Passive and low-energy strategies can improve thermal comfort and resilience during sleep

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# Summary

Sleep is a pillar of human health and wellbeing. In the U.S. and other developed countries, there is a high reliance on heating ventilation and air conditioning systems (HVAC) to control the interior thermal environment in the bedroom. However, these systems are problematic for several reasons: they are energy intensive, less accessible due to energy poverty, and their suitability is further compounded by climate change. Passive and low-energy strategies, such as personal comfort systems, may address this challenge, but their effectiveness has not been extensively studied for sleeping. We show that many passive and low-energy strategies are highly effective in supplementing or replacing HVAC systems during sleep. Using passive strategies in combination with low-energy strategies that elevate air movement like ceiling or pedestal fans can enhance the cooling effect by 3 times. We applied our experimentally-measured heating and cooling effect to two historical case studies: the 2015 Pakistan heat wave and the 2021 Texas power crisis. Passive and low-energy strategies can reduce the sleep time heat or cold exposure by as much as 90%. The low-energy strategies we tested consume one to two orders of magnitude less energy than HVAC systems, and the passive strategies require no energy input. Our results demonstrate that these strategies can also help reduce peak load surges in extreme temperature events. This reduces the need for utility loadshedding, which can put individuals at risk of heat or cold exposure. Our results may serve as a starting point for evidence-based public health guidelines on how individuals can sleep better during heat waves and cold snaps without HVAC.

1. Introduction

The quantity and quality of sleep affects human health1–4 and cognitive performance5–7. Indoor air temperature is among the key environmental parameters that influence sleep quality8,9. The strong link between sleep and thermoregulation means both excessively high and low temperatures have a negative impact on sleep outcomes10. Heat exposure during sleep increases wakefulness and decreases time in shortwave sleep prominent in the initial sleep segments, and rapid eye movement (REM) in the later stages11. Cold exposure during sleep primarily effects the later stages of sleep, where REM is dominant10. Other studies report no significant reduction in sleep quality in ambient temperatures as low as 3°C due to bed covers maintaining a near constant bed climate temperature12. However, cold exposure significantly affects heart rate variability during sleep12 which may contribute to higher frequencies of myocardial infarctions (i.e., heart attacks) in the morning13 and in winter14. This suggests that cold exposure may be a public health issue as well as sleep quality.

Despite the importance of the thermal environment to sleep, there are few regulations or guidelines that specifically address the design temperature in sleeping environments. Therefore, design practitioners generally assume that the same conditions for thermal comfort during waking hours apply to sleep. In the United Kingdom, the Chartered Institution of Building Services Engineers’ (CIBSE) TM59 Design Methodology for the Assessment of Overheating Risk in Homes recommends that the operative temperature in the bedroom from 10 p.m. to 7 a.m. shall not exceed 26°C for more than 1% of annual hours15. Nicol, who was involved in the standard’s development, later suggests that this criteria may be highly conservative as people sleep comfortably at temperatures of 29-31°C within their personal bed space16. Lomas et al.17 also finds that the TM59 criterion suggests a much higher prevalence of overheating than was reported by the English Housing Surveys (EHS).

Conventional heating, ventilation, and air conditioning (HVAC) systems are a common way to regulate the interior ambient temperature in residential buildings. These technologies have high penetration in the United States, where over 95% of homes have some form of space heating and 88% have some form of space cooling18. However, space heating and cooling is energy intensive (upwards of 1000 W) and historically represents over 50% of energy end use in residential buildings19. In a survey of New York City residents, 91% of respondents with air conditioning at home had it installed in their bedroom20. Bedroom air conditioning is especially energy intensive because it typically operates continuously throughout the night. Survey data has recorded this behavior in New York City20, Hong Kong21, China22, and Singapore23. This indicates a priority for comfortable sleeping environments in many different contexts. Yet HVAC systems are cost-prohibitive for many households. Over a quarter of the 123.5 million households in the U.S. report energy insecurity, which may result in leaving the home at uncomfortable temperatures (12.2 million households), receiving a disconnect or delivery stop notice (12.4 million households), or unable to use heating (5.1 million households) or air-conditioning equipment (6.4 million households)18. When taking a broader world view, access to HVAC systems as well as reliable and affordable energy is a luxury. According to the International Energy Agency (IEA)’s report on the future of cooling, of the 2.8 billion people living in the hottest parts of the world, only 8% currently have access to air conditioning24.

Climate change further challenges the viability of conventional HVAC systems as a means towards comfortable and healthy sleep in several ways. First, diurnal warming asymmetry25 means nighttime temperatures are warming faster than daytime temperatures in much of the world. Studies already demonstrate that atypically warm nighttime temperatures are associated with elevated mortality26 and poor sleep quality27 particularly among those with limited ability to cope, such as the poor and elderly. Higher nighttime temperatures will also increase the energy consumption of existing air conditioners and drive installation of new air conditioners, further exacerbating climate change. Second, the greater frequency and intensity of climate change impacts like heat waves, cold snaps, and wildfires increases the probability of power disruptions. These events compound the disaster28 as was seen recently in British Columbia, Canada and the U.S. Pacific Northwest in summer 2021 and in Texas in Winter 202129. The lack of resiliency and energy intensity of conventional HVAC systems necessitate an alternate strategy, such as personal comfort systems (PCS) to maintain comfortable and health indoor air temperatures during sleep.

PCS are a class of technologies that decentralize heating and cooling control, and target conditioning to the person rather than the entire space. Most research on applications of PCS focus on increasing thermal comfort and reducing energy consumption in office buildings30. However, PCS may be well-suited for sleeping due to the stationary nature of the person for long stretches of time. They are cheaper to operate as they use significantly less energy than conventional HVAC systems (1-100 W). Some devices are so efficient that they can be battery operated, making them resilient to utility power interruptions. PCS can also be implemented as part of a strategy to reduce building energy consumption by extending air temperature set points31.

