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Prioritizing Heat Mitigation Actions in Indian Cities

A Cost-Benefit Analysis under Climate Change Scenarios

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Abstract

Although deaths and economic losses due to extreme heat are rising globally, heatwaves remain a "hidden hazard" whose impacts are underrecognized due to measurement and valuation challenges. Cities in India are developing Heat Action Plans that combine physical cooling measures (such as urban greening and reflective roofs) with public health measures (such as heat-health early warning systems). However, there is a key knowledge gap on the relative efficacy of these actions. To inform debate on how scarce public funds could most efficiently be allocated to reduce deaths and productivity loss due to extreme heat, this paper develops spatially explicit heat risk maps for Lucknow, Chennai, and Surat under climate scenarios; models future health and economic losses under a "no intervention" scenario; and estimates the costs and benefits of alternative sets of heat mitigation actions. The modeling suggests that by 2050, the number of heat-related deaths could rise by one-third for the case study cities, while labor productivity losses could affect between 2 and 4 percent of their economic output. Among the interventions typically considered in city Heat Action Plans, benefit-to-cost ratios are favorable but vary significantly. Urban greening investments more than cover their costs based on the health and labor productivity benefits of the heat stress reduction they yield (benefit-cost ratio of 3:1). However, heat-health early warning systems offer the greatest harm reduction per dollar invested (benefit-cost ratios exceeding 50:1), suggesting that they are "low-hanging fruit" whose wider implementation across Indian and global cities should be prioritized.

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1. Introduction

Heatwaves are a growing concern for city leaders in India and globally due to their adverse effects on nearly all aspects of urban life, including health, the economy and infrastructure. Extreme periods of hot temperatures are associated with increased deaths and illnesses (Gasparrini et al, 2017), reduced productivity within heat-exposed sectors of the workforce (Kjellstrom 2016), increased suicide and accident rates (Park, Pankratz, and Behrer 2021), higher operating costs and reduced asset lifespans for energy and transport infrastructure (Chapman et al, 2013) and reduced learning outcomes for schoolchildren (Zivin et al. 2016). Global air temperatures may increase by up to 3.2°C by 2100 depending on global emission trends, but the frequency, duration and intensity of heatwaves is projected to increase even if global warming is limited to 1.5°C (Masson-Delmotte et al 2021). A national assessment conducted by the Indian government on climate change projects increasing temperatures for India through the 21st century, including increasing extreme heat events (Krishnan et al, 2020). India faces particularly acute challenges due to the projected increase in heat stress since limited access to domestic water sources, insulated buildings and air conditioning makes it harder for a significant portion of the 1.4 billion population to cope during periods of high heat stress (Azhar 2019, World Bank 2022).

Since the early 2000s, improved quantification of the losses caused by flooding, seismic risk and landslides have helped strengthen the global disaster risk management agenda and underpin increased investment in measures to reduce the losses they cause. By contrast, heatwaves have been described as a “hidden hazard” whose impacts often remain under-counted (Roberts et al 2023). Whereas storms, floods and earthquakes destroy physical assets such as houses, factories, roads and hospitals whose replacement cost can be quantified quickly, the most important channels through which heat waves cause harm are their impacts on human bodies: either through ill health or loss of productivity at work. Methods to assess heat hazard and quantify its health and economic impacts are well established, but their uptake has remained confined to research settings – such as geography and public health departments of universities – to a greater degree than with flood or seismic risk assessment (property-centered hazards for which the insurance and real estate industries have created a large market for risk assessment services). Mortality related to heat waves is known to be significantly under-counted in official statistics (Azhar et al 2014). This has contributed to a relatively low prioritization of heat risks among scientific stakeholders, policy stakeholders and the public.

With studies suggesting that parts of the Indian subcontinent will increasingly experience heat and humidity conditions that approach limits of human survivability by the late 21st century (Im et al 2017), heatwave preparedness and mitigation actions are an increasingly urgent consideration. Fortunately, resilience to heatwaves is a challenge that South Asian cities can address decisively and effectively given policy actions that are feasible at the urban scale. Indeed, focusing on these cities is strategic, as urban regions are more accessible, easier to govern, and efficient for implementing interventions compared to rural areas. India’s first city-level Heat Action Plan was developed in Ahmedabad, a city of 7.6 million people in the western state of Gujarat, where researchers documented a tripling of the daily all-cause mortality rate during the heat wave of May 2010 (Azhar et al 2014). The action plan – which combines short-run actions to prevent deaths during an active heatwave with long-run investments in cooling city spaces through vegetation and building design – was credited with averting some 1,200 deaths per year in the city in the years immediately after its introduction (Hess et al, 2018). Its model of a 'threshold-based' heat action plan, in which localized temperature thresholds based on all-cause mortality data are used to trigger sector-specific actions in the health system, labor practices and public communications (among other domains), was recognized by the National Disaster Management Agency (NDMA) as a model for the development of city-wide heat action plans across the country.

A key feature of city Heat Action Plans as implemented in India and internationally is the large number of stakeholders that need to be involved for their successful implementation. Given the diverse physical and social settings in which heat stress affects humans – including homes, workplaces, streetscapes, transport settings, and public amenities such as hospitals and schools – agencies responsible for city planning, transportation and buildings management may have capacity to reduce heat within their sphere of influence. During a heat emergency, stakeholders that have points of contact with vulnerable individuals include city health departments, health care providers, employers, labor unions, community associations, NGOs and media (Knowlton et al. 2014). Adding complexity to the development of Heat Action Plans is the range of policy instruments that vary from direct governmental interventions (e.g., publicly funded heat wave alert system, provision of emergency medical care, green spaces) to mandatory regulations (e.g., building code amendments) as well as incentive-based and information-based interventions (e.g., subsidies for cool roofs and public awareness campaigns on staying healthy during extreme heat).

Studies have established heat mitigation benefits of (i) 'place-based' interventions such as urban greening and cool building materials, (ii) 'people-based' interventions such as heat health early warning systems as well as (iii) 'resource-based' interventions such as additional water and electrical power during heat waves (Roberts et al, ibid). A review of 220 studies of vegetation, water or cool building material-based interventions found that temperatures at project sites fell by up to 2°C in approximately two-thirds of cases and by more than 2°C in the remaining cases (Santamouris et al, 2017). Introduction of heat health warning systems in Asian, North American and European settings have shown reduction in excess mortality of 30% or more vis-à-vis expected levels (see studies of Hong Kong SAR, China; Ahmedabad; Florence; and Milwaukee, respectively: Chau, Chan and Woo 2009, Hess et al, 2018, Morabito et al. 2012, Weisskopf et al, 2002). However, while existing studies have created a rich evidence base on the efficacy of individual heat mitigation actions, less research has been conducted on their relative costs and benefits. This is an important gap since city leaders face resource constraints and a consequent need to prioritize among heat mitigation options.

This paper contributes to the literature in two ways. First, we estimate impacts of extreme heat for Indian cities in a no-intervention scenario. Second, we identify feasible packages of heat mitigation interventions that could feasibly be adopted by Indian cities. We introduce two intervention packages, namely 'medium ambition' and 'high ambition,' which vary in terms of resource requirements (see Table 1). We then assess the potential costs and benefits of these intervention packages through two impact channels: health and labor productivity. The analysis is performed by means of an urban climate model that simulates expected future heat stress conditions with and without interventions combined with quantitative methods utilized in the public health and labor productivity impacts literature. We conducted simulations in three 'deep dive' cities: Surat, Chennai, and Lucknow. These cities were chosen as intervention areas due to their diverse climatic regions and regional importance. The findings are further generalized to the wider setting of large cities in India. The work is intended to provide an order-of-magnitude understanding of heat impacts and adaptation financing needs, and to support prioritization of measures within Heat Action Plans.

