Commentary

Humid heat stress overlooked for one billion people in urban informal settlements

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Humid heat stress is an underestimated threat to the one billion people living in urban informal settlements without effective adaptation strategies. Expanded climate monitoring is essential to accurately assess exposure for this vulnerable demographic and inform urgently needed community adaptation.

Rising humid heat threatens the ability of tropical cities to sustain human populations.[1] Extreme wet-bulb temperatures (T_w), which capture the combined effects of temperature and humidity, surpassing the 35°C theoretical limit of human survival[2] have already been reported from global meteorological station networks.[3] Meanwhile, recent physiological studies of fit, healthy adults show that uncompensable heat stress, where the human body is unable to thermoregulate, occurs at T_w below 31°C in humid conditions.[1] Humid heat recorded by meteorological stations frequently approaches the 31°C uncompensable limit across tropical Asia and Africa.[3] Yet heat stress and its effects on human health are realized at local scales, and these broad-scale assessments likely still underestimate heat in dense urban settlements. Facing the reality that parts of the world are on track to experience extended periods of uncompensable heat, even with moderate global mean warming,[1] better local assessment and management of heat stress is urgently required, especially in vulnerable populations.

Informal settlements

More than one billion people are estimated to live in urban informal settlements globally. Informal settlements fall outside formal planning and regulations, lacking secure land tenure and the provision of centralized services such as electricity, water, and sanitation. As such, they are typically characterized by low-quality housing and infrastructure, and residents face a range of socioeconomic and health challenges.[4] Despite efforts to improve informal settlement conditions in line with Sustainable Development Goal 11, Sustainable Cities and Communities, the United Nations anticipates an additional 2 billion informal settlement dwellers over the next 30 years, driven largely by rapid urbanization and unaffordable housing.[5]

Informal settlements are concentrated in developing countries across the tropics, with settlements in sub-Saharan Africa and Asia comprising 85% of informal populations globally[5] (Figure 1). These intersect almost exactly with regions of current and future extreme T_w exposure. Sub-Saharan Africa, for example, is expected to be one of the first regions to experience frequent uncompensable T_w even with less than 2°C global mean warming.[1] Thus, countries where the vast majority of urban populations live informally will have to cope with the socioeconomic and political impacts of life-altering humid heat exposure. The IPCC AR6 report on "Impacts, Adaptation and Vulnerability" is clear that informal settlement communities are some of the most vulnerable to climate change and must be prioritized for resilience and adaptation efforts.[6] Yet a dearth of local climate data and accurate exposure assessments preclude effective adaptation measures.

Climate monitoring in informal settlements

The low density of meteorological stations across the tropics (Figure 1) fails to capture humid heat extremes in complex urban environments.[7,8] The majority of the world's population lives more than 25 km from a meteorological station,[9] but these data gaps are most severe in low-income countries with large populations living informally. In sub-Saharan Africa, for example, only 6% of urban settlements have a meteorological station within 5 km of their boundary (see experimental procedures).

Temperature and humidity, and consequently heat stress exposure, can vary substantially across cities. Urban heat islands, where temperatures in cities are warmer than non-urban surrounds due to urban morphology and reduced vegetation coverage, are well-documented in cities globally, including in tropical cities where rapid urbanization is accompanied by expanding heat islands. Localized temperature anomalies can be exacerbated in informal settlements where dense housing and limited green and open spaces worsen temperature extremes.[10] In some cities, however, lower urban humidity caused by reduced evaporation over urban surfaces can offset the heat stress caused by higher urban temperatures. In contrast to these expectations, urban T_w in tropical cities consistently exceed those measured at rural stations, averaging 0.17°C warmer in the daytime and 0.27 °C at night, though these estimates are hampered by the small number of urban-rural station pairs.[11]

