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Extreme weather should be defined according to impacts on climate-vulnerable communities

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Samantha C. Winter[1] ✉, **Mark R. Winter**[2], **LaNae Plaxico**[1], **Anna K. Balakrishnan**[1], **Millicent Dzombo**[2], **Loni Philip Tabb**[3], **Ebuka Ukoh**[1], **Chloe Lincoln**[1], **Lena Moraa Obara**[4], **Stephanie Achieng Otieno**[2], **Richard Muita**[5] & **Susan S. Witte**[1]

Climate change and related extreme weather events (EWEs) are expected to widen social and health inequalities. Yet, EWE thresholds and associated adaptation strategies do not centre experiences of vulnerable communities. This study explored the impacts of temperature- and precipitation-based EWEs for women in informal settlements, whether meteorological definitions of these EWEs capture impacts and whether self-reported impacts can be used to develop impact-based thresholds. We combined meteorological data with longitudinal monthly survey data collected from September 2022 through February 2023 from a probability sample of 800 women in two informal settlements in Nairobi, Kenya. Findings suggest that women experience health, economic, environmental, emotional, social and property impacts; thresholds of EWEs currently used for early action and preparedness are not capturing impacts; and, while self-reported impact data may provide an excellent first step in the process of (re)defining thresholds for some EWEs (for example, precipitation-based), more research and discussions with communities are needed.

Climate change and related extreme weather events (EWEs) are expected to widen social and environmental inequalities. As an issue of climate justice, those who least contribute to the conditions that exacerbate climate change are disproportionately harmed[1]. Residents of informal settlements are especially vulnerable to climate change because they live in ecologically sensitive areas (for example, riverbanks, floodplains, waste dumps and hillsides) and substandard structures more susceptible to EWEs[2,3]. Residents also face barriers to adaptation, including political and social marginalization, government disinvestment, poverty, exclusion from essential services and tenuous land tenure[2]. Approximately one billion people reside in informal settlements, most in sub-Saharan Africa, Eastern and South-Eastern Asia and Central and Southern Asia[4]. Yet, limited research focuses on the impacts of EWEs in these communities or incorporates residents' experiences into scientific definitions of 'extremes' and related climate change adaptation[5].

The Intergovernmental Panel on Climate Change defines an EWE as "an event that is rare at a particular place and time of year"[6]. Practically, however, scientists use various methods to define an event as 'extreme',[7] which leads to different definitions—some based on statistical (relative) or absolute thresholds[6,7]. Thresholds are critical in preventative climate adaptation interventions, such as pre-event emergency or evacuation warnings and response plans based on meteorological forecasting. However, they are usually set using data from general populations that exclude or obscure data from climate-vulnerable communities (for example, informal settlements)—defined as those most susceptible to

[1]Columbia University, New York, NY, USA. [2]Drexel University, Philadelphia, PA, USA. [3]Columbia Global Center, Nairobi, Kenya. [4]Rutgers University, New Brunswick, NJ, USA. [5]Kenya Meteorological Dept, Nairobi, Kenya. ✉e-mail: scw2154@columbia.edu