A few studies have reviewed the impact of PCS on sleep quality and thermal comfort. Lan et al32 found localized cooling of the back and/or head with a hypothermia blanket significantly improved objective and subjective measures of sleep quality in a relatively hot environment (32°C). Other studies found that head cooling by means of special pillows improved sleep quality33 and decreased the sweat rate34, a physiological measure of thermal strain. Increased air movement with fans in a relatively hot environment (30°C) maintained thermal comfort and sleep quality compared to conventional air-conditioning set to 27°C35. In cold ambient temperatures (5°C), Song et al.36 found a partial-body heating system with a heated electric blanket improved thermal comfort and sleep quality. Okamoto-Mizuno et al.37 also found a heated electric blanket to decrease cold stress in a 3°C environment during sleep.

Fans are a relatively common amenity in U.S. homes, with over 70% of households having at least one ceiling fan and over 40% have at least one floor or window fan18. Elevated air movement using fans can replace or augment cooling from air conditioning. The elevated air movement from fans increases thermal comfort at higher air temperatures by accelerating convective and evaporative heat loss. Other benefits of fans include improved air distribution, improved perceived air quality, HVAC first cost savings, and energy savings38.

Although the power consumption of PCS is significantly less than conventional HVAC systems, both are considered active strategies as they require an energy input. Alternatively, there are many passive adaptations to improve sleep quality that do not require energy input. Examples include change of bedclothes, tucking blankets into the mattress, and changing posture16. In a hot environment, a rope bed, such as the *charpai* in South Asia or the *zonbang* in southern China, may provide more cooling than a conventional mattress. Other behavioral adaptations include migrating to different parts of a building based on the principle of heat rising i.e., sleeping downstairs or on the floor in the summer and sleeping upstairs in the winter, or even sleeping outside to take advantage of radiative sky cooling. These practices are not just limited to traditional societies. For example, after a ten-day heat wave in New York City in 1908, the New York Times reported an uptake of roof sleeping even among the elite39. One reason for high mortality in the 1995 Chicago Heat Wave may have been a pervasive fear of crime that kept Chicagoans from sleeping outside as they had done in prior heat waves in the 1950’s and 60’s40.

We know that sleep is crucial for human health and wellbeing, and that temperature can affect sleep quality, the current approach of relying on conventional HVAC to control indoor air temperature is problematic from an energy and equity perspective – issues further exacerbated by climate change. We do not know the role that localized interventions like PCS and other personal adaptations can play in improving sleep quality. To address this, we used a dry heat loss thermal manikin in a controlled environmental chamber to evaluate the heating or cooling effect of different passive and low-energy strategies in the context of sleeping. The evaluated strategies ranged from simple measures such as extra bedding through to more advanced products like a hydro-powered mattress pad. We found that the interventions can increase the adaptive capacity of individuals to cope with warmer or colder bedroom temperatures.

1. Results

The results of the thermal manikin tests in show that many of the common interventions provide significant heating or cooling effects. While the passive personal adaptations equivalent to (or exceed) the effects of low-energy strategies, the combined effect is particularly effective at helping to offset more extreme bedroom temperatures.

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Figure : Absolute value of heating and cooling thermal effect grouped by passive and active strategies and ordered by decreasing magnitude. The heating or cooling effect is a relative metric, so a value of 0 means there is no heating or cooling effective relative to the baseline and higher values indicate a stronger heating or cooling effect relative to the baseline. Vertical reference lines show no heating or cooling effect (dashed) and a combination of passive strategies (dotted) for comparison to low-energy strategies. Error bars represent 95% confidence interval (CI).

All the tested passive strategies for heating had a measurable effect in isolation. The highest effect came from the heated blanket, followed by the hydro-powered mattress pad, and then the electric mattress pad. The hot water bottle had a significantly lower effect, likely because it is a highly localized strategy. Combining the passive strategies led to a heating effect close to 6°C. The magnitude of the heating effect is similar between passive and low-energy strategies, meaning individuals could select the most appropriate strategy depending on their circumstances. For example, someone with back problems may not be able to sleep in a fetal position but could consider an electric mattress pad for a similar heating effect. An emergency blanket may not be preferred on a day-to-day basis but could be considered under more dire circumstances like a power outage.

On the cooling side, only two of the four passive strategies had a measurable cooling effect in isolation. Removing bedding and removing the mattress had a cooling effect of about 1°C each, while changing sleeping posture or removing clothing had a negligible effect. The cooling effect increases when different combinations of passive strategies are used. We chose the reference case as the best combination without removing the mattress (2.5°C), since that is not common in the U.S. and other western countries. However, a more ventilated bed type, as is traditional in many cultures, can be highly effective especially in combination with other passive strategies. For the low-energy strategies, the ceiling and pedestal fan both had a strong cooling effect when operated on the high speed. Neither fan type generated enough air movement in the low setting due to the insulative effects of bedding. The cooling effect from both fan types is almost three times higher when combined with the passive and low-energy strategies such as minimal clothing and bedding.