Table 1: City heat action: Intervention packages

Category of intervention	'Medium ambition' package	'High ambition' package	Impacts quantified
Urban greening	Increase tree cover by 10% from by 2050	Increase tree cover by 30% by 2050	Averted mortality Averted labor productivity loss
Heatwave early warnings	Introduce heatwave early warnings reducing heat related excess mortality by 20%	Introduce heatwave early warnings reducing heat related excess mortality by 40%	Averted mortality
Working hours shift	Shift working hours towards early morning and late afternoon for 25% of outdoor workers	Shift working hours towards early morning and late afternoon for 50% of outdoor workers	Averted labor productivity loss
Cool roofs program (homes/workplaces/public buildings)	Introduce cool roofs on representing 12.5% of the total roof area of the city	Introduce cool roofs on representing 25% of the total roof area of the city	Avoided cooling costs

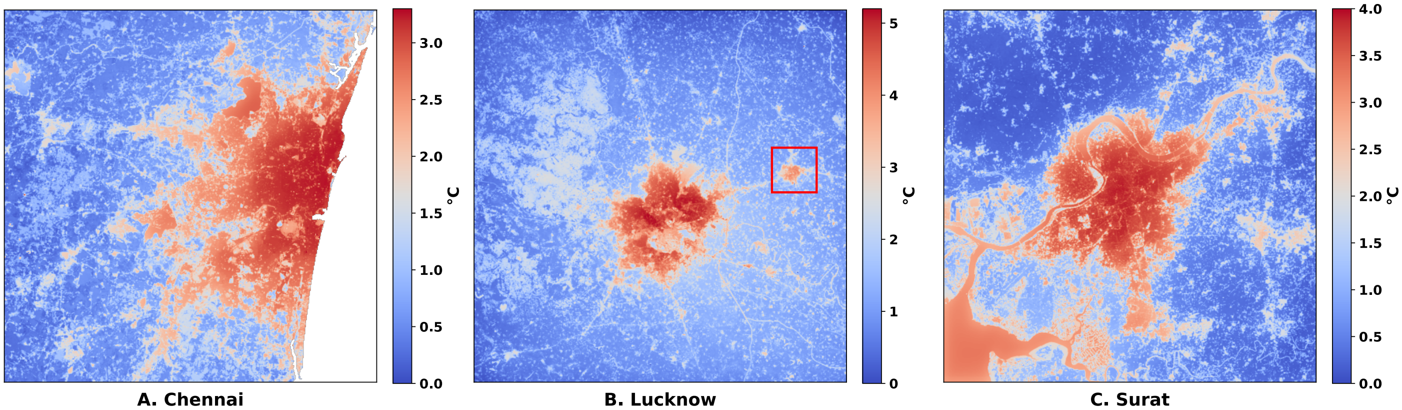
2. Methods

2.1 Heat hazard for three Indian cities under climate scenarios up to 2050

Heat hazard was modeled for Chennai, Surat and Lucknow using UrbClim, a computer-based framework for modeling climate variables and high spatial resolution (De Ridder et al. 2015). A detailed representation of each city's surface including land cover, built-up and vegetated area, terrain, and human-generated heat were constructed using remote sensing datasets (see Supplementary Figures - Table 1); this information was combined with data on the historical and projected future climate from the ERA-5 and CMIP-6 datasets respectively. For future periods, urban growth was incorporated into the modeling through use of projected population extents corresponding to future Shared Socioeconomic Pathway (SSP) scenarios calculated in a separate study (Wang et al. 2022). Model runs were performed for a present-day reference period and two future time periods. For the future time periods, separate model runs were conducted under low- and high-emission scenarios (SSPs 1-1.7 and 3-3.7 respectively). Urbclim temperature output was then used to calculate Wet Bulb Globe Temperature (WBGT), a heat stress index that takes not just temperature into account but also humidity and radiation from the sun and nearby surfaces. Model outputs included a suite of climate variables at 30-meter horizontal resolution including expected daily air temperature values (daily minimum, mean and maximums); number of days per year exceeding temperature thresholds; and WBGT heat stress values.

The simulations highlight the presence of significant Urban Heat Island (UHI) effects for the three cities as well as significant expected increases in heat exposure in future. Lucknow, with its inland location, experiences a stronger UHI effect than do the coastal cities of Chennai and Surat (Figure 1). The night-time UHI effect for Lucknow reaches as high as 5°C. UHI intensity is seen to increase with proximity to the dense urban core; the satellite city of Barabanki, with its lower density of buildings and sealed surfaces, also experiences a UHI intensity some 2°C lower than central Lucknow does. The spatially explicit estimates of future heat stress variables are a key input for the modeling conducted under this paper, while the significant increase in heat exposure – the magnitude of which differs depending upon global emissions scenarios – are themselves informative results for adaptation planning (see Section 3).

Figure 1: Present-day Urban Heat Island effect in Chennai, Lucknow and Surat (degrees Celsius).



Note: The figure presents the modelled night-time Urban Heat Island (UHI) effect for Chennai, Lucknow and Surat. UHI is defined as the temperature disparity in degrees Celsius of an urban location vis-à-vis a rural reference location. The red inset in Panel B highlights Barabanki, an urban settlement close to Lucknow, which manifests a lower UHI intensity.

2.2 Heat impacts on health and labor productivity under the 'no intervention' scenario

(i) Health channel

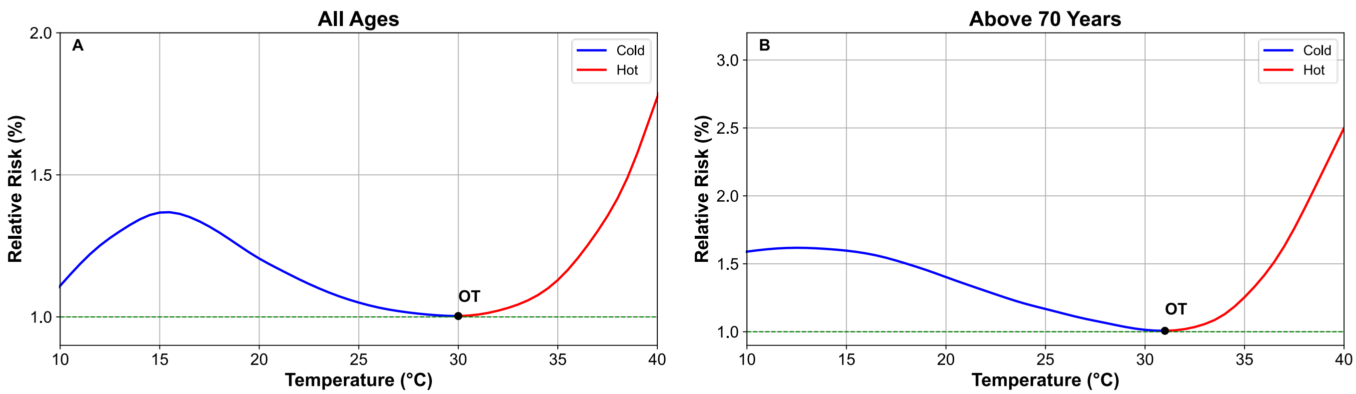
In epidemiology research, the relationship between temperature extremes and the mortality rate are characterized through exposure-response curves derived from time-series data on daily deaths and corresponding temperatures (see Gasparinni et al 2017, ibid., for an overview). Our study utilized temperature-mortality functions reconstructed from an existing study (Fu et al, 2018). The temperature at which daily mortality is minimized (the optimum temperature – OT) is noted and separate curves are derived for all ages (panel A) and people aged 70 or above (panel B). The relative risk of mortality, depicted on the Y-axis, increases in a parabolic manner as temperatures exceed the OT.

Using the relative risk of mortality (RR) and the crude death rate (CDR) associated with expected temperatures under current and future climate scenarios, excess mortality can be calculated with the following equation (WHO, 2014 and Dholakia et al 2015):

$$Excess\ mortality = \frac{RR-1}{RR} * \ CDR * population$$

We then estimated excess mortality for the present and future climate scenarios using urban climate modeling outputs at 100m spatial resolution. Population density data were sourced from the Global Human Settlement Layer (Shiavina et al. 2023) and Wang et al. (2022) for future periods. Crude death rates were obtained from state data (urban area crude death rate – NITI Aayong, 2022).