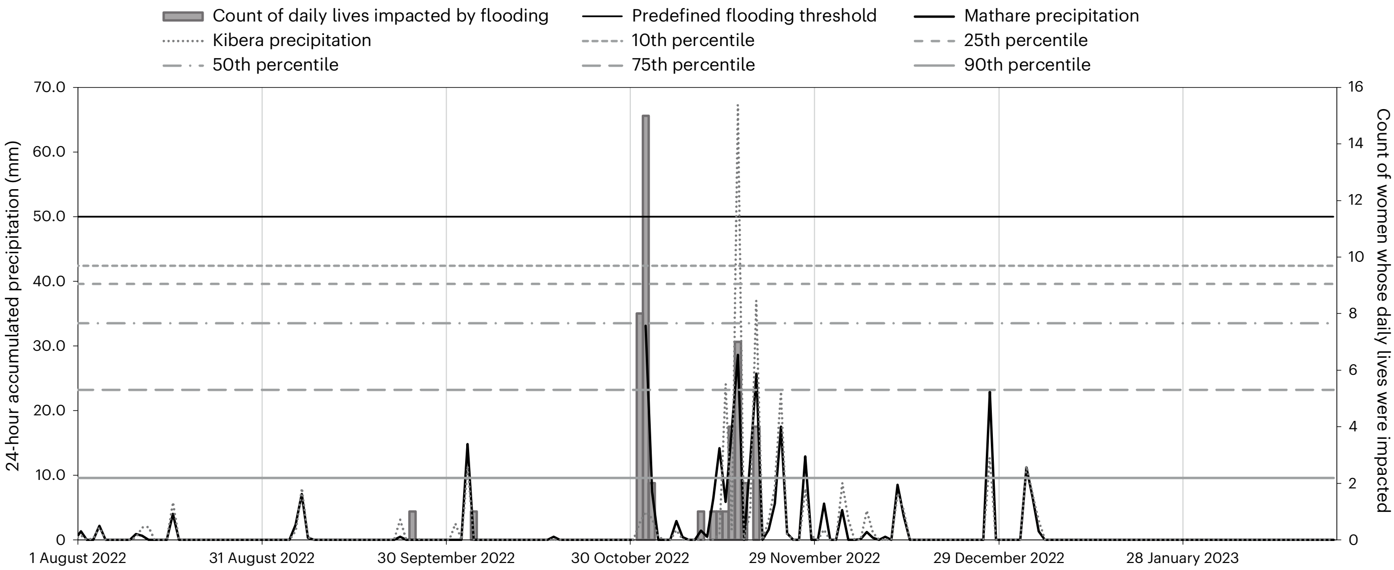

Fig. 1 | Precipitation, flooding impact counts and modelled impact-based thresholds. The 24-hour accumulated precipitation readings are overlaid with the daily count of women reporting a flooding event, modelled impact-based thresholds and the predefined threshold (50 mm) for heavy precipitation events.

or least able to cope with adverse effects of climate change, including climate variability and extremes[3].

Women in informal settlements are at greater risk of experiencing worse health-related outcomes than men due to climate change and related EWEs[8–12]. They also have more limited access to health-related services—to cope with or mediate climate-related health outcomes—than men in the same communities[8,13]. Despite this, EWE research has not focused on this vulnerable population[5].

EWE research needs more attention to rigour related to establishing adequate thresholds or impact-based forecasting models for vulnerable communities[5]. No articles in a recent scoping review on climate change health impacts in informal settlements examined meteorological thresholds versus first-person impact accounts. A narrative review of 54 primary research studies on EWE health impacts in informal settlements[5] found no studies using meteorological data in combination with first-person accounts to compare whether thresholds accurately account for impacts.

The purpose of this study was to explore what types of impacts women and household members experience in informal settlements (R1), whether meteorological definitions of specific types of EWEs (precipitation-based, heat-based and cold-based) capture these impacts (R2) and whether women's self-reported impact data can provide a first step in the process of (re)defining impact-based thresholds for these communities (R3). We evaluate R1 by describing how participants report being affected by precipitation-based events (heavy downpours and flooding), extreme heat or extreme cold; R2 by comparing meteorological data for these specific EWEs with women's reported experiences of them; and R3 by modelling the probability of women being impacted by these EWEs, given a weather parameter-based threshold (for example, maximum/minimum temperatures or accumulated precipitation). We use longitudinal survey data collected monthly between 1 September 2022 and 28 February 2023 from a probability sample of 800 women living in the Kibera (n = 400) and Mathare (n = 400) informal settlements in Nairobi, Kenya. Details are presented in Methods.

Impacts of EWEs on daily lives

Broad categories of impacts (and frequencies) from floods, downpours, heat and cold included: emotional (36), financial (217), health (664), environmental (460), property (472) and social (16). Common impacts of flooding included economic issues such as disruptions to businesses (12); property issues, including houses flooding with water and sewage (48); and destroyed belongings (4). Common impacts from heavy downpours included property damage, such as flooding houses (270), destroyed goods (17) and roofs leaking (93); economic impacts, including disruptions to businesses and employment (56); and health impacts, including losing sleep (23) and colds/flu (7). Common impacts of heat extremes included health impacts, for example, fatigue (86), sleep issues (50), headaches (37), overheating (29) and difficulty walking (19) for women and their children (20). Women also described housing material (18) and economic issues, including disrupted businesses or employment (59) and increased water and food costs (28). The impacts of cold extremes included health issues, such as colds/flu (51), especially among children (19) and economic issues, such as disruptions to businesses or employment (24).

Precipitation events

We compare meteorological data and participant perceptions of precipitation extremes using plots of 24-hour accumulated precipitation readings from the Kenya Meteorological Department (KMD) for the period 1 August 2022 through 28 February 2023 (Figs. 1 and 2). We overlaid the predefined precipitation-related EWE threshold, the count of women reporting being impacted by a precipitation-related EWE each day and five impact-based thresholds derived from our precipitation-based probability models representing percentiles of women impacted (10%, 25%, 50%, 75% and 90%). In the first 6 months of data collection, Mathare experienced no days of precipitation that exceeded the predefined threshold of 50 mm, yet 50 women (6%) reported that their daily lives were impacted by at least one flooding event and 150 (19%) reported being impacted by a heavy downpour. Kibera experienced one day above the threshold on 16 November 2022. Twenty two women (3%) reported being impacted by at least one flooding event and 122 (15%) reported a heavy downpour.