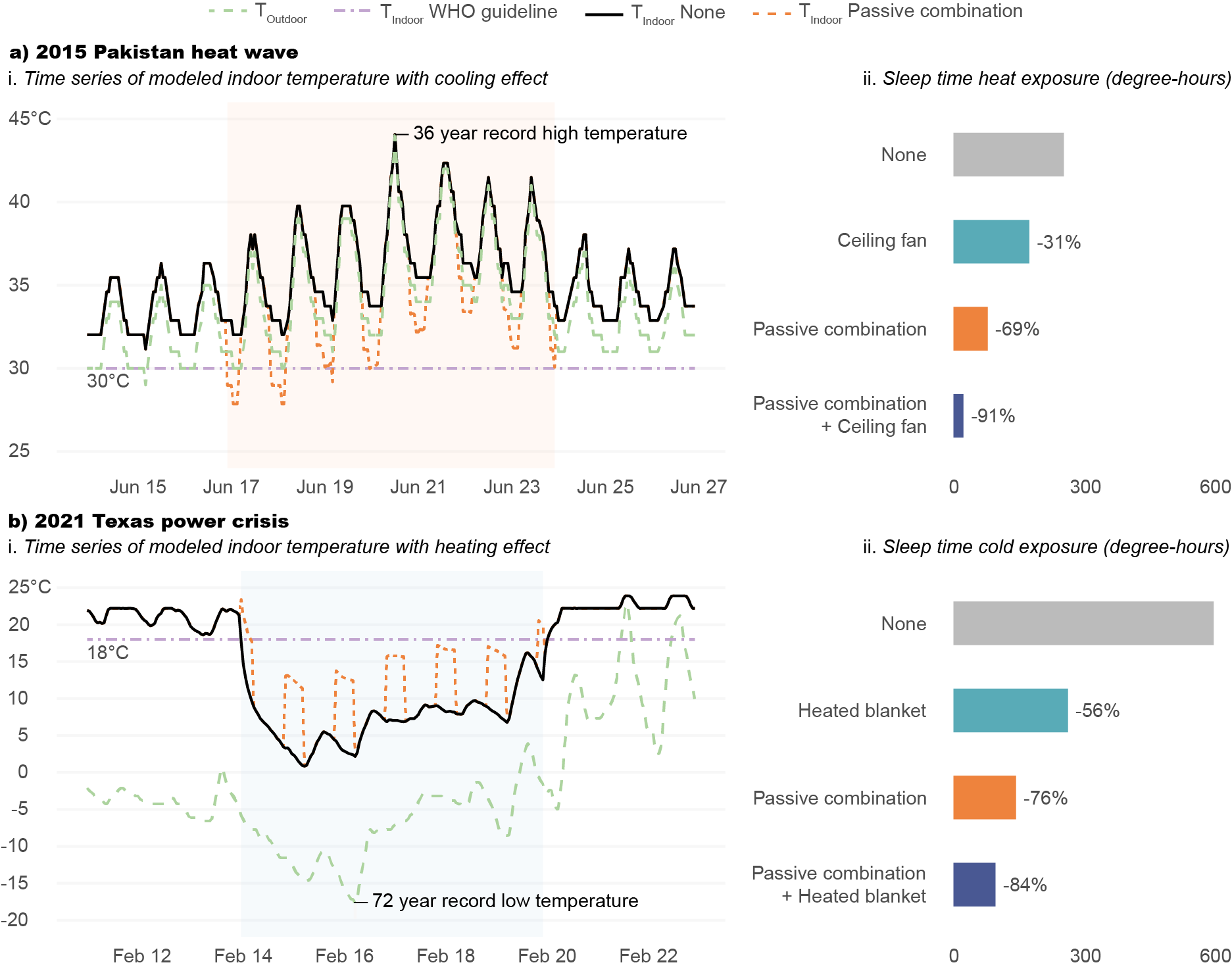


Figure : Application of laboratory results to two historical case studies a) 2015 Pakistan heat wave (June 17-24) and b) 2021 Texas power crisis (February 14-19) as a i. time series of modeled indoor temperature with heating or cooling effect and ii. sleep time (10 p.m. – 7 a.m.) heat or cold exposure based on the World Health Organization (WHO)’s indoor minimal risk temperature guideline.

The results of the thermal manikin test demonstrate the potential for passive and low-energy solutions for heating and cooling to minimize thermal discomfort in sleeping environments. To better contextualize these findings, we applied our results to two historical case studies: the 2015 Pakistan heat wave and the 2021 Texas power crisis. These represent extreme heat and extreme cold events where conventional HVAC systems were not available due to lack of access or a multi-day power outage. We calculated the sleep time (10 p.m. – 7 a.m.) heat or cold exposure with and without the top-performing heating and cooling interventions from Figure 1 based on guidelines from the World Health Organization (WHO) for the indoor minimal risk temperature for adverse health effects41. The results in Figure 2 show that a combination of passive and low-energy strategies could reduce sleep-time heat exposure by as much as 91% and cold exposure by as much as 84%. Relying only on passive strategies, which may be necessitated by a power outage, could still reduce sleep-time heat exposure by 69% and cold exposure by 76%. These reductions in thermal discomfort or stress demonstrate the potential of passive and low-energy strategies to alleviate heat and cold exposure and improve the resiliency of buildings during extreme temperature events.

1. Discussion

Our laboratory results demonstrate that many passive and low-energy strategies can provide a significant heating or cooling effect, making them viable alternatives or supplements to air-conditioning for sleeping environments. In comparison to conventional HVAC systems, low-energy strategies consume 1-2 orders of magnitude less energy. In extreme events like the 2015 Pakistan heat wave and the 2021 Texas power crisis, load shedding or rolling blackouts by utility providers to manage the surge in demand puts individuals at risk of prolonged exposure to hazardous indoor air temperatures. Utility providers and emergency planning and public health agencies must consider ways to reduce peak loads during extreme events to avoid more drastic curtailment measures. Encouraging use of effective passive and low-energy strategies during sleep could help minimize load on energy grids while reducing exposure to extreme indoor temperatures. This may take the form of free distribution or subsidies for low-energy devices, particularly to members of vulnerable populations, and public service announcements encouraging use of passive strategies.