Figure 2: Relationships between temperature and all-cause mortality for demographic groups in India



Note: Relative risk describes the ratio of excess mortality compared to the mortality rate prevailing at the Optimal Temperature (OT). The Optimal Temperature is defined as the temperature at which mortality rates are lowest. Source: Adapted from Fu et al (2018).

We adopt a Value of Life Years (VOLY) approach to translate mortality impacts into economic terms (Desaigues et al 2011). This economic term has been employed in prior studies to illustrate the overall expenses associated with premature deaths resulting from excessive heat (as demonstrated in studies by Ebi et al., 2004, and Chiabai et al., 2018). Previous studies we examined indicated that each heatwave-related death was estimated to result in a loss of life years ranging from 6 to 9. For example, the 2003 heatwave in France, which led to approximately 15,000 excess deaths, was associated with an estimated 100,000 lost life years, equivalent to an average of 6.7 lost life years per excess death (Keller 2015). In contrast, Bosello and Schechter (2013) adopted a fixed value of 8 years for their calculations for the Mediterranean region. When determining the value for lost life years in our study, we considered the fact that India's overall life expectancy is lower than that of France and the demographic structure of India is characterized by a predominantly young population. We calculated the total cost of heat-related impacts by multiplying the 8 lost years by the VOLY metric for India.

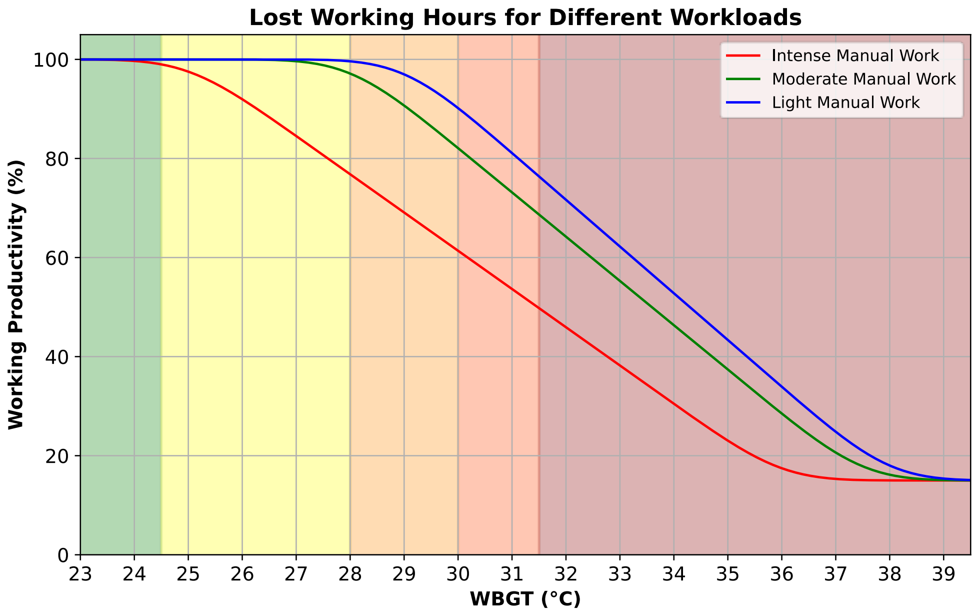
(ii) Labor productivity channel

High temperature and humidity place the human body under strain, resulting in health risks to workers (particularly those in high physical exertion roles) and reduced physical and cognitive performance.

We utilize heat stress threshold values based upon the US Association Advancing Occupational and Environmental Health non-acclimatized standard by the National Institute for Occupational Safety and Health (NIOSH) and measured on the WBGT scale (Centers For Disease Control, 2018). We derive lost working hours (LWH) by applying productivity loss functions to WBGT heat stress values modeled through the UrbClim simulations. Separate productivity loss functions are applied for occupations with low, medium and high physical intensity (Figure 3).

We model labor productivity loss under climate scenarios in several steps. The working-age population for each city is divided into occupational sector based on the Periodic Labor Force Survey (PLFS, 2023). Sectors are categorized into low, medium and high work intensity (see Supplementary Figures – SF3). Average daily earnings by category are identified from the PLFS (2023) and city-specific sources. Foregone work output is calculated by applying productivity loss functions to sector-wise economic output and expected future losses are adjusted to present-day real prices to account for inflation.

Figure 3: Loss of work capacity at varying heat stress levels for occupations of light, moderate and high physical intensity.



Note: The figure presents the relationship of labor productivity (y-axis) with heat stress (x-axis) for occupations of differing physical intensities. As heat stress increases, work capacity decreases. Heat stress is measured in degrees Centigrade on the Wet Bulb Globe Temperature (WBGT) scale. Background colors denote heat stress categories varying from "no heat stress" (green background) to "extreme heat stress" (dark red background). The blue curve denotes light-intensity activities such as office work (physical effort of 180 Watts); the green curve denotes moderate-intensity activities such as retailing and light manual work (300 Watts); the red curve denotes high-intensity activities such as construction labor (415 Watts).

2.3 Heat mitigation interventions: Definition and costing

In practice, city action plans to address extreme heat tend to comprise a 'bundle' of diverse types of interventions ranging from planting more trees and promoting a cooler built environment to introducing heatwave emergency actions including early warnings and health sector preparedness. Indeed, past studies by the World Bank have advocated a 'Places, People, Institutions' approach to city heat action planning in which actions target cooler city spaces, protection of vulnerable groups during heat emergencies, and mainstreaming of extreme heat mitigation across line agencies (Jones et al, 2022; Roberts et al, 2023). Based on desk review of existing Heat Action Plans and other strategy documents, we set out to identify feasible packages of interventions that could be adopted by cities vulnerable to heat in India. For each action area, we identified 'medium ambition' and 'high ambition' alternatives. The cost of each action was estimated based on local unit costs where available and international unit costs otherwise. All costs and benefits were converted to real 2020 US dollars. International costs were adjusted using Purchasing Power Parity (PPP). Here we focus on four major actions that are widely included in Heat Action Plans:

(i) Urban greening. Based on review of existing Heat Action Plans and urban greening interventions, we established that a medium-ambition investment involves increasing the city's total tree canopy area by 10%, while a high-ambition investment entails a 30% increase. For example, if the city currently has a 10% tree canopy coverage, the medium-ambition plan aims to raise it to 20%, and the high-ambition plan seeks to raise it to 40% within the city boundaries. It was assumed that two trees can be planted on a 10 x 10-meter square. The unit cost for each additional tree planted was US$ 2.50. Maintenance cost per newly planted tree was estimated at US$ 5 per year based on US reference values with PPP conversion applied (Vogt et al, 2015).

(ii) *Early warning systems*. Heat health early warning systems are designed to convert weather forecasts of potentially harmful conditions into alerts that prompt individuals and institutions to take action to prevent heat-related illnesses and deaths. In our study, we used international benchmarks to estimate the initial setup and annual operating costs of implementing such a system in a large Indian city. The startup costs were estimated at US$ 150,000, using data from the U.S. city of Philadelphia, adjusted for PPP and inflation (Ebi et al., ibid).

We based the operating costs on a model for managing heatwave alert systems, with cost references from Madrid, Spain. Rather than relying on a fixed annual cost, as done in Toloo et al. (2013), we used a per-heatwave-day cost approach, using data from Chiabai et al. 2018. The operating costs, converted from Spain to India using the PPP index, were approximately US$ 1,800 per heatwave day.

Additionally, some actions, such as operating the public heat advisory service (‘Heatline’) and deploying extra Emergency Medical Service (EMS) crews, incur direct costs, primarily in the form of additional wages. Based on Ebi et al. (2004), we estimated these wage costs to be approximately US$ 4,750 per day, with around 40% allocated to EMS crews, up to 30% for maintaining the Heatline during heatwaves, and the remainder for other medical assistance.