The impact-based threshold probability models (logistic regressions) for flooding and heavy downpours fit the impact data well, with Cox and Snell pseudo-r^2 values of 0.8865 and 0.9992, respectively. Comparing the impact counts and the modelled impact-based thresholds with the predefined EWE threshold shows that the predefined threshold is unlikely to capture reported impacts or modelled impacts for flooding and heavy downpours. Additional reports of the types and frequencies of events impacting daily lives are summarized in Table 1.

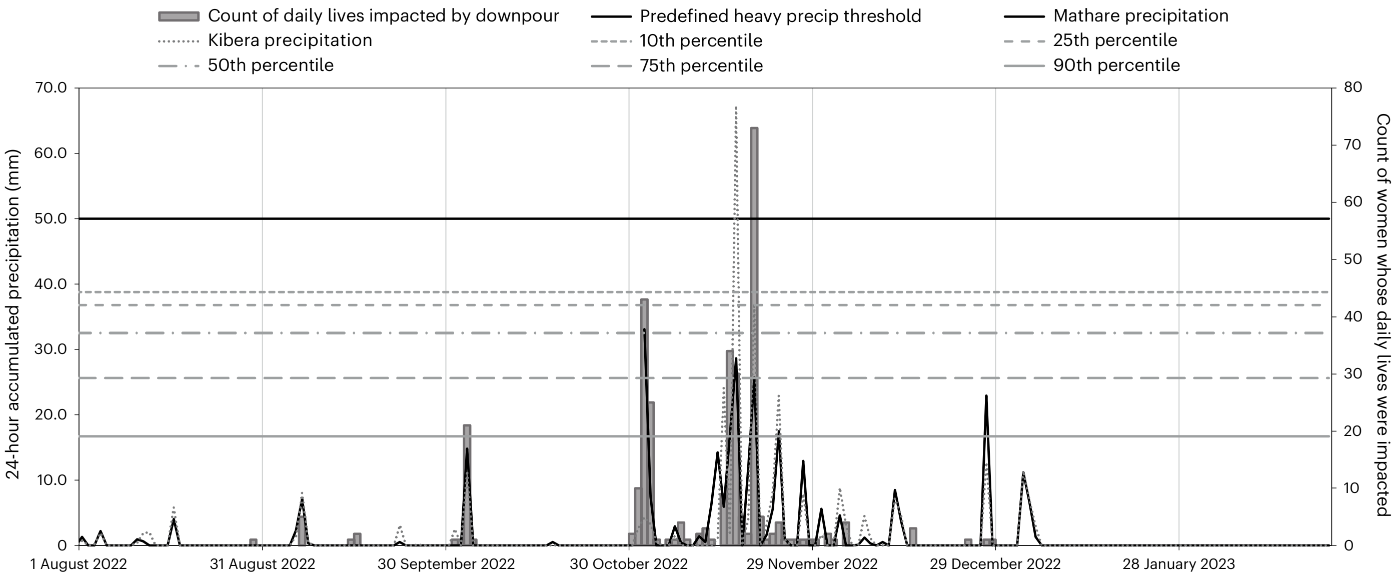

Fig. 2 | Precipitation, heavy downpour impact counts and modelled impact-based thresholds. The 24-hour accumulated precipitation readings are overlaid with the daily count of women reporting a heavy downpour event, modelled impact-based thresholds and the predefined threshold (50 mm) for heavy precipitation events.

Table 1 | Count of women's experiences of events impacting theirs and/or members of their households' daily lives

Type of event	One event			Two events			Three events			Four events			Total
	Mathare	Kibera	Total	Mathare	Kibera	Total	Mathare	Kibera	Total	Mathare	Kibera	Total	
Flood	49	19	68	1	2	3	0	1	1	0	0	0	72
Heat	161	105	266	75	36	111	27	12	39	7	3	10	426
Cold	178	163	341	48	39	87	14	4	18	3	0	3	449
Downpour	128	110	238	19	11	30	3	1	4	0	0	0	272

Heat events

We compared meteorological data and participant perceptions of extreme heat using a plot of the maximum temperature readings from KMD for the period 1 August 2022 through 28 February 2023 (Fig. 3). We overlaid the predefined heat-related EWE threshold ($T_{97.5}$), the count of women reporting being impacted by a heat-related EWE each day and five impact-based thresholds derived from a maximum temperature probability model (10th, 25th, 50th, 75th and 90th percentiles). The temperature rose above $T_{97.5}$ = 29.8 °C on 9 days in Mathare. A total of 161 (20%) women reported that their daily lives were impacted by one extreme heat event, 75 (9%) reported being impacted by two events, 27 (3%) reported being impacted by three events and 7 (1%) reported being impacted by four. Although Kibera did not experience any days with temperatures above $T_{97.5}$ = 30.1 °C, 105 women (13%) reported that their daily lives were impacted by one extreme heat event, 36 (5%) reported impacts from two events, 12 (2%) reported impacts from three events and 3 (<1%) reported impacts from four events.