Passive strategies are less commonly used than other environmental modifications such as turning on the air conditioning or electric fan20. There are social and cultural barriers to the use of passive strategies, with many people behaviorally conditioned to sleep with a covering, regardless of the indoor air temperature, because it is associated with feelings of safety and security42. This is further reinforced by recent research on the use of weighted blankets to treat anxiety and insomnia43. Individuals may also be reluctant to remove clothing due to privacy and modesty concerns. Likewise, swapping a mattress for a more ventilated bed type may not be a realistic strategy in many parts of the world. While we tested an innerspring mattress, solid foam mattresses with higher insulation are becoming increasingly common in the United States and other western countries44. Our study suggests the actual heat transfer impact may not be as significant as clothing or bedding due to higher contact surface areas with those layers compared to the relatively limited contact surface with the mattress.

Elevated air movement is an accessible and highly effective cooling strategy that is enhanced when coupled with passive strategies that increase exposed skin area. However, fan use during sleep has a negative public perception due to popular consumer publications which list allergic reactions, dry air, sinus irritation, and sore muscles as potential issues45. These claims are not supported by research which, on the contrary fan, suggests the use of fans during sleep may reduce the risk of sudden infant death syndrome (SIDS)46.

There are some important limitations in our experimental methodology. First, we tested the heating and cooling interventions at relatively mild conditions due to constraints from the experimental facility and thermal manikin. Moving towards more extreme conditions, we would expect the absolute value of heating and cooling effect to nonlinearly decrease. Second, the thermal manikin used in this study measures dry heat loss only. Our measurements therefore underestimate the cooling effect by ignoring evaporative cooling from sweating. This conservative assumption may hold for populations vulnerable to extreme heat, such as the elderly, who have a reduced ability to sweat47. Third, we only considered the whole-body thermal effect and not asymmetric heating or cooling of different body segments. This is more important for localized PCS, such as the mattress pads, pedestal fan, or hot water bottle, as the thermal sensation perceived for individual body parts affects thermal sensation and comfort for the whole body48. Fourth, the mannikin-based equivalent temperature does not consider human sensation, perception, and other subjective aspects of thermal comfort. Lastly, we assume that someone closer to a state of thermal comfort will have improve sleep quantity and quality, and subsequently other health outcomes.

1. Methods
   1. Experimental facilities

We conducted the study in the controlled environmental chamber (CEC) at the University of California, Berkeley. The chamber measures 5.5 m x 5.5 m x 2.5 m (18 ft x 18 ft x 8 ft 4 in) and is described in detail by Bauman and Arens49 and Arens et al.50. Though the CEC’s design resembles a modern office, its mechanical systems provide a high degree of control over the thermal environment. The chamber’s air handling unit (AHU) can control dry-bulb temperature to within 0.2°C. There are windows on two sides (south and east) with external shades and internal venetian blinds on both windows to control heat gains from solar radiation. We set the temperature of the inner glass windowpane to be isothermal with the interior to ensure mean radiant temperature was the same as the dry-bulb temperature.

* 1. Measuring instruments

We used a dry heat loss thermal manikin to evaluate the effect of different heating and cooling strategies for sleeping environments. A thermal manikin is a heated dummy designed to simulate heat exchange between the human body and its thermal environment51. We used a female thermal manikin developed by PT Teknik52. The manikin consists of a molded polystyrene shell wound with embedded nickel wire. The manikin is 1.68 m tall, has a surface area of 1.48 m2, and weighs approximately 18 kg. The manikin has 16 independently controlled body parts (Table 1) and measures the sensible heat loss, *Qt* [W/m2] and the skin temperature *Tsk* [°C] of each segment.

We operated the manikin in “comfort control” mode, which calculates the power supplied to each body segment based on the deep body or core temperature, the measured surface temperature, and the thermal resistance of the skin53. This mode of control most realistically represents the temperature distribution of the human body54. We set the core temperature of each body segment based on the Berkeley Comfort Model55 for a person in in a neutral environment. Prior to data collection, we calibrated the manikin per manufacturer’s instructions to 16°C and 28°C56.

Table : Thermal manikin body parts and associated surface area and core temperature setting for comfort mode per the Berkeley Comfort Model55.

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Body part** | **Surface area (m2)** | **Core temperature (°C)** |
| 1 | Left foot | 0.05 | 35.1 |
| 2 | Right foot | 0.04 | 35.1 |
| 3 | Left lower leg | 0.09 | 35.6 |
| 4 | Right lower leg | 0.09 | 35.6 |
| 5 | Left thigh | 0.16 | 35.8 |
| 6 | Right thigh | 0.17 | 35.8 |
| 7 | Pelvis | 0.17 | 36.3 |
| 8 | Head | 0.11 | 36.9 |
| 9 | Left hand | 0.04 | 35.4 |
| 10 | Right hand | 0.04 | 35.4 |
| 11 | Left forearm | 0.05 | 35.5 |
| 12 | Right forearm | 0.05 | 35.5 |
| 13 | Left upper arm | 0.07 | 35.8 |
| 14 | Right upper arm | 0.08 | 35.8 |
| 15 | Chest | 0.14 | 36.5 |
| 16 | Back | 0.13 | 36.5 |
|  | Total | 1.48 | 36.7 |

We monitored the ambient dry-bulb temperature at five locations around the thermal manikin with the Onset HOBO Temperature/Humidity Data Logger (model U12-013 or U12-006) and an air/water/soil temperature sensor (model TMC1-HA) which has a -40°C to 100°C measuring range and 0.25°C accuracy for temperature. We positioned the temperature 0.2 m away from the thermal manikin and elevated it to be vertically centered to the tangent body part. We calibrated each temperature sensor at three temperatures (15°C, 25°C, and 35°C) using a Polyscience Low-Profile Refrigerated Circulator (model PD7LR-20-A-11B) with a -20 to 200°C measuring range and 0.005°C temperature stability based on a linear regression model for each temperature sensor.