(iii) *Working hours shift*. One of the most straightforward but challenging adaptation measures to implement is shifting working hours to an "early morning" and "late afternoon" schedule. This change is particularly important for workers engaged in intense outdoor physical activities, who are most affected by excessive heat, leading to reduced productivity, especially during the middle of the day. Assuming current working hours are from 8 AM to 6 PM, including a one-hour break at 1 PM, the proposed adjustment involves shifting to a schedule of 6 AM to 11 AM and 3 PM to 7 PM for 25% (medium-ambition package) and 50% (high-ambition package) of outdoor workers. This shift aims to reduce the loss of working hours due to intense mid-day heat. Although this midday break policy effectively reduces heat-related issues, it can be challenging for workers who have long commutes between home and work. However, the United Arab Emirates has successfully addressed this concern by implementing a break from 12:30 to 3:00 PM from June to September (MoHRE, n.d.).

(iv) Cool roofs. Various cool roof interventions can be adopted, ranging from low-cost to high-cost options. In this context, we focused on the most affordable option. Studies of cool roof treatments in Indian cities provide per-meter unit costs for several treatments, including lime wash—a natural mineral-based paint—and high-density polyethylene (HDPE) cool roof membranes (NRDC, n.d). We applied a unit cost for lime wash of US$ 0.75 per m^2 and for HDPE cool roof membrane of US$ 2.10 per m^2. Lime wash is assumed to be effective for 2 years, while the HDPE cool roof membrane is expected to last for 5 years. In the medium-ambition package, we assume that 12.5% of buildings' roofs will be treated with cool roof interventions, while in the high-ambition package, we assume 25% coverage of the buildings being covered.

2.4 Benefits of intervention options

For each action, we identified expected benefits in terms of reducing adverse impacts of urban heat and adopted a suitable approach to value these benefits (see Table 2).

(i) *Urban greening*. Past studies have estimated heat reduction benefits from tree planting considering the sensitivity of local heat stress metrics to canopy cover (Lonsdorf et al. 2021). We apply a linear regression of tree canopy coverage within the study cities against present-day daily temperatures as well as WBGT temperatures to derive our own local estimates of temperature-tree canopy coverage relationships (see Supplementary Figures – Figure SF2). Temperature reduction benefits from the assumed 10% tree canopy area increase (medium ambition scenario) and 30% increase (high ambition scenario) are derived based on this relationship.

The temperature reductions were used to calculate the decrease in the Relative Risk (RR) of mortality. This reduction in RR was then subtracted from the summed daily relative risks of each city at each timestep (which are calculated when temperatures exceed the optimal level for each city, as illustrated in Figures 5A and 5B). The adjusted RR values were then applied to population distribution maps for each city to estimate the overall impact on mortality rates. Through a similar procedure, predicted heat stress reductions due to the greening interventions were used to derive expected benefits in terms of averted labor productivity loss.

(ii) *Heat-health early warnings*. A study of the Ahmedabad heat early warning system identified a 23% reduction of heat-related excess mortality in the years immediately following its introduction, while a study of France's heat early warning system noted a reduction of up to 60% in heat-related excess mortality (Hess et al. 2018, Fouillet et al. 2004). We assume that mortality-reduction efficacy will vary according to the level of effort invested in developing a robust system grounded in extensive stakeholder consultation and supported by proactive communication and outreach efforts to the most vulnerable. Based on the range of mortality reduction benefits reported in the literature, we defined a 'medium-ambition' intervention as achieving a 20% reduction in heat-related excess mortality and a 'high-ambition' intervention as achieving a 40% reduction. These reduction factors were applied to the projections of heat-related mortality under a 'no intervention' scenario to estimate the benefits of introducing an early warning system by calculating the number of deaths avoided.

(iii) *Working hours shift*. We apply the shift of working hours to daily modelled heat exposure under future climate scenarios produced through the UrbClim simulations. The number of lost working hours averted through this 'early mornings/late afternoons' working regime is quantified and valued based on projected economic output.

(iv) *Cool roofs*. Evaluation of cool roof interventions in India has shown that indoor air temperatures can be reduced by 2°C-5°C depending on building type and treatment type, resulting in reduced energy needs for air conditioning (NRDC, ibid). In Hyderabad, cool roofs reduced cooling energy usage by 14%-26% for previously black roofs and 10%-19% for previously uncoated concrete roofs, resulting in energy savings of 13-14 kWh per square meter for uncoated concrete roofs and 20-22 kWh per square meter for black roofs annually. We assume an annual energy saving of 17 kWh per square meter.

Table 2: Heat mitigation interventions, their outputs and outcomes, and valuation approach

Intervention	Output	Intermediate outcome	Value metric	Valuation approach
Urban greening	Increase in tree canopy cover	Temperature reduction	Mortality risk (% change) Labor productivity (% change)	Relative risk of mortality as a function of temperature Labor productivity loss as a function of temperature
Heat-health early warnings	Heatwave early warnings	Individuals adopt exposure reduction and health-preserving behaviors	Mortality risk (% change)	Relative risk of mortality as a function of temperature
Working hours shift	Change in working hours for heat affected workers	Reduced heat exposure of workers	Labor productivity (% change)	Labor productivity loss as a function of temperature
Cool roofs	Increase in building area with cool roof treatments	Reduced cooling energy demand	Private cost of cooling (% change)	Cooling expenditure as a function of temperature

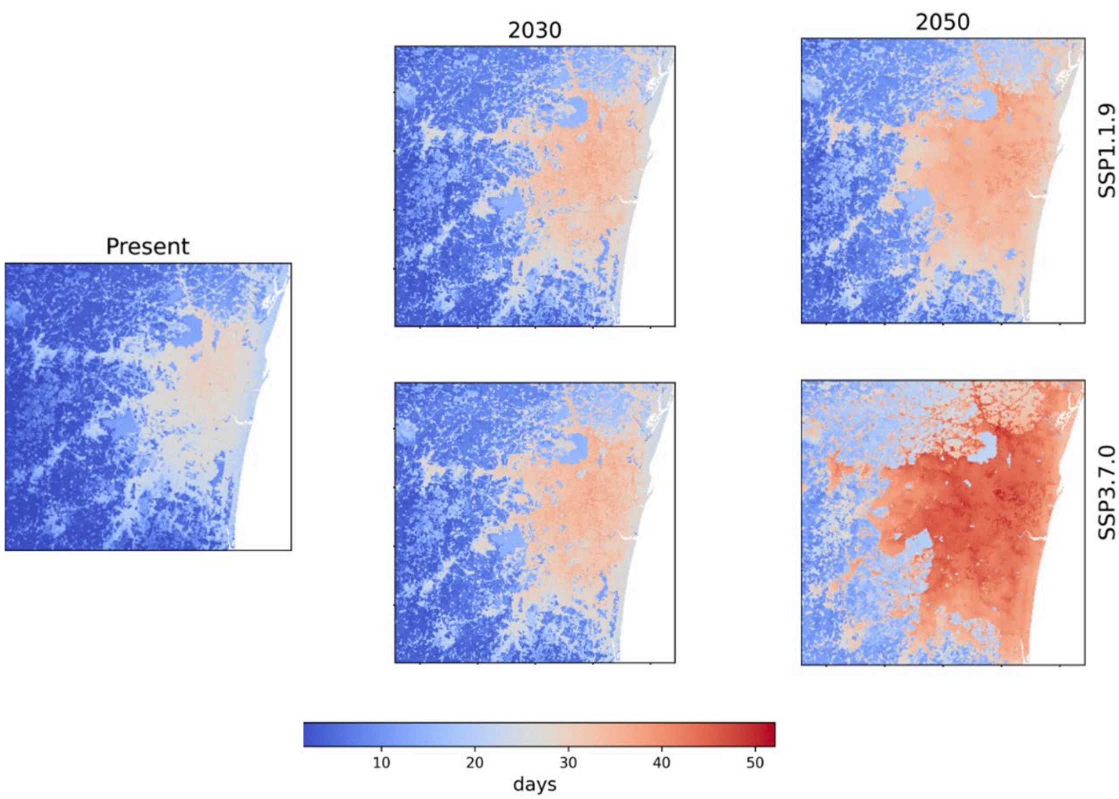
3. Results

(i) Heat hazard

The urban climate simulations confirm that Indian cities already exhibit significantly higher temperatures than surrounding areas, particularly at night. Strong night-time UHI effects are found for all three cities. Chennai and Surat exhibit average night-time temperatures approximately 3°C-4°C higher on average than nearby rural areas while Lucknow (an inland city) exhibits night-time temperatures 5°C higher than nearby rural areas. For daytime the UHI effect is significantly positive for Lucknow but only marginal for Chennai and Surat where the coastal environment including sea breezes provides cooling benefits.