The impact-based threshold probability model (logistic regression) for extreme heat for Mathare and Kibera had Cox and Snell pseudo-r^2 values of 0.1609 and 0.0024, respectively. Given the high unexplained variability in the temperature probability models, we cannot rely on them to provide accurate impact-based thresholds for this population and, consequently, cannot quantify the mismatch between the predefined thresholds and more appropriate impact-based thresholds with these models alone.

Cold events

We compared meteorological data and participant perceptions of extreme cold using a plot of the minimum temperature readings from KMD for the period 1 August 2022 to 28 February 2023 (Fig. 4). We overlaid the predefined cold-related EWE threshold ($T_{2.5}$), the count of women reporting being impacted by a cold-related EWE each day and five impact-based thresholds from the minimum temperature probability model (10th, 25th, 50th, 75th and 90th percentiles). The temperature dropped below $T_{2.5}$ = 10.9 °C on 3 days in Mathare. A total of 178 women (22%) reported that their daily lives were impacted by one cold spell, 48 (6%) reported impacts by two, 14 (2%) reported impacts by three and 3 (<1%) reported impacts by four. In Kibera, temperatures dropped below $T_{2.5}$ = 9.2 °C on the same 3 days and 163 women (20%) reported that their daily lives were impacted by one cold spell, 39 (5%) reported impacts by two events and 4 (<1%) reported impacts by three events.

The impact-based threshold probability models (logistic regressions) for extreme cold for Mathare and Kibera had Cox and Snell pseudo-r^2 values of 0.2865 and 0.0946, respectively. Again, given the high unexplained variability in the models, we cannot rely on them to provide accurate impact-based thresholds for this population and, consequently, cannot quantify the mismatch between the predefined thresholds and more appropriate impact-based thresholds with these models alone.

Discussion

Findings highlight that women in informal settlements experience a variety of impacts from EWEs that affect daily life in compounding ways. Findings also suggest that predefined thresholds of EWEs based on meteorological data, population-level data and health threshold literature may not be well-aligned with the impacts of EWEs experienced by climate-vulnerable communities, such as women in informal settlements. Further, while self-reported impact data may provide adequate information to serve as an excellent first step in the process of (re)

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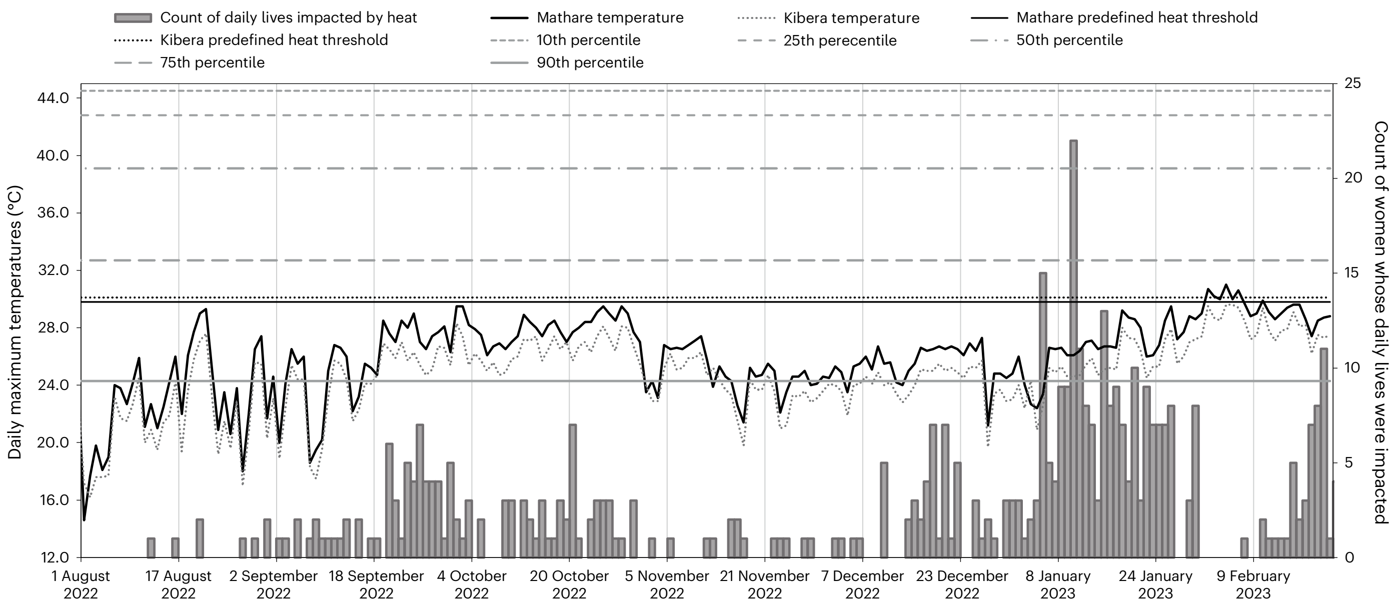