* 1. Evaluating the heating and cooling effect

To quantify the heating or cooling effect of different passive and active strategies, we measured the skin temperature and sensible heat loss for each thermal manikin body segment and transformed it into the manikin-based equivalent temperature. The equivalent temperature is defined as the temperature of a uniform enclosure in which a thermal manikin with realistic skin surface temperature would lose heat at the same rate as it would in the actual environment51. We calculated the manikin-based equivalent temperature, [°C], as follows in Equation (1), where [°C] is the skin temperature, is the sensible heat loss [W/m2], and is the dry heat transfer coefficient [W/m2-°C], which we calculated from a nude manikin as described in Section 4.6.

(1)

The absolute value of the difference in the manikin-based equivalent temperature relative to a baseline condition gives the heating or cooling effect of the strategy, Equation (2). This approach is similar to prior studies measuring the heating effect of personal heaters57 or the cooling effect of elevated air movement58,59.

(2)

We defined the baseline condition (Figure 3) as a thermal manikin in the same ambient temperature with light clothing (0.25 Clo), a sheet (0.61 Clo) covering from below the shoulders, laying in log posture (i.e. laying on the right side with one arm outstretched) on a conventional mattress (0.34 Clo) with no emergency blanket or active heating or cooling system .

Diagram

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Figure : Composite illustration of the baseline condition for the thermal manikin from multiple licensed sources (author and Adobe Stock). The baseline condition is used to calculate the difference in manikin-based equivalent temperature as shown in Equation 2.

* 1. Experimental conditions

We measured performance of heating and cooling strategies at 16°C and 28°C respectively. The lower temperature was constrained by the CEC’s setpoint limits, which are intended for studies of thermal comfort and not thermal resilience. The upper temperature was constrained by the thermal manikin, which can only measure dry-heat loss and not heat gain. We assume a linear relationship between heating or cooling effect and ambient temperature59, so the ranking of heating and cooling strategies will not change under more extreme environmental conditions. Relative humidity does not affect thermal manikin measurements and therefore we did not measure or control it.

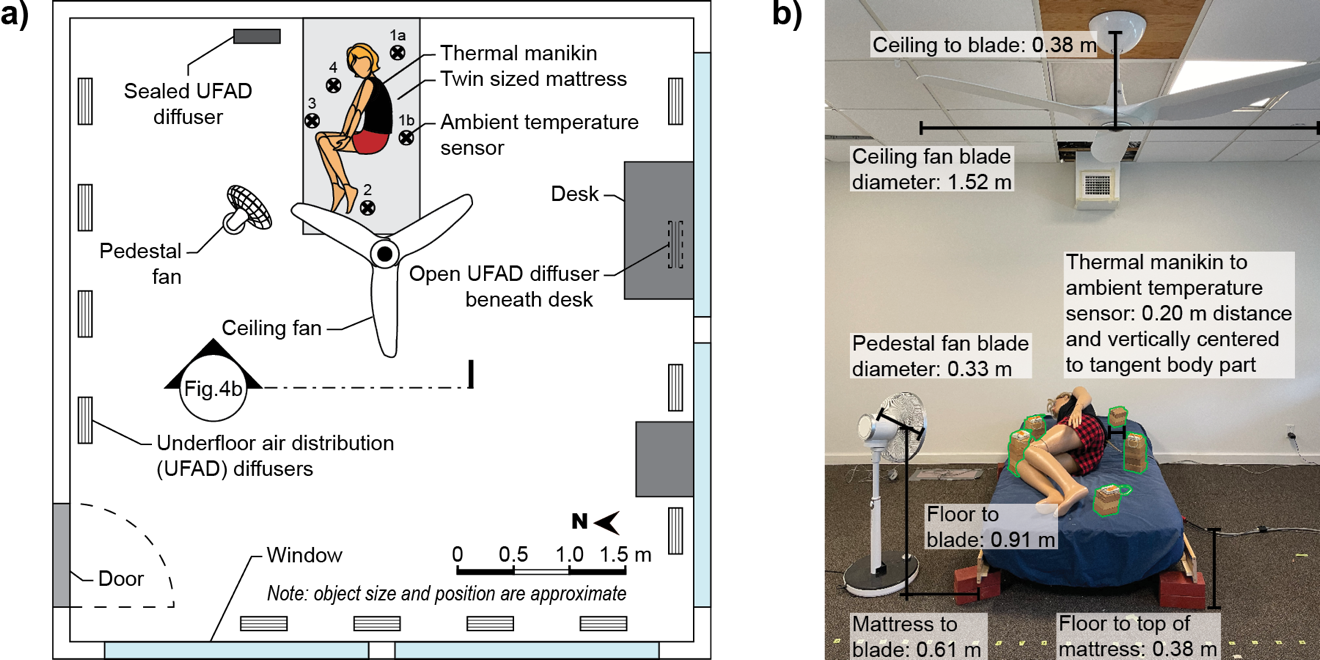


Figure : a) Plan view of controlled environmental chamber (CEC) and experimental setup; b) Section view of CEC setup prior to experiment with annotations. Ambient temperature sensors (green outline) added with Adobe Photoshop for clarity. Ambient temperature sensors were present during experimental run.

Figure 4 shows a diagram of the experimental set up in the CEC. We oriented the head of the bed against the wall, as is typical in a bedroom, where it is away from windows and floor registers. We sealed the floor register nearest to the bed to avoid disrupting the manikin’s thermal plume. We measured the heating or cooling effect of a variety of passive and low-energy strategies depicted in Figure 5.