The simulations also indicate that heat hazard will increase significantly in coming decades with the magnitude of the increase depending on the global emissions scenario. In Chennai, the number of heatwave days at present is seen to vary spatially with central districts experiencing as many as 50% more such days than outlying suburban districts at present (Figure 4). The number of heatwave days is projected to increase, from 30 to 50 days for central districts of Chennai under the high emissions scenario (SSP3-7.0) by 2050. The simulations also underscore the expected contribution of urban expansion to heat exposure with a larger territorial extent and total population being subjected to high UHI effects and the urban footprint expands.

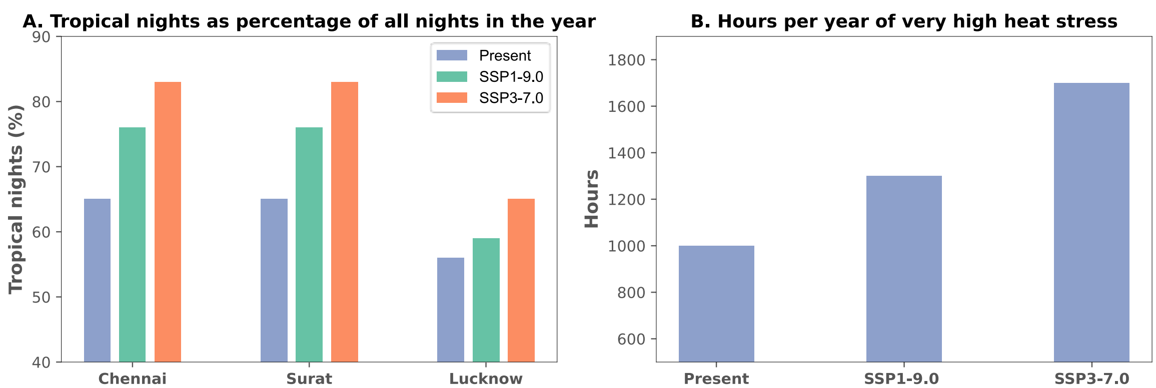
Figure 4: Chennai - expected number of hot days per year for present and future periods under climate scenarios



Note: Heatwave days are defined as days where the highest temperature exceeds the 90th percentile of the temperature distribution for a present-day reference period. Shared Socioeconomic Pathways (SSPs) are standardized scenarios developed in connection with the Intergovernmental Panel on Climate Change. SSP1-1.9 represents a scenario in which global emissions peak early; SSP3-7.0 is a scenario in which emissions remain high until after mid-century.

Looking to future periods, the projections point to significant intensification in heat stress metrics that will affect human health and the economy. Figure 5(A) depicts the expected change in the number of tropical nights (defined as nights where temperature do not fall below 25°C). In Surat, roughly 65% of nights per year currently fall into this category, but this would rise to 82% of nights. In the most densely built neighborhoods, the frequency of hot nights will be even higher with nocturnal temperatures rarely falling below 25°C. Figure 5(B) depicts the number of hours per year at high heat stress (>30°C WBGT) across all three cities, where high heat stress is defined using the WBGT metric. At present, we observe that some 25% of working hours in the year meet the high heat stress threshold for the three cities combined. Under a high emissions scenario, the number of high heat stress hours per year would rise by more than two-thirds for all cities amounting to some 40% of annual working hours.

Figure 5: Projected change in key heat stress metrics for Chennai, Surat and Lucknow (2050 vs. present-day)



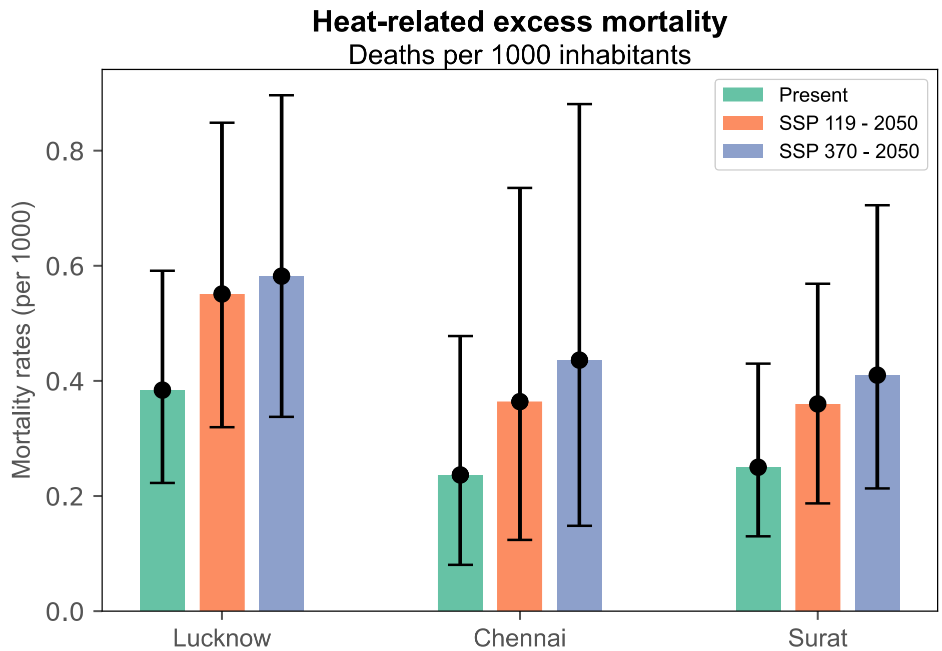
Note: Panel A depicts the expected number of tropical nights (defined as nights where temperatures remain above 25°C). Panel B depicts number of hours per year with very high heat stress (defined as temperatures exceeding 30°C on the Wet Bulb Globe Temperature scale) for Chennai, Surat and Lucknow. SSP1-1.9 refers to a moderate scenario for global greenhouse gas emissions while SSP3-7.0 refers to a high emissions scenario.

(ii) Impacts under a 'no intervention' scenario

Health impacts

Heat-related excess mortality is, at present, estimated to range between 0.2 to 0.4 per 1,000 people for the cities of Lucknow, Chennai and Surat according to our modeling. This translates to approximately 1,000 deaths per year for both Surat and Lucknow and around 2,500 excess deaths per year for Chennai. The heat-related excess mortality rate is roughly 20% higher for individuals aged 70 or above. By 2050, under a low-emissions scenario, our modeling estimates a 30% increase in annual heat-related deaths per 1,000 residents for Chennai and Surat and a 38% increase in the case of Lucknow. The increase is greater in the high-emissions scenario, with each city experiencing a rise of over 50% in the per capita heat-related excess mortality rate. When factoring in urban expansion this results in more than 3,000 heat-related deaths per year for Lucknow and Surat, and approximately 6,500 annual deaths for Chennai (Figure 6).