Fig. 3 | Maximum temperature, extreme heat impact counts and modelled impact-based thresholds. Daily maximum temperature readings are overlaid with the daily count of women reporting extreme heat, modelled impact-based thresholds and the predefined threshold for extreme heat ($T_{97.5}$).

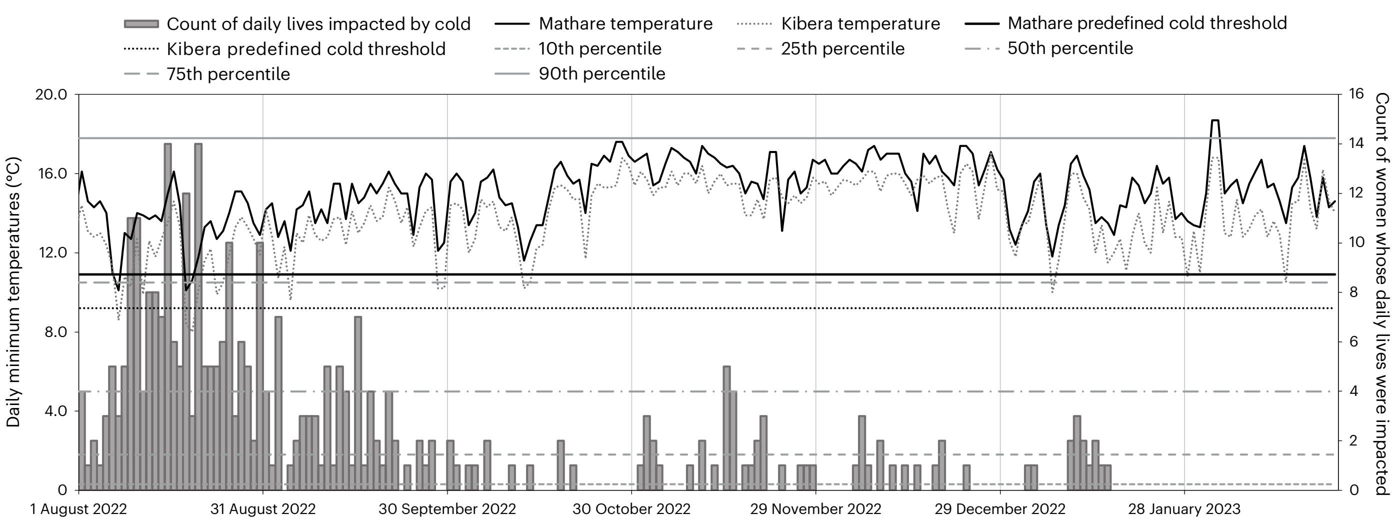

Fig. 4 | Minimum temperatures, extreme cold impact counts and modelled impact-based thresholds. Daily minimum temperature readings are overlaid with the daily count of women reporting extreme cold, modelled impact-based thresholds and the predefined threshold for extreme cold ($T_{2.5}$).

defining thresholds for precipitation-based events, such as flooding and heavy downpours, in these communities, a rigorous scientific and climate-justice-centred process requires continued engagement with communities and more research to develop and/or test appropriate impact-based thresholds, especially those based on temperature data.

Findings describe a range of EWE-related impacts, many in combination. For example, property issues during flooding were often associated with health and financial issues. In the case of high temperatures, businesses or employment disruptions were associated with water and food costs increasing due to environmental factors such as water rationing and rapid food spoilage.

Our precipitation probability models demonstrate a clear gap between the meteorological thresholds defining EWEs and people's perceptions and experiences of these events. Models based on women's self-reported impacts for flooding and heavy downpours showed that the predefined meteorological threshold of 50 mm of accumulated rainfall in 24 hours is too high to capture community impacts. Even the 10th percentile impact-based flood (42.4 mm) and heavy downpour (38.8 mm) thresholds were well below the predefined threshold. While we used an absolute precipitation threshold based on the KMD threshold of heavy rainfall associated with flash flooding in Nairobi, which currently serves as the basis for early action and preparedness in Kenya[14], our findings show that these absolute EWE thresholds are often inadequate for capturing impacts, as they do not integrate local vulnerabilities, tolerance or adaptations. This suggests a critical need for impact-based threshold models that capture residents' experiences.