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Figure : Composite illustration of experimental conditions representing a variety of passive and active heating and cooling strategies. Image created in Adobe InDesign from a variety of licensed sources (author, Adobe Stock, FlatIcon by FreePik, Adventure Ready Brands, and Sleepme)

* + 1. Clothing and bedding insulation

Clothing and bedding affect heat transfer via conduction by providing thermal resistance and radiation and convection by trapping a layer of still air between the fabric and skin. The baseline clothing ensemble (“Light”) consists of a cotton short-sleeve t-shirt and cotton shorts (0.25 Clo). The “Heavy” clothing ensemble consists of a polyester long-sleeve button front pajama shirt, long pants, and socks (0.55 Clo). The baseline bedding (“Light”) consists of a cotton U.S. standard twin sized bed sheet (0.61 Clo). The “Heavy” bedding consists of the cotton sheet with the addition of a polyester twin sized blanket (1.94 Clo). We smoothed out clothing and bedding so that it conformed to the manikin body to minimize trapped air between fabric layers.

* + 1. Posture

Change of posture is a common physiological response to discomfort during sleep. Nicol16 posits that the change in surface area in contact with the bed versus other body parts can significantly effect heat loss. We considered three postures as part of this study. In the baseline “Log” posture, the manikin is on its right side with the right arm outstretched by the head and the left arm and legs extended straight. In the “Fetal” posture the manikin is on its right side with the left and right arm extended straight and the legs bent towards the chest. The manikin’s rigidity, such as lack of elbow joint, meant we could not achieve a true fetal posture. In the “Starfish” posture the manikin is on its back with both arms outstretched by the head and both legs outstretched.

* + 1. Emergency blanket

An emergency blanket, also known as a space blanket or Mylar blanket, is a lightweight blanket made of heat-reflective, thin, plastic sheathing. We used an emergency blanket manufactured by Survive Outdoors Longer (SOL) made of vacuum-metalized polyethylene that weighs 0.08 kg (2.9 oz)60. First responders often deploy these blankets in emergency situations to prevent or counter hyperthermia. Emergency blankets reduce heat loss by several mechanisms. The air and watertight foil reduces heat loss through convection and evaporation of perspiration, and the reflective surface reduces heat loss by thermal radiation. Emergency blankets may also be used in conjunction with other bedding to reduce heat loss by conduction. Emergency blankets are very inexpensive and commercially available, making them a highly feasible intervention for cold thermal emergencies.

* + 1. Bed type

Modern mattresses are highly insulating (0.34 Clo), so we considered the cooling effect of removing the mattress and laying the manikin directly on the wooden slat bed frame. This type of bed is similar to a rope bed traditionally used in hot environments, such as the *charpai* in South Asia or the *zonbang* in southern China. We elevated the bed frame so that the manikin was at the same height (0.32 m) as the other test conditions with the mattress.

* + 1. Hydro-powered mattress pad

A hydro-powered mattress pad consists of silicone tubing integrated into a fabric and a control unit that circulates conditioned water. Like an electric mattress pad, a hydro-powered mattress pad is placed below the bottom bed sheet. We used the Cube Sleep System by ChiliSleep which has a temperature range of 13-46°C subject to environmental conditions. We operated the hydro-powered mattress pad at 18°C under cooling mode and 46°C under heating mode. In preliminary testing, we found the hydro-powered mattress pad was unable to sustain temperatures below 18°C at an ambient temperature of 28°C.

* + 1. Electric mattress pad and heated blanket

An electric mattress pad and heated blanket both consist of an insulated wire or heating element inserted into a fabric that heats up when powered. The difference between these two devices lies in their placement. An electric mattress pad is placed above the mattress and below the bottom bed sheet while a heated blanket is placed over the top bed sheet. We used a SunBeam electric pad under two settings: 1/10 which we describe as “Low” and 3/10 which we describe as “High”. We did not test the electric mattress pad under higher settings because the thermal manikin is unable to measure power when in a state of heat gain. We used a SunBeam heated blanket with both the heated blanket turned “off” and “on” to separate the effect of the electric heated element and the additional insulation.

* + 1. Hot water bottle

A hot water bottle is a sealed vessel filled with hot water and used to provide warmth in bed or apply heat to specific body parts for pain relief. We used a rubber hot water in a conventional square shape with a capacity of 1.25 L. Immediately prior to each experimental run, we filled the hot water bottle with 1 L of water heated to 37.8°C (100°F). We analyzed thermal manikin data starting from 30 minutes after hot water bottle placement based on the thermal stability of hot water bottle. We tested the heating effect of a hot water bottle at the feet and pelvis, which are both common locations for hot water bottle use.

* + 1. Pedestal fan and ceiling fan

We tested the cooling effect of a ceiling fan positioned 0.38 m from the ceiling and a pedestal fan positioned 0.61 m from the base of the bed. We tested both fan types at their highest and lowest speed setting. We recorded the air speed four times in a continuous three-minute interval. Figure 6 shows the spatial distribution of average air speed across the bed as measured by a handheld anemometer (TSI VelociCalc Air Velocity Meter Model 8347) at a height of 0.3 m (1 ft) above the mattress. Table 2 records the spatially averaged air speed for both fan types and speed settings.

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Figure : Spatial distribution of average air speed across the bed as measured by a handheld anemometer 0.3 m above the mattress.