Figure 6: Projected rate of heat-related excess mortality for selected cities (present-day and 2050 under moderate and high global emissions scenarios)

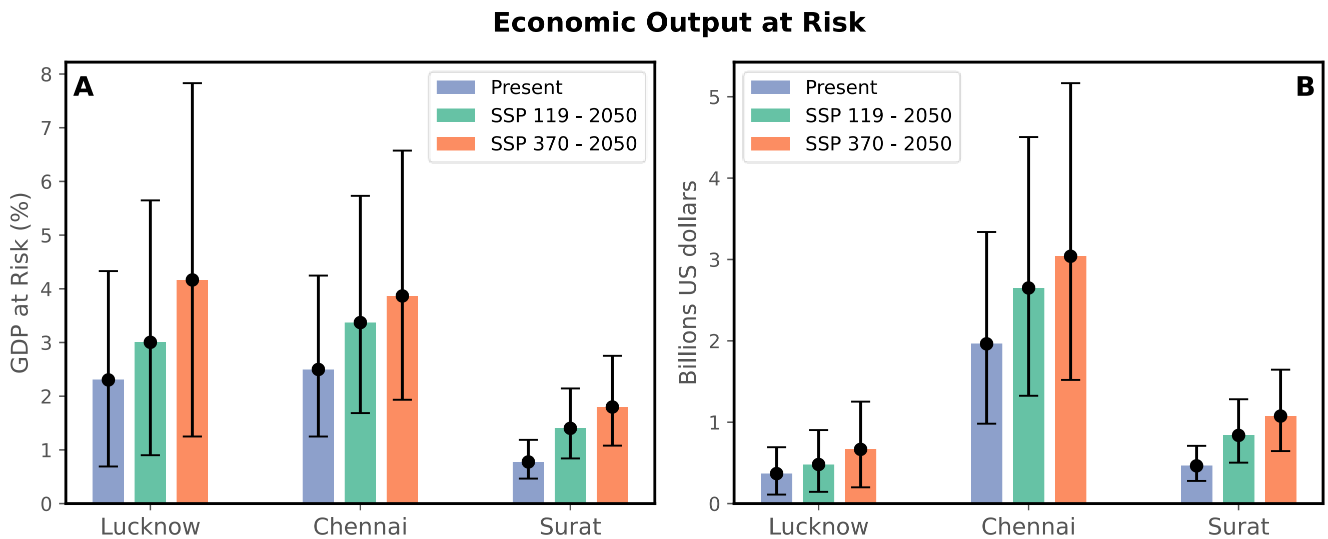


Note: The figure depicts annual projected heat-related excess mortality per 1,000 residents. SSP1-1.9 refers to a moderate scenario for global greenhouse gas emissions while SSP3-7.0 refers to a high emissions scenario.

Labor productivity impacts

Currently, about 20% of annual working hours in these cities exceed safe heat stress levels, measured by the WBGT over 31°C. Under a high-emission scenario, this could rise to 30%-40%, significantly reducing productivity and causing economic losses of billions of US dollars per year, affecting up to 4% of each city's GDP. For example, Chennai currently loses about 1.9 billion USD annually, or 2.3% of its GDP, due to extreme heat. By 2050, these losses could increase by 50% under the high-emission scenario. Cities such as Surat and Lucknow, both projected to undergo significant demographic growth, could see their economic losses double (Figure 7).

Figure 7: Projected economic output loss due to labor productivity effects under climate scenarios for selected cities (present-day and 2050 under alternate moderate and high climate change scenarios)



Note: The figures depict economic output that is at risk due to heat stress. This is defined as the value of working hours which take place under heat stress levels considered hazardous to human health according to occupational health and safety guidelines. SSP1-1.9 refers to a moderate scenario for global greenhouse gas emissions while refers to a high emissions scenario.

(iii) Benefits and costs of mitigation options

Our study's conclusions about the benefits and costs of adopting the range of heat mitigation interventions under consideration are summarized in Figure 8 and described below:

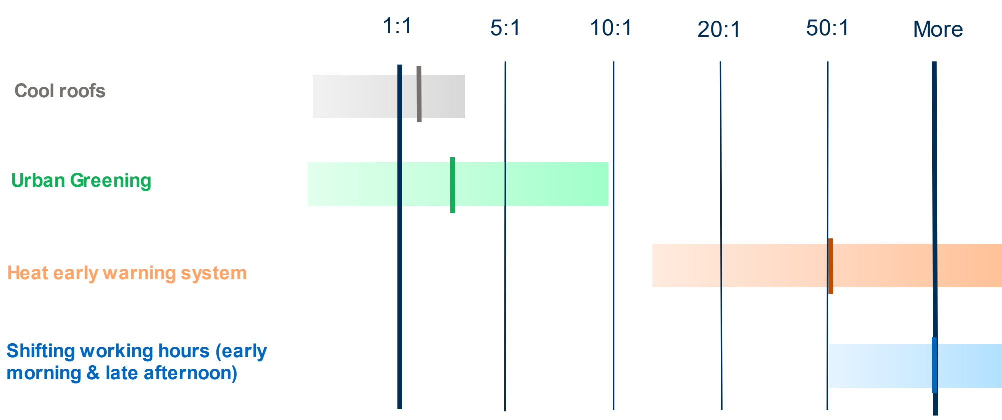
Urban greening. Tree canopy expansion is expected to have a strongly positive effect. In Surat, Chennai, and Lucknow, our high-ambition investment package (involving a 30% increase in tree coverage) results in 800 to 1,700 fewer excess deaths per year by 2050 assuming a low global emissions scenario. In a high-emissions scenario, the averted deaths are estimated to range between 1,100 and 2,700 (see Table SF4). The benefits of planting trees outweigh the costs, with a benefit-to-cost ratio (BCR) ranging from 1:1 to 5:1 depending on the intervention package and global emissions scenario chosen.

Working hours shift. Shifting the workday to a 'late morning / early afternoon' model produces a high benefit-cost ratio. Such a schedule modification can, in theory, recover 5%-10% of lost working hours in the climate of our case study cities. Assuming our high ambition goal of shifting working hours for 50% of affected workers, this could avert a productivity loss equivalent to 0.15% of the economic output of Lucknow by 2050 under a high global emissions scenario. Despite the high theoretical BCR of over 50:1, implementing this approach in practice can be difficult due to logistical challenges and acceptance by workers and employers.

Early warning systems. The benefit-to-cost ratio for heat-health early warning systems is high especially in highly populated cities like Chennai. For Chennai under the high ambition package, an early warning system could prevent between 1,400 and 3,500 excess deaths per year by 2050 under low and high global emission projections respectively. This would result in an economic gain of US$ 39 million to US$ 57 million per year. The results show a BCR ranging from 50:1 to 120:1 for the high ambition packages by 2050. The BCR would be half as large when considering the low ambition package (see Table SF5).

Cool roofs. Cool roof interventions show a favorable benefit-cost ratio which varies based on the type of materials utilized. Applications of lime wash are expected to yield avoided energy costs of US$ 22 million per year for Surat and US$ 45 million per year for Chennai, with the benefit-cost ratio of approximately 3:1. When lime wash is combined with concrete reinforcement of roofs – a measure is advantageous for safety purposes – the benefit-cost ratio declines to around 0.6:1 (see Table SF6).

Figure 8: Benefits-Cost Ratios of Illustrative Investments in Urban Heat Mitigation



Note: The bars illustrate the range of expected benefit-cost ratios for three categories of heat mitigation interventions in Indian cities; the dark lines indicate the mean expected benefit-cost ratio for the intervention type.

4. Discussion

This work confirms that Indian cities will face a significant rise in heat stress over the coming decades, with the magnitude of the increase depending upon global carbon emissions.

Through urban-scale climate modeling, the study underscores the spatial differences in extreme heat in the present day – with residents of city-center locations experiencing night-time temperatures up to 5°C higher than those in nearby rural areas. The modeling also makes it clear that these spatial disparities will persist with time and combine with heat intensification driven by global climate change, with the result that residents of densely built neighborhoods of Surat, Chennai and Lucknow will experience between 30% and 50% more extremely hot days and nights by 2050 than at present (assuming a high global emissions scenario).