The fit for the probability models we developed to explore impact-based thresholds for precipitation-based EWEs was excellent—suggesting that self-reported impact data may be a relatively low-cost first step in setting appropriate impact-based thresholds for precipitation-based EWEs in these communities. This may be because, while self-reported data are often susceptible to recall bias, precipitation-related events can be isolated or easier to pinpoint. The impacts, for example, damage to belongings, houses and businesses/places of employment, can also be acute, which may help women recall such events with more accuracy.

While findings suggest precipitation-based models may be a low-cost first step in (re)defining impact-based thresholds or the 'extremeness' of climate and weather events and related adaptation strategies, we suggest an iterative, staged, coproduction process for enhancing the rigour and justice of defining thresholds done with people living in these communities. We suggest three subsequent steps in this process: (step 2) engage the community in deciding on a tolerable level of impact (for example, in our models, a threshold of 9.6 mm of accumulated rain captures 90% of reported flooding impacts and a threshold of 16.7 mm captures 90% of heavy downpour impacts); (step 3) carry out a causal impact analysis with KMD and communities to test whether the new threshold is accurate and adequate for early warning systems (EWSs); and (step 4) work with communities, government and service providers to develop and test additional interventions to reduce impacts of EWEs in these communities.

Deciding on an acceptable threshold based on a 'tolerable' level of impact on populations requires working with communities to interpret findings from impact-based probability models, redefining parameters if necessary and choosing tolerable thresholds for them. Modelled thresholds are often based on health-related outcomes. The most common is mortality[15,16], followed by mental health[17], emergency hospital admissions[18], children's health[19] and others. We chose to base our impact-based threshold models on all categories or 'any impacts' to explore whether predefined thresholds were doing an adequate job of capturing women's experiences of EWEs in informal settlements; however, communities may prefer models to focus on a single or specific impact. As a research team, we are mostly outsiders to informal settlements; thus, it is critical for community members from within to decide. Since marginalized communities are more vulnerable to climate change and top-down interventions could exacerbate existing inequalities[20], it is critical in step 2 for residents to be involved in the process of determining (1) what outcomes should be chosen and (2) what should be considered a 'tolerable' level of risk for these impacts based on the models (for example, the threshold associated with the 90th percentile). In fact, community members could select a range of impact-based thresholds used to develop a hazard matrix for EWSs.

In step 3, we suggest carrying out a causal impact analysis. For example, working with KMD—whose mandate is to provide timely early warning weather and climate information—to test the accuracy of modelled impact-based thresholds (for example, they capture at least the percentage of impacts experienced by residents), and whether EWSs based on the (re)defined (lower) thresholds and delivered to these communities via early warnings substantially reduce the impacts of precipitation-related events for residents. Involving national meteorological authorities throughout the research process is critical in helping integrate research findings into EWSs.

In step 4, we suggest co-refinement of EWSs between the KMD and communities (for example, working with communities to determine delivery strategies to ensure all community members receive early warnings) and codevelopment of interventions to reduce EWE impacts between communities, government and service providers. For example, findings showed that inadequate housing materials allowed for rain from heavy downpour events to enter houses. Forecast-based financing[14], which involves distribution of funds to communities to help prepare for impacts of forecasted EWEs, is a potential strategy governments and communities could test to support residents to pay for housing renovations or other preparedness strategies. Additionally, women in our study suggested that the absence of formal solid waste collection exacerbates flooding because trash collects in drainage systems (informal and formal) and rivers, blocking/clogging them and causing spillover. Governments could work with communities to explore solid waste collection and disposal systems to reduce flooding risks. These are just examples of potential codeveloped interventions to further reduce impacts of precipitation-based EWEs in these communities.

Our temperature-based probabilistic models suggest that more research is needed to (re)define impact-based thresholds for these EWEs. The models had substantial unexplained variability. One possibility for differences in model fit between the precipitation-based and temperature-based models could be related to recall bias. In this study, for example, 64 women stated that they could not pinpoint an exact date for extreme heat and 93 for extreme cold. Recall for temperature-related EWEs may be particularly prone to bias for several reasons. Heatwaves are often multiday events; however, our surveys captured information about women's experiences of EWEs with a single date format—not multiple events of the same type in 1 month or multiday events. Thus, recalling which day was the hottest may have been challenging. Additionally, some even moderate temperature-related events have an extreme effect on communities when compounded with other events or experienced over a prolonged period[6]. The perception of an event as extreme and the consequences women experience may result from cumulative effects or prolonged exposure rather than the effects of a single threshold-defined EWE. Once they have identified a heat/cold event, women may also adapt or adjust to the temperature extremes, such as not going to work, wearing different clothing and so on, which could also contribute to misidentification of the date on which the most extreme temperature occurred.