In situ monitoring data from informal settlements[7,8,10,12] confirm that local T_w is severely underestimated by station data, far exceeding average urban-rural differences. We synthesized local climate monitoring data from informal settlements in seven cities across Asia and Africa (Figure 1) and compared *in situ* heat stress exposure to that measured at the nearest meteorological station (see experimental procedures). Although

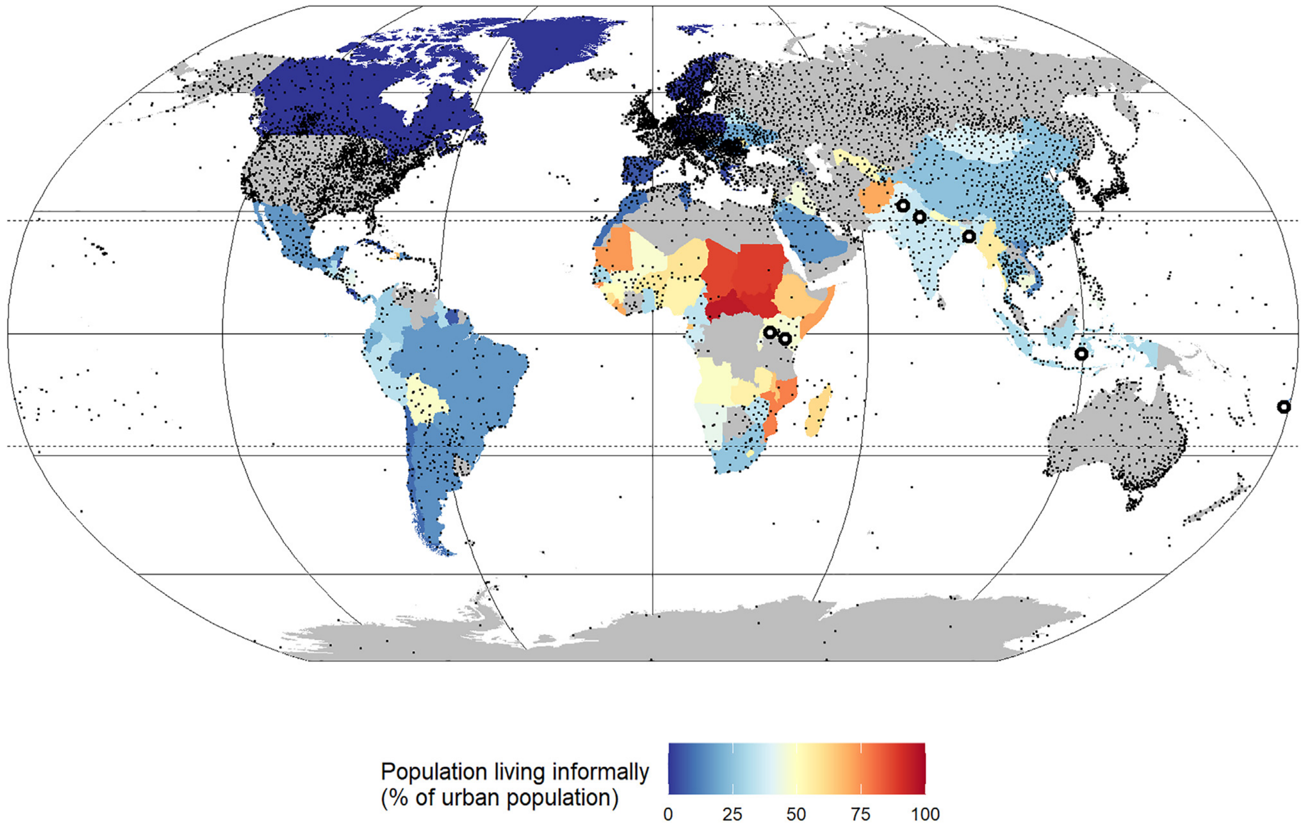

Figure 1. Meteorological stations are sparsely distributed across the tropics where urban informal settlements are most prevalent
Map shows the % of urban population living in informal settlements (termed "slums" in the United Nations reporting data) from the United Nations Human Settlements Program (data.worldbank.org/indicator/EN.POP.SLUM.UR.ZS; gray indicates NA). Points show station locations from the United Kingdom Met Office Hadley Centre Integrated Surface Database (global sub-daily station dataset). Circles show locations of *in situ* climate monitoring studies in informal settlements shown in Figure 2.