While past studies have estimated health and labor productivity impacts of extreme heat, our work contributes to the literature by combining these two channels to assess their expected joint impact on cities as global climate change progresses. At present, around one-fifth of working hours per year are currently too hot for high-intensity physical work to be conducted safely based on occupational health and safety standards. The number of lost working hours due to extreme heat is expected to rise by up to 30% in the case of Chennai, putting more than 4% of the city's economic output at risk. While labor productivity outputs are crucial, it is however important to analyze these alongside expected health impacts, given that heatwaves result in illness and premature death concentrated among vulnerable segments of the population including the elderly. Consistent with existing epidemiological studies of extreme heat in India, our modeling estimates that the crude death rate may rise by 50% by 2050 under high emission scenario assuming a 'no intervention' scenario (Zhao et al. 2021).

Cities in India, and globally, are increasingly adopting measures to mitigate the diverse adverse impacts of extreme heat upon their citizens, economies, and infrastructure. The Ahmedabad Heat Action Plan has emerged as one 'best practice' model that other cities in India and internationally have emulated considering its multi-sectoral actions ranging from measures with a long time horizon that cool the physical spaces of the city (e.g., tree planting and cool roofs) and measures with a short time horizon that seek to save lives during heatwaves (e.g., issuance of color-coded alerts, activation of extreme heat protocols in hospitals, and measures to protect heat-affected workers). In this paper, we set out to model the benefits from adopting multi-sectoral packages of heat mitigation actions in Indian cities and to compare the benefit-cost ratios of the different actions.

We found benefit-cost ratios for the urban greening and heat-health early warning system interventions to be significantly positive. Increasing the area under tree canopy cover by 10% to 30% can be expected to yield air temperature reductions of up to 1.5°C on a localized basis, according to our analysis, which is in line with findings of a meta-analysis from European city-level studies of tree canopy cooling benefits (Iungman et al. 2023). Quantifying benefits of such temperature reduction based on averted mortality and labor productivity loss yields a positive benefit-cost ratio for urban tree planting. It is important to note that increasing tree cover and other natural assets in urban areas offers multiple advantages beyond reducing daily temperatures and heat stress. These enhancements create cooling areas for laborers, street vendors, workers, and commuters during hot days. Secondly, they play a significant role in flood risk management and provide a range of physical and mental health benefits to residents. This would be a significant advantage in labor surplus economies such as India, which are grappling with the challenge of addressing youth unemployment. These broader benefits may be equally or even more substantial in scale compared to the effects discussed here. Our finding that tree planting yields a benefit-cost ratio of 3:1 or higher suggests that such interventions 'pay for themselves' through mitigating adverse impacts of extreme heat on health and labor productivity alone, with their real benefit-cost ratios likely to be significantly higher, particularly in cases where tree planting brings significant flood mitigation benefits.

Our analysis also suggests that, among the heat mitigation interventions that cities can adopt, heat-health early warning systems has a particularly high ratio of benefits to costs. Indeed, with a benefit-cost ratio of 50:1 or higher, for heat warning systems – as well as high levels of implementation feasibility – this intervention can be considered 'low hanging fruit' that produce strongly beneficial outcomes for limited financial outlays. The finding suggests that cities would be well advised to prioritize heat-health early warning systems.

Implementing heat early warning systems is shown to be a highly effective strategy. Our research, along with other studies, consistently shows a significant reduction in mortality rates and a benefit-cost ratio (BCR) exceeding 50. These findings are not unique; similar BCR values are observed in studies worldwide. For instance, research by Chiabai et al. (2018) and Ebi et al. (2004) revealed BCRs well above 50 for cities like Madrid and Philadelphia.

Our study has several limitations. The health impacts analysis examined mortality without performing estimates of health costs associated with non-fatal illness. The exposure-response curves utilized were derived from all-India mortality data; our analysis could be improved through use of locally derived temperature-mortality relationships that would better characterize heat impacts in India's varied climatic zones. In future work, labor productivity impacts should be modeled with improved treatment of difference in heat exposure between occupations (eg. indoor vs. outdoor work). Despite these limitations, the present work contributes to advancing modeling approaches for urban heat mitigation and adaptation while pointing to strong policy conclusions about the urgency and efficacy of heat mitigation and adaptation actions that can be championed at the city level. Additional impact channels that could be analyzed would include extreme heat impacts on transport, power and water infrastructure and city services.

5. Conclusion

Indian cities already experience night-time temperatures 5°C or more higher than outlying rural areas due to the urban heat island effect, with densely packed neighborhoods most affected. Combined with impacts of global climate change, cities such as Chennai, Surat and Lucknow will see 30%-50% more heatwave days and hot nights per year. The rise in heat stress will increase the number of working hours per year which are too hot to safely perform work – particularly in high physical-intensity and heat-exposed outdoor sectors such as construction, agricultural work, policing, etc. – putting as much as 4% of economic output in cities such as Lucknow and Chennai at risk by 2050 under a high carbon emissions scenario. In parallel, based on existing heat-mortality relationships and accounting for a reasonable degree of additional heat-tolerance as urban Indians acclimatize to hotter conditions, heat-related excess mortality is expected to rise by approximately one-third by 2050, regularly resulting in hundreds of additional excess deaths per city during heatwaves, particularly among elderly and vulnerable populations. Cities are uniquely positioned to address the challenge of urban heat through policy instruments and investments such as tree canopy expansion, cool roofs and heat-health early warning systems. Benefit-cost ratios are particularly high in the case of heat-health early warning systems, suggesting that such measures should be prioritized for more widespread implementation in Indian and global cities.

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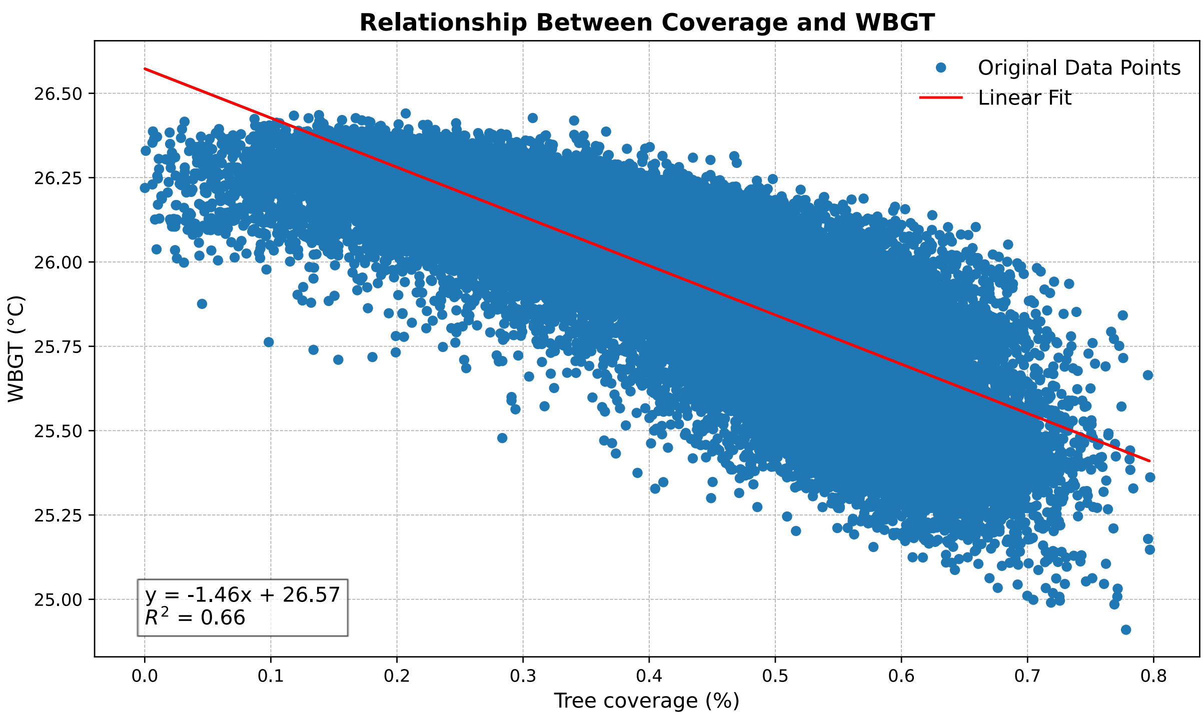
Supplementary Figures

Table SF1: Input datasets used for urban climate modeling

Type	*Source*	*Spatial resolution*
Land use	ESA WorldCover (Zanaga et al., 2021)	10m
Soil Sealing	Zhang et al. (2020)	30m
Vegetation (NDVI)	Landsat 8 archive	30m
Anthropogenic heat flux	Jin et al. (2019)	30m
Population density	Corbane et al. (2021)	10m
Soil texture	Hengl and MacMillan (2019)	250m
Digital elevation model	Copernicus DEM	30m

Figure SF2: Relationship of tree canopy coverage with heat stress



Note: Figure shows the fitted relationship between mean daily heat stress, measured on the Wet Bulb Globe Temperature scale (modelled through UrbClim simulations) with tree canopy coverage.