Adding potential cofounders or covariates in the probabilistic models exploring temperature-related impact-based thresholds, for example, the location or materials of homes, may be important and, ideally, community members will help determine which factors to include. Also, capturing temperature data from within informal settlements could help the alignment between meteorological data and women's experiences of extremes in future studies. We relied on temperature data from KMD stations located 1–2 km away from the informal settlements, which may have contributed to the poor fit for the temperature-based models. Research suggests temperatures are hotter in these settlements than at nearby stations[21]. Thus, women might report the impacts of heat-related events on days with temperatures well below the station-based predefined EWE thresholds because they are experiencing hotter temperatures in the settlements. Community engagement in the collection of localized temperature data could also improve alignment with impact reports.

Conclusion and impact

Findings highlight that while defining EWEs and setting appropriate impact-based thresholds is important, climate-justice considerations centre people's experiences from the most climate-vulnerable communities. We found that relatively simple probability models based on a single weather parameter may be a good first step in exploring impact-based thresholds for precipitation events, such as flooding or heavy downpours; however, more research and discussions with communities are needed to refine and develop appropriate impact-based thresholds, especially for temperature-related EWEs. We emphasize the importance of including women in informal settlements and other climate-vulnerable communities in iteratively defining EWEs, setting and testing impact-based thresholds and developing interventions to reduce impacts.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-024-01983-7.

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Methods

Research design

Study data, collected between 1 September 2022 and 28 February 2023, are part of a longitudinal, quantitative study investigating associations and mediating effects between climate, mental health and violence in informal settlements in Kenya. The study included monthly household-level surveys collected from 800 women living in informal settlements in Nairobi. The findings in this paper draw on responses from the first 6 of 18 monthly surveys or a total of 4,800 surveys.

Research setting

Participants were recruited from two of the largest informal settlements in Nairobi—Kibera and Mathare. These settlements are situated in lowlands along Nairobi's main rivers, exposing residents to annual flooding and mudslides during heavy rains[22,23]. Research suggests that temperatures in the settlements are several degrees Celsius higher than in surrounding areas, including at the closest national weather stations[21]. While informal settlements in Nairobi share similar resource constraints, localized climate (for example, temperature and precipitation) varies[21].

Study sample

A probability sample of 800 women in Kibera ($n = 400$) and Mathare ($n = 400$) was drawn using a sampling method previously executed by the authors[24]. The study used satellite data from OpenStreetMap (.osm). A fishnet grid was superimposed on the OpenStreetMaps in ArcGISPro v.3.0. Each grid cell was 9 m^2 (3 × 3 m^2)—the approximate size of a tin or mud house or a room in a high-rise. A random selection function was used to identify 400 random grid cells for sampling in each informal settlement. GPS coordinates for 50 random grid cells were loaded onto 16 community data collector's (CDC) tablets. CDCs used Google Earth and Google Maps on their tablets to navigate to the closest household to the GPS coordinate. The quasi-random 'last birthday' method was then used to identify one woman within each randomly selected household to invite to participate[25]. Participants had to be 18 years or older, speak English or Swahili and be residents of the informal settlement. Swahili is the lingua franca in informal settlements.

Enrolled participants ranged from 18 to 79 years (mean = 47 years, s.d. = 17). More than half (55%) were married, 17% were single, 18% were divorced or widowed and 9% had a partner but were not married. Most women (93%) had at least one child, 45% were head of their household. Over 42% live in households with three or four people. Most women completed primary school; less than 5% had no education.

Data collection

Household-level surveys were collected by 16 trained women residents (CDCs) of Kibera (8) and Mathare (8)—a data collection strategy used in previous studies[24] and in other informal settlement studies in Nairobi[26,27]. CDCs were trained on the principles of ethical research, quantitative data collection, study protocols and the World Health Organization's ethical and safety recommendations for research on violence against women and sensitive topics[28]. In accordance with these recommendations, investigators, local collaborators and CDCs agreed on safety protocols if a participant reported violence and adverse mental health outcomes. The 60–90 min survey was collected one-on-one in participants' homes and responses were recorded on tablets, including verbatim responses to open-ended questions. A quality assurance exercise conducted before study initiation and at 6 months ensured objectivity and best practices in survey implementation. Each CDC was observed conducting an interview. Any variances or changes in the protocol were discussed and the CDC was retrained in that portion of the interview.