these monitoring efforts are currently scarce and non-standardized, our synthesis is representative of geographically diverse cities home to some of the largest informal settlement populations (Figure 1) and substantial current and future heat stress exposure.

Indoor and outdoor T_w measured *in situ* in informal settlements exceed those measured at the nearest meteorological station (typically located at the airport) by upwards of 1°C (Figure 2). In consequence, informal settlement residents likely experience worse heat stress than that estimated using meteorological station data and their derivatives, both during the day and night (Figure 2) and even on extreme heat stress days (where maximum T_w exceeds 28°C; Figure S1). Such a difference in T_w indicates that the 31°C uncompensable limit is crossed far more frequently than estimated by global assessments,[3] and the onset and severity of frequent uncompensable humid heat is much closer than estimated by global-scale projections.[1]

Implications for adaptation in informal settlements

For many informal settlement residents, exposure to humid heat is compounded by a lack of household adaptation strategies. Informal housing provides little relief from heat stress, especially at night (Figure 2), likely increasing exposure for the most vulnerable, such as the elderly and very young. Houses in informal settlements are typically built using low-cost materials, such as tin sheets, and have poor ventilation and insulation.[12] Air-conditioning ownership in low-income households is less than 10%[13] and typically less than 5% in informal settlements.[8] Additionally, the lack of reliable electricity connections in informal settlements[4] and the high cost of electricity usage are likely prohibitive, especially in times of high demand, such as during heatwaves. Electric fans are cheaper and more accessible but are insufficient to mitigate the heat stress caused by extreme T_w.[14] Moreover, increased water loss from evaporative cooling via sweating also represents a substantial risk to the many people in informal settlements who lack access to clean drinking water and may already be experiencing water stress.[4] In consequence, public health advice to mitigate the impacts of heat stress, which is often focused on drinking water or sheltering indoors,[14] is either ineffective or exposes informal settlement residents to further risk owing to water insecurity.

Household exposure is compounded by occupational exposure for workers in the informal economy. The informal work sector comprises primarily high heat stress occupations such as outdoor labor or indoor work in poorly ventilated factories.[15] Occupational heat stress has financial impacts through reduced efficiency and productivity as well as increased morbidity

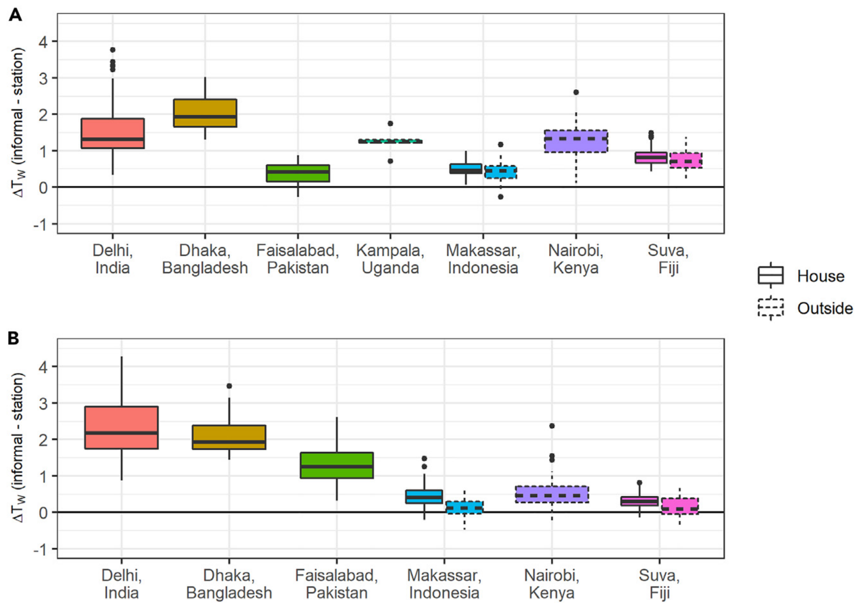

Figure 2. Meteorological station data severely underestimate *in situ* T_w in informal settlements during the day and at night