Table : Spatially averaged air speed over the bed by fan type and speed setting. Air speed measurements taken from nine points, 0.61 m from the base of the bed and recorded four times in a continuous three-minute interval.

|  |  |  |
| --- | --- | --- |
|  | **Air speed, high (m/s)** | **Air speed, low (m/s)** |
| Ceiling fan | 0.4 | 0.1 |
| Pedestal fan | 0.3 | 0.1 |

* 1. Experimental procedure

We carried out testing after the CEC ambient temperature had equilibrated to within 0.2°C of the target temperature based on the level of accuracy in the setpoint temperature50. We recorded the surface temperature and power consumption of each body segment for ten minutes after reaching steady-state conditions. We defined steady state conditions as when the time-averaged surface temperature difference of each body segment changed less than 0.05 °C in the preceding ten minutes59. When starting measurements with a cold thermal manikin, we allowed for at least three hours of warmup time61.

* 1. Dry-heat transfer coefficient to free convection

We obtained the dry-heat transfer coefficient due to free convection, , for each body segment by calibrating the thermal manikin in a uniform thermal environment i.e. air temperature equal to the mean radiant temperature and air speed less than 0.06 m/s. In this condition, the room air temperature is equal to the equivalent temperature, , defined in Equation 1. We performed the calibration at two ambient air temperatures (16°C and 28°C) and two postures (log, and fetal at 16°C and starfish at 28°C). During the calibration, the thermal manikin was nude and lay directly on the wooden slat bed frame i.e., no mattress. The thermal manikin did not have any bedding, an emergency blanket, or active systems. The results in Table 3 show for each body segment. This value combined with the thermal manikin skin temperature and power consumption as shown in Equation (1) allow use to calculate the equivalent temperature.

Table : Dry-heat transfer coefficient of each body segment of the thermal manikin

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **16°C** | | **28°C** | |
| **Body segment** | **Log** | **Fetal** | **Log** | **Starfish** |
| Back | 7.8 | 7.7 | 7.2 | 6.8 |
| Chest | 7.8 | 6.9 | 6.9 | 6.0 |
| Head | 5.1 | 5.3 | 4.6 | 4.5 |
| Left foot | 8.5 | 8.3 | 7.0 | 7.9 |
| Left forearm | 8.5 | 8.7 | 7.7 | 8.1 |
| Left hand | 8.9 | 9.0 | 8.3 | 8.4 |
| Left lower leg | 8.5 | 8.2 | 7.7 | 8.1 |
| Left thigh | 7.6 | 7.4 | 7.3 | 7.6 |
| Left upper arm | 7.9 | 8.0 | 7.5 | 7.9 |
| Pelvis | 8.2 | 7.8 | 7.7 | 6.9 |
| Right foot | 8.7 | 8.1 | 7.6 | 7.9 |
| Right forearm | 9.1 | 8.0 | 8.1 | 7.9 |
| Right hand | 9.2 | 8.5 | 8.4 | 8.1 |
| Right lower leg | 8.7 | 8.2 | 7.9 | 8.1 |
| Right thigh | 8.0 | 7.7 | 7.5 | 7.4 |
| Right upper arm | 8.5 | 7.7 | 7.4 | 7.4 |

* 1. Error and uncertainty

We analyzed the data in accordance with the ISO guideline for the expression of uncertainty in measurement62. We calculated the combined standard uncertainty by considering equipment intrinsic uncertainty, equipment measurement uncertainty, measurement stability during steady state, and repeated trials of calibration, baseline conditions, and select experimental conditions in accordance with Bell63. When presented, we indicate the uncertainty with error bars with a confidence level of 95% (coverage factor of 2).

* 1. Case studies

We applied the laboratory findings to two historical case studies: the 2015 Pakistan heat wave and the 2021 Texas power crisis. In both cases, climate change contributed to the unprecedented weather events64,65. The two case studies also represent very different contexts in terms of conventional HVAC availability and construction typology. We assumed conventional HVAC systems were not available either due to lack of access (Pakistan) or multi-day power outage (Texas). For each case study, we modeled the indoor air temperature and the heating and cooling effect as a function of that temperature. We then calculated heat or cold exposure during sleep time, defined as 10 p.m. – 7 a.m. based on CIBSE TM5915, according to guidelines from the World Health Organization (WHO) for the indoor minimal risk temperature for adverse health effects41. Figure 7 shows the geographic locations of both case studies and provides pertinent information about the modeled historical events. The subsequent text describes modeling methods specific to each case study.

A map of the world

Description automatically generated with low confidence

Figure : Geographic location of case studies and high-level information about the modeled historical event. In both cases, we assumed conventional HVAC systems were not available either due to lack of access (Pakistan) or multi-day power outage (Texas).

## 2015 Pakistan heat wave

In June 2015, Sindh Province in southern Pakistan experienced a severe heat wave with temperatures as high as 49°C. Overall the heat wave claimed at least 2,000 lives and remains one of the deadliest heat waves worldwide within the past 10 years66. Factors contributing to the high death toll include widespread power outages leaving individuals without access to air conditioners, fans, and water pumps. Power outages aside, only around 10% of the Pakistani population has access to residential air conditioning67. The heat wave also occurred during the Islamic holy month of a Ramadan, a time when Muslims abstain from food and drink from dawn until sunset. This increased the population’s risk of dehydration despite religious guidelines to break the fast if medically necessary and public service announcements from local clerics68.

To quantify the potential impact of passive and low-energy strategies in alleviating heat exposure, we modeled a multi-family residence in Karachi, Pakistan, the most populous city in Pakistan. Karachi is one of the most densely populated cities in South Asia and the limited land resources have shaped a high-density urban morphology69, hence the suitability of modeling a multi-family residence. This construction typology may place inhabitants at higher risk of heat exposure due to limited opportunities for natural ventilation17.

