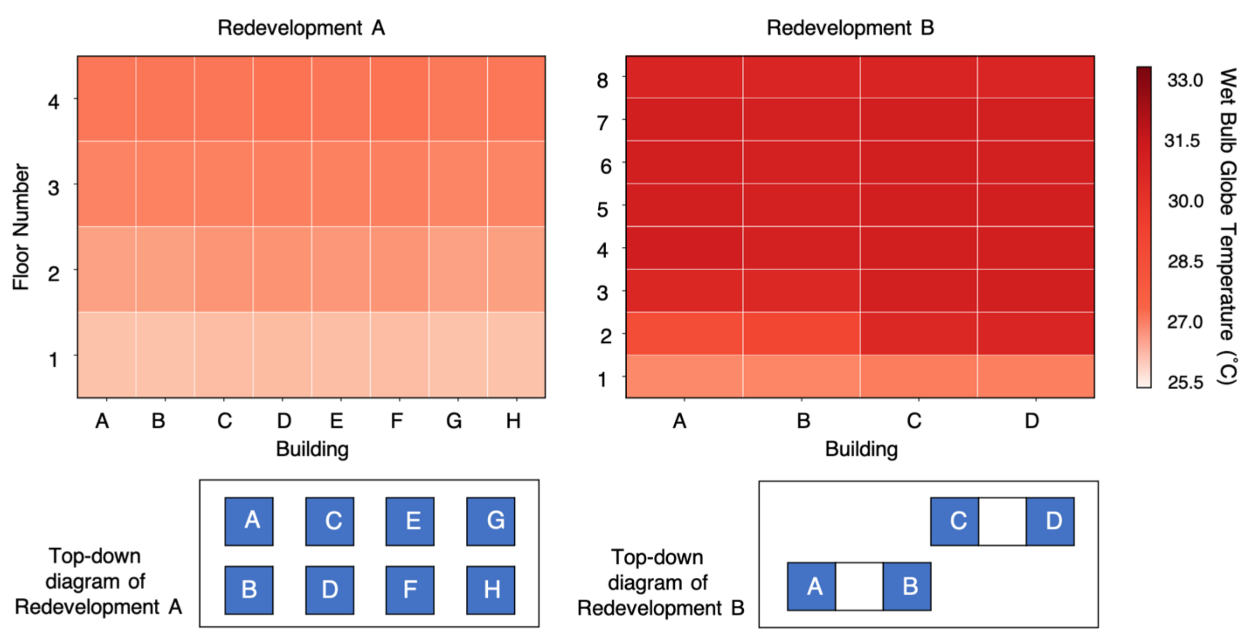

Figure 10. Median WBGT by dwelling for Redevelopment Options A and B in Mumbai, India. The redevelopment options are based on designs proposed by Mumbai's Informal settlement Redevelopment

Authority[97] that represent mid-rise morphologies constructed under building code-compliant construction materials.

Overall, the best solutions tend to recur across each of the five cities. This suggests that the identified heat stress mitigation measures simulated in tropical cities can be broadly applied elsewhere. Broader cross-national policies or funding packages can be proposed to improve indoor thermal comfort for an extensive group of climate-vulnerable communities without the need to rely exclusively on energy-intensive active cooling solutions.

5 Conclusion

In this paper, our objective was to assess the impact of building design-related drivers on heat stress exposure and space cooling-driven energy demand for the 800+ million informal settlement inhabitants across the world. Our analysis confirms that urban informal settlements located in tropical climate zones are at greater risk to heat stress and will require energy-intensive active cooling to maintain livable indoor conditions. The materials that create the building envelope, which include the roof, walls, and floor, affect indoor heat stress the greatest. By improving the building envelope to local building codes, the number of annual heat stress incidents in a city can drop by up to 98%. Finally, we found that cool roof retrofits can outperform government-proposed mid-rise redevelopment schemes and curb up to 91% of heat stress incidents during the year – pointing to viable policy and interventional retrofit pathways. We use heat stress exposure as a proxy to measure potential energy demand for space cooling resulting from various in-situ retrofits and redevelopment schemes. Together, these solutions would immediately improve comfort and well-being outcomes of the 800+ million global informal settlement inhabitants without introducing the dependence of indoor thermal comfort on energy and cost-intensive air conditioning or the social costs of redevelopment.

While low-cost cool roof retrofits provide an effective, short-term strategy to improve thermal comfort, more advanced solutions (e.g., insulated and reflective concrete roofs) would further reduce the vulnerability to indoor heat stress. However, these intensive building design strategies would require additional building reinforcement and investment, which would likely not make sense in existing informal settlements if implemented without consideration for other deprivations (e.g., sanitation, adequate living space, security of tenure) as well. These advanced solutions should come as part of a broader, holistic informal settlement upgrading plan that addresses these other shortcomings and involves a deeper rethinking of urban housing design. While these other deprivations are out of the scope of this paper, we argue that policymaking for informal settlement redevelopment should strongly consider thermal comfort in its design and implementation.

An important contribution of our work is the proposed highly extensible and generalizable modeling framework for informal settlements. While a significant body of work exists to understand where heat stress is mostly likely to impact people globally, such work has been limited in its ability to account for how building design decisions impact this phenomenon – especially in data scarce environments like informal settlements. They often lack comprehensive building plans, material quantifications, and/or information regarding occupancy dynamics – making such buildings difficult to model. Relying on a combination of remote observational data and a small sample of in-situ data, our proposed framework develops representative models that enable researchers and policymakers to understand first-order impacts of various building design considerations on human comfort and heat stress vulnerability. While the selection of building materials and design practices we utilized in our parametric analysis is not exhaustive, both our proposed framework and the cross-city solutions found to best reduce heat stress exposure have been shown to be generalizable across many geographic locations in the world. As a result, our work demonstrates how increasingly detailed data can provide more localized simulations and targeted results. While this is a first step in assessing the broad energy implications of cooling energy demand in informal settlements, our future work aims to assess the life cycle impacts of operational cooling energy and embodied energy in construction materials.

Historic levels of global warming are dramatically increasing demand for cost and energy-intensive active cooling, especially in developing countries of the Global South. Informal settlements are often characterized by poor housing quality, and their occupants' lack of financial or energy access to cooling creates a significant equity issue. However, our assessment of building design drivers and their influence on human heat stress can provide researchers and policymakers with a basis for creating programs that aid adoption of specific energy efficiency in-situ interventions (i.e., thermal insulation, reflective roof surfaces) to help meet the global cooling gap.

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