(A and B) Boxplots show the median ΔT_w (informal settlement T_w – meteorological station T_w) at each outdoor or household sensor for the day (A; 06:00–19:00) and night (B; 20:00–05:00) from *in situ* monitoring in informal settlements.

and mortality risks associated with chronic heat exposure. Surveys of informal sector workers report an inability to manage occupational heat exposure either due to adaptation measures being unavailable or the uptake of such measures resulting in economic losses.[15] For example, taking a break or reducing work hours to avoid the worst heat exposure may reduce a worker's earnings.

Given the paucity of household- and individual-level adaptations, community-based strategies are essential to mitigate the morbidity and mortality risks of humid heat in informal settlements. Owing to their informal status, however, residents generally lack representation at the local and national government levels where decisions about urban planning, green space, and public health are made.[4] Moreover, government-led efforts to mitigate urban heat by greening cities are unlikely to include informal settlements due to political preferences or lack of funding. Upgrading initiatives, led by non-governmental organisations and development banks, represent an opportunity to integrate green and blue space alongside essential improvements to water and sanitation infrastructure.[4] Yet, such efforts still require spatially explicit climate data to prioritize heat mitigation, data which are conspicuously lacking for informal settlements.

Similarly, early-warning systems are activated by forecasts of heat stress currently parameterized by historical meteorological station observations that underestimate the magnitude of humid heat in informal settlements (Figure 2). Moreover, the lack of local-scale climate data means that such systems are unable to deliver targeted advice specific to an individual or community's socioeconomic context. In consequence, informal settlement residents have little means to prepare for extreme heat and to implement the few adaptation options that may be available to them. Given the global coverage of smart phones and social media, even in low-income settings,[14] early-warning systems could readily leverage these technologies to deliver targeted advice to local communities, but only if the necessary climate data were collected. Unexpected extreme heat events, some of which may be protracted, are increasing in step with increasing global mean temperatures as a significant component of global warming.[6] Protecting the most vulnerable from such events is, therefore, urgent.

A valuable first step to improve climate monitoring would be to expand meteorological networks across the tropics, ensuring their data are integrated into global products and reanalyses, so that data better reflect the distribution of human populations and represent those with an inherently greater risk of exposure. Additionally, microclimate monitoring networks should be deployed to capture the human-lived experience across complex urban environments. This means designing networks that are representative of both biophysical and socioeconomic variation, and that capture the full extent of potential exposure, including indoor environments. To ensure that data can be streamlined into early-warning systems and exposure assessments, microclimate monitoring should be integrated into existing meteorological networks and managed by national meteorological institutes.[16]

Informal settlements currently constitute a blind spot in global climate monitoring. Assessing the true magnitude and extent of humid heat exposure, accurately and at local scales, is essential for risk management. Such efforts must be prioritized to protect the most vulnerable from the existential threat of humid heat.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Emma E. Ramsay (emma.ramsay@ntu.edu.sg).

Materials availability

This study did not generate new unique materials.

Data and code availability

All unpublished data have been deposited in a Figshare repository (https://doi.org/10.26180/24635133) and are publicly available as of the date of publication. All other data is available from the original studies (https://doi.org/10.6084/m9.figshare.12546368.v1; https://doi.org/10.5281/zenodo.5105570; https://github.com/gottscott/cityheat/tree/master/Nairobi/data) or from publicly available repositories of meteorological station data.