We obtained outdoor dry-bulb temperature and relative humidity data for June 2015 from the Jinnah International Airport weather station through [www.visualcrossing.com](http://www.visualcrossing.com/), a third-party interface for publicly available weather data70. We estimated indoor temperature as a function of the outdoor temperature based on a linear regression model of field measurements in the ASHRAE Global Thermal Comfort Database II v 2.171. For the linear interpolation, we used a subset of the full database consisting of 1728 paired indoor-outdoor temperature observations from approximately 50 naturally ventilated multi-family buildings in Ahmedabad, India. This was the closest construction typology and geographic location to Karachi. Generally, the indoor temperature is a few degrees warmer than the outdoor temperature. We assumed inside and outside air had the same vapor pressure and recalculated the relative humidity from the saturation vapor pressure of the modeled indoor temperature.

Our experimentally measured cooling effect only accounted for dry-heat loss and not evaporative heat loss. Therefore, we modeled the cooling effect of passive and low-energy strategies with the Standard Effective Temperature (SET) based on the 2-Node Model by Gagge et al.72 as implemented in the comf package in the R programming language73. The SET model requires six input parameters: indoor air temperature, mean radiant temperature, relative humidity, air velocity, metabolic rate, and clothing insulation. We assumed the mean radiant temperature is equivalent to the indoor air temperature. For still air, we assumed an air velocity of 0.1 m/s. For cases with elevated air movement, we used the spatially averaged air speed over the bed listed in Table 2. We set the metabolic rate to 0.7 met for a sleeping person and the clothing insulation as the sum of the mattress, bedding, and clothing from the laboratory experimental condition.

The difference between the modeled SET for the baseline condition and any cooling intervention gives the cooling effect. We then subtracted this cooling effect from the calculated indoor air temperature to compute the sleep time heat exposure. We considered June 17-24, 2015, as the dates of the heat wave for our heat exposure analysis. WHO acknowledges that the minimal risk temperature for heat-related exposure requires further research and provides conditional recommendations based on the climate region. We selected an indoor minimal risk temperature of 30°C, which WHO provides as an example for Thailand, the closest match to Pakistan in terms of climate (tropical/subtropical) and AC penetration rates below 20%67,74.

## 2021 Texas power crisis

On February 13, 2021, a major blizzard and ice storm named Winter Storm Uri75 moved across the Southern United States, causing record low temperatures of -19°C in northeastern Texas. The storm triggered a major infrastructure failure across the state due to a lack of equipment winterization and a surge in electrical demand from the low temperatures. The state’s electric grid operator reported significant power generation outages from February 14-1929, leaving millions of homes and businesses without power76.

We used the 2021 Texas power crisis as a case study to quantify the potential impact of passive and low-energy strategies to mitigate cold exposure. According to the U.S. Energy Information Agency, 61% of Texas homes rely on electricity as their primary heating source77. Additionally, homes tend to be poor insulated78 due to Texas’s relatively mild climate and historical emphasis on minimal government regulation. Consequently, the winter storm power outages left many Texans with frigid temperatures inside their homes and caused 246 deaths79. We used EnergyPlus v. 22.2.080 to model indoor air temperature in a single-family home with a slab-on-grade foundation based on historical trends for building permit data81 and typical constructional practices in Texas82. Using energy simulation software more accurately represents the building’s thermal response to the power outage, which would lag behind due to material heat capacity We selected Dallas, the Texas’s capital and third most populous urban area, as a representative city due to the unprecedented low temperatures in that region of that state.

We used the residential prototype building model developed by the Pacific Northwest National Laboratory (PNNL)83,84 in the simulation. We selected the single-family, climate zone 3A, electrical resistance heating, slab foundation, International Energy Conservation Code (IECC) 2015 energy model. We made the following modifications to the reference model: updated the file version from EnergyPlus v. 9.5 to EnergyPlus v. 22.2.0 using the EnergyPlus auxiliary preprocessing program IDFVersionEditor, replaced the existing design day data objects with those for Dallas/Fort Worth International Airport, and changed the schedules of all electrical equipment and HVAC to be unavailable from midnight February 14 until midnight February 19.

We created a custom historical EnergyPlus weather file to use for simulation. We obtained the hourly dry-bulb temperature, dew point temperature, relative humidity, seal level pressure, global horizontal radiation, wind direction, wind speed, opaque sky cover, visibility, snow depth, and rain quantity for February 2021 from the Dallas/Fort Worth International Airport weather station through [www.visualcrossing.com](http://www.visualcrossing.com/)70. We converted the sea level pressure to atmospheric pressure based on the dry-bulb temperature and an elevation of 171 m (weather station elevation). We used the EnergyPlus auxiliary preprocessing program WeatherConverter to split the global horizontal radiation into direct and diffuse horizontal radiation components. We ran the simulation for the entire month of February to ensure an adequate initialization period.

To approximate the relationship between our experimentally measured heating effect and indoor air temperature, we assumed the heat transfer coefficient between the person and the environment would remain constant, as represented in Equation (3), where is the sensible heat loss [W/m2], is the dry heat transfer coefficient [W/m2-°C], [°C] is the skin temperature, and [°C] is the indoor air temperature. At our experimental conditions, and come from the thermal manikin and from the

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From the 2-Node Model by Gagge et al.72, the skin temperature varies by less than 2°C over a 30°C dry-bulb temperature range, so we approximated it as a constant over the range of modeled indoor air temperatures. We calculated the heat transfer coefficient at an indoor air temperature of 16°C based on the measured skin temperature and power supplied to each thermal manikin body segment. Holding the heat transfer coefficient and skin temperature, we then approximated the power needed for new indoor air temperatures to calculate a new equivalent temperature. The difference in equivalent temperature between the baseline and any heating intervention gives the heating effect. We then added this heating effect from the modeled indoor air temperature to compute the sleep time cold exposure based on WHO’s recommendation for minimal risk temperature of 18°C during the cold season in temperate and colder climates41. We considered February 14-19, 2021, as the dates of the power outage for our cold exposure analysis.

1. Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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