Table SF3: Categorization of occupations in terms of physical labor intensity

To calculate economic losses, we segmented the total workforce estimates by industry, work intensity (intense, moderate, light), and location (urban vs. rural) for all climate scenarios and future time periods. We considered the working population between the ages of 15 and 65, which constitutes around 65% of the total population for all cities. Employment rates for each city are as follows: Surat (99%), Chennai (95%), and Lucknow (97%) taken from Periodic Labor Force Survey (PLFS, 2023).

The proportion of people working in each sector, intensity of work, and location has been extracted from the Periodic Labor Force Survey. Economic losses are then calculated by multiplying the number of people working in each sector, lost working hours corresponding to place and work intensity, and the average daily earnings per day from casual labor work, excluding public works, obtained from the Periodic Labor Force Survey. Average daily earnings per day for casual labor work were also further taken from the Periodic Labor Force Survey.

	Corresponding type of work	**Surat/Gujarat**	**Chennai/Tamil Nadu**	**Lucknow/Uttar Pradesh**
A - Agriculture, Forestry and Fishing	Intense -rural	41.22	30.96	54.63
B - Mining and Quarrying	Intense -rural	0.2	0.2	0.04
C - Manufacturing	Indoor-NA	24.23	17.41	8.34
D - Electricity, Gas, Steam and Air Conditioning Supply	Intense-urban	0.32	0.32	0.18
E - Water Supply; Sewerage, Waste Management and Remediation Activities	Moderate - Urban	0.11	0.54	0.27
F - Construction	Intense - Urban	6.7	16.46	13.52
G - Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles	Indoor -NA	10.33	10.2	10.14
H - Transportation and Storage	Moderate - urban	4.29	5.45	3.1
I - Accommodation and Food Service Activities	Indoor -NA	1.36	2.96	1.17
J - Information and Communication	Indoor -NA	0.66	3.1	0.39
K - Financial and Insurance Activities	Indoor -NA	1.3	1.74	0.44
L - Real Estate Activities	Indoor -NA	0.12	0.2	0.14
M - Professional, Scientific and Technical Activities	Indoor -NA	0.62	0.94	0.47
N - Administrative and Support Service Activities	Indoor -NA	0.96	0.8	0.79
O - Public Administration and Defence; Compulsory Social Security	Indoor -NA	1.67	1.25	0.87
P - Education	Indoor -NA	1.75	2.94	2.2
Q –Human Health and Social Work Activities	Light -urban	1.59	1.35	0.8
R - Arts, Entertainment and Recreation	Light -urban	0.09	0.23	0.22
S - Other Service Activities	Light -urban	1.59	1.82	1.87

T - Activities of Households as Employers; Undifferentiated Goods and Services Producing Activities of Households for Own Use	Indoor -NA	0.88	1.12	0.42
U - Activities of Extraterritorial	Indoor -NA	0	0	0
Total		100	100	100

Table SF4: Overview Benefit-Cost analysis for tree cover increase (by 2050)

		10% increase (low ambition package)		30% increase (high ambition package)	
		SSP1-1.9	**SSP3-7.0**	**SSP1-1.9**	**SSP3-7.0**
Surat	Trees to be planted (million)	0.43	0.43	1.29	1.29
	Tree planting costs & maintenance (USD million)	2.2	2.2	6.6	6.6
	Heat-related deaths avoided	272	365	816	1095
	Benefit (USD million)	4.4	5.8	13.1	17.5
	Total win in labor productivity (USD million)	4.0	6.2	12.0	18.6
	Benefit-cost ratio	**3.9**	**5.6**	**3.9**	**5.6**
Chennai	Trees to be planted (million)	1.5	1.5	4.5	4.5
	Tree planting costs & maintenance (USD million)	7.4	7.4	22.1	22.1
	Heat-related deaths avoided	580	914	1740	2741
	Benefit (USD million)	9.3	14.6	27.8	43.9
	Total win in productivity (USD Million)	28.0	33.0	84.0	99.0
	Benefit-cost ratio	**5.1**	**6.5**	**5.1**	**6.5**
Lucknow	Trees to be planted	0.8	0.8	2.4	2.4
	Tree planting costs & maintenance (USD million)	3.9	3.9	11.8	11.8
	Heat-related deaths avoided	269	418	806	1253
	Benefit (USD million)	4.3	6.7	12.9	20.0
	Total win in productivity (USD Million)	6.0	7.5	18.0	22.5
	Benefit-cost ratio	**2.6**	**3.6**	**2.6**	**3.6**

Table SF5: Overview Benefit-to-cost ratio analysis for heat early warning systems

		Low ambition package			High ambition package		
		Present	**SSP1-1.9**	**SSP3-7.0**	**Present**	**SSP1-1.9**	**SSP3-7.0**
Surat	Average price cost of early warning system (building & operating costs - USD million)	0.314	0.347	0.445	0.314	0.347	0.445
	Heat-related excess mortality	1,520	3,437	4,131	1,520	3,437	4,131
	Avoided Heat-related mortality	304	687	826	608	1,375	1,652
	Value of heat-related mortality avoided (USD million)	4.87	11.00	13.22	9.73	22.00	26.44
	Benefit-Cost Ratio	**16**	**32**	**30**	**31**	**63**	**59**
Chennai	Average price cost of early warning system (building & operating costs - USD million)	0.320	0.353	0.451	0.320	0.353	0.451
	Heat-related excess mortality	3,564	6,106	8,700	3,564	6,106	8,700
	Avoided Heat-related mortality	713	1,221	1,740	1,426	2,442	3,480
	Value of heat-related mortality avoided (USD million)	11.40	19.54	27.84	22.81	39.08	55.68
	Benefit-Cost Ratio	**36**	**55**	**62**	**71**	**111**	**123**
Lucknow	Average price cost of early warning system (building & operating costs - USD million)	0.353	0.412	0.478	0.353	0.412	0.478
	Heat-related excess mortality	1,557	2,829	3,977	1,557	2,829	3,977
	Avoided Heat-related mortality	311	566	795	623	1,132	1,591
	Value of heat-related mortality avoided (USD million)	4.98	9.05	12.73	9.96	18.11	25.45
	Benefit-Cost Ratio	**14**	**22**	**27**	**28**	**44**	**53**

Table SF6: Benefit-Cost assessment for cool roofs

	Surat	Lucknow	Chennai
Total roof area - km²	75.1	120.4	161.0
25% roof area - km²	18.8	30.1	40.3
Applied multiple times over 10 years			
Cost roof change – applied 5x - lime wash (USD million)	70.8	113.4	151.6
Cost roof change – applied 2x- HDPE membrane (USD million)	80.9	129.6	173.3
Cost roof change – applied 1x - concrete and lime wash (USD million)	363.9	583.0	779.8
Savings over 10 year			
Energy saved (Gwh)	3193.1	5115.6	6842.5
Price energy saved (USD million)	223.5	358.1	479.0
Benefit -Cost Ratio - lime wash	**3.16**		
Benefit -Cost Ratio - White paint	**2.76**		
Benefit -Cost Ratio - Concrete and lime wash	**0.61**		