All original code has been deposited in a Figshare repository (https://doi.org/10.26180/24635133) and is publicly available as of the date of publication. Any additional information required to reanalyse the data reported in this paper is available from the lead contact upon request.

Method details

Informal settlement data were retrieved from four studies and one unpublished dataset that recorded extended temperature and humidity time series[7,8,10,12] (Table S1). These studies used stationary, low-cost temperature and humidity sensors to measure urban microclimate outdoors and in houses. Although unshaded sensors may be prone to overestimating temperatures, especially when measuring near-ground microclimates, all studies mitigated these problems by recording air temperatures at "human-relevant" heights (i.e., not near ground level) and deploying sensors either inside buildings, where they were not exposed to direct insolation, or in vented radiation shields, which shielded sensors from sunlight without substantially restricting airflow. For more in-depth analyses of the effects of building and sensor placement we direct readers to the original studies. We restricted analyses to data collected from sensors deployed in informal settlements, excluding data collected from any other study locales. Where sub-hourly data were reported, we calculated hourly means. Where data was collected from more than one sensor in a house, we calculated hourly means at the household level.

Meteorological station data were retrieved for each city over the same time period as *in situ* monitoring, from the UK Met Office Hadley Center HadISD global sub-daily station dataset (version 3.3.0.202209p),[17] or from the NOAA ISD global hourly dataset in the case of Kampala (Station ID: 636800). Pressure data to calculate T_w were retrieved from the ERA5 hourly reanalysis data retrieved from the Copernicus Climate Change Service Climate Data Store at the geographic coordinates of each meteorological station.

T_w was calculated for all informal settlement and station time series, where both temperature and humidity data were available, using the Davies-Jones formula[18] (implemented at https://github.com/cr2630git/wetbulb_dj08_spedup). We calculated ΔT_w (informal settlement T_w – meteorological station T_w) for all data with matching hourly time points. For example, if a station only reported 3-hourly measurements we restricted comparisons to informal settlement data collected at the same hour. For each outdoor sensor or house we then computed the median ΔT_w for the day (06:00–19:00) and night (20:00–05:00). A comparison of hourly ΔT_w for days where the maximum T_w recorded at the meteorological station exceeded 28°C is available in Figure S1.

We computed the number of urban settlements containing a HadISD meteorological station within their boundaries by cross referencing the HadISD global sub-daily station dataset station locations with the Global Human Settlement Urban Centers database (GHS_STAT_UCDB2015MT_GLOBE_R2019A_V1_2), buffered by 5 km.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2023.12.005.

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AUTHOR CONTRIBUTIONS

Conceptualization: E.E.R., S.L.C., and G.A.D.; methodology: E.E.R. and G.A.D.; formal analysis: E.E.R.; writing – original draft: E.E.R. and G.A.D.; writing – review & editing: P.H. and S.L.C.; supervision: G.A.D., P.H., and S.L.C.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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Supplemental information

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Table S1. Details of *in situ* climate monitoring studies in informal settlements

Location and methodological details of climate monitoring studies and corresponding Integrated Surface Database Station IDs. See the original studies for further information.

Location	Publication	DOI	n days	Sensor	n outdoor sensors	n houses	Station ID
Delhi, India	Tasgaonkar *et al.* 2022[1]	https://doi.org/10.6084/m9.figshare.12546368.v1	199	HOBO	NA	55	421810
Dhaka, Bangladesh	Tasgaonkar *et al.* 2022[1]	https://doi.org/10.6084/m9.figshare.12546368.v1	208	HOBO	NA	59	419220
Faisalabad, Pakistan	Tasgaonkar *et al.* 2022[1]	https://doi.org/10.6084/m9.figshare.12546368.v1	226	HOBO	NA	45	416300
Kampala, Uganda	Van de Walle *et al.* 2022[2]	https://doi.org/10.5281/zenodo.5105570	167	iButton	6	NA	636800
Makassar, Indonesia	Updated dataset from Ramsay *et al*. 2021[3]	https://doi.org/10.26180/24635133	1145	iButton	55	117	971800
Nairobi, Kenya	Scott *et al.* 2017[4]	https://github.com/gottscott/cityheat/tree/master/Nairobi/data	97	iButton	34	NA	637420
Suva, Fiji	Unpublished, following Ramsay *et al.* 2021[3]	https://doi.org/10.26180/24635133	875	iButton	45	114	916830

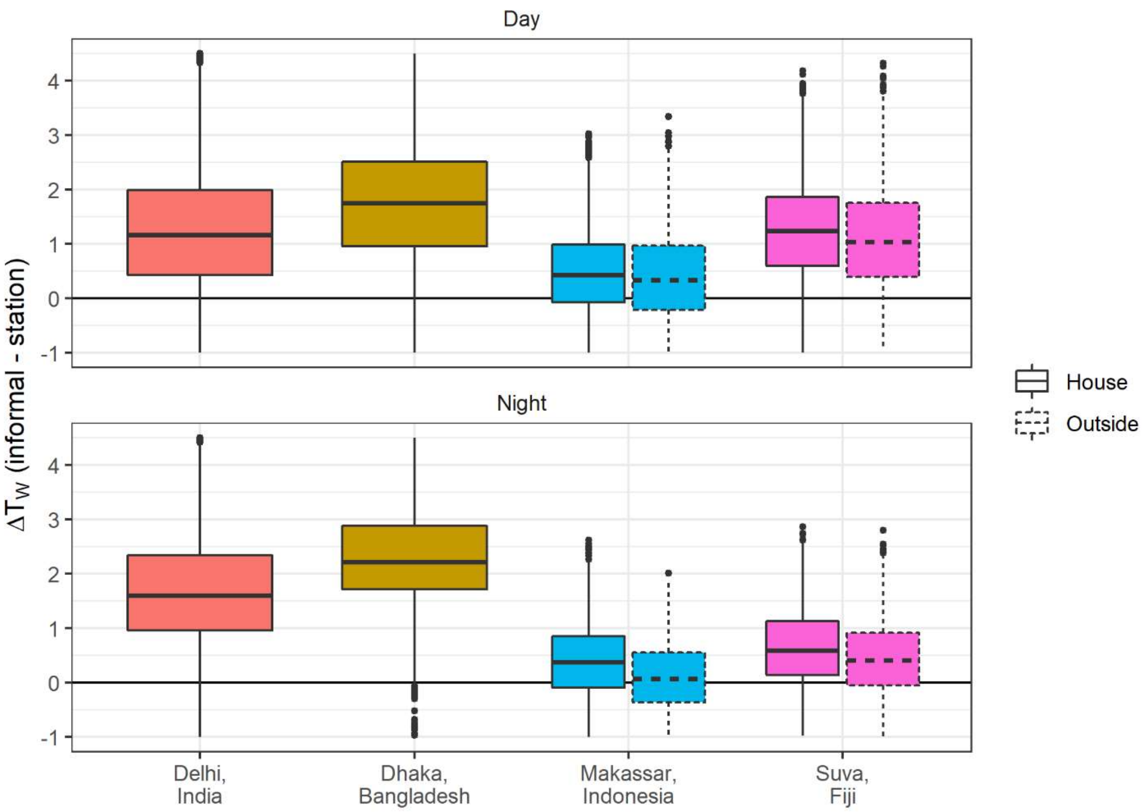

Figure S1. *In situ* T_w in informal settlements versus meteorological station data on extreme heat stress days.
Hourly ΔT_w (informal settlement T_w – meteorological station T_w) household sensor for the day (A; 06:00 – 19:00) and night (B; 20:00 – 05:00) on days where maximum T_w recorded by the meteorological station exceeded 28 °C.

Supplemental References

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