Meteorological measures

The KMD provided daily readings for 24 h accumulated rainfall and maximum and minimum temperatures for the study period from two KMD weather stations 1.1 km from the border of Mathare (Moi Air Base) and 1.5 km from the border of Kibera (Dagoretti Corner). We defined EWEs according to meteorological thresholds associated with adverse impacts in the literature. Specifically, we defined a precipitation-based EWE as (1) cumulative rainfall of 50 mm or more in 24 h—the KMD threshold of heavy rainfall associated with flash flooding in Nairobi[14]; (2) a maximum daily temperature exceeding the 97.5th percentile of the long-term (30 year) temperature record ($T_{97.5}$)—a value significantly associated with adverse health effects and mortality[15]; and (3) a minimum daily temperature below the 2.5th percentile of the long-term temperature record ($T_{2.5}$)—a value also associated with negative health effects and mortality[15]. Before the study, we calculated $T_{97.5}$ and $T_{2.5}$ for Moi Air Base station ($T_{97.5}$ = 29.8 °C; $T_{2.5}$ = 10.9 °C) and Dagoretti Corner ($T_{97.5}$ = 30.1 °C; $T_{2.5}$ = 9.2 °C), separately, using data from 1998 to 2018.

Measures of impacts of EWEs

At each survey, participants were asked whether they or members of their household experienced any EWE(s) in their settlement in the past month. If 'yes', they were asked to specify the type(s) of event(s) and the date(s) of the event(s). Women were also provided with a list of common EWEs, including floods, extreme heat, extreme cold, heavy downpours, drought, landslides, extreme wind and bad air quality and asked if they or members of their household had experienced any of those events and, if so, to specify the date(s) of the event(s). For the purpose of this analysis, we focused on women's experiences of EWEs most closely aligned with the three meteorological measures we had access to through KMD, specifically extreme heat (aligned with maximum temperature values), extreme cold (aligned with minimum temperature values) and flooding and heavy downpours (aligned with accumulated rainfall values). The reason we chose to focus on impacts of floods and heavy downpours instead of choosing one is because different women may experience different precipitation-based EWEs depending on where they reside, work and walk in informal settlements. For example, if a woman lives near a river or drainage she may experience flooding as a result of high levels of accumulated rainfall in 24 h. A woman who lives at higher altitudes or away from rivers/drainages may be less likely to experience flooding from high levels of accumulated rainfall but may experience impacts from a heavy downpour including, as many women described, precipitation leaking into households because of inadequate roofing materials.

To capture the impacts of EWEs, participants who stated that they or members of their household had experienced EWEs were asked follow-up questions about whether and how the event(s) impacted their (or members of their households') daily lives during or since the event(s). Impact responses were recorded verbatim.

Inclusion and ethics statement

This study has been approved by the Columbia Internal Review Board (IRB-AAAU0353); the Scientific Ethics Review Unit at the Kenya Medical Research Institute (protocol no. 4476); and the Kenya National Commission on Science, Technology and Innovation (license no. NACOSTI/P/22/19316). All participants in this study provided written informed consent.

Data analysis

Our research questions guided the analysis. To explore R1, five team members coded and categorized women's verbatim descriptions of the EWE impacts on theirs (or members of their households') daily lives. Two team members independently coded the verbatim responses in the baseline survey (September 2022) to develop a working codebook. Three coders used the codebook to code monthly follow-up surveys from October 2022 through February 2023. A fourth coder reviewed codes separately to confirm congruency and accuracy. Discrepancies in coding and codebook adjustments were discussed with the entire research team. Once the research team approved the coding, we analysed the EWE impact frequency.

To explore R2 and R3, we used standard binomial logistic regression models to model the probability of each individual in a community being impacted by an EWE, given a weather parameter (in this case, maximum or minimum temperatures or accumulated precipitation). Binomial regression assumes that each individual's probability of experiencing EWE will be independent conditioned on the input parameters (for example, precipitation). The logistic equation we used was:

$$P_{\mathrm{EWE}}\left(x\right)=\left(1+\mathrm{e}^{-\left(\beta_{0}+\beta_{1}x\right)}\right)^{-1},$$

where P_{EWE} is the probability of an individual experiencing the EWE (for example, flooding), x is the input parameter (for example, precipitation) and β_0, β_1 are the regression coefficients. For example, given a fixed precipitation amount, in mm per day, the model predicts a probability of any individual experiencing flooding, which corresponds with a percentile of total observed flooding reports from the survey. The logistic regression models were fit using standard generalized linear regression tools in Python statsmodels package[29]. Once the model was fit, five thresholds representing percentiles (10%, 25%, 50%, 75% and 90%) of the total number of people reporting EWEs impacts were computed. Model goodness of fit was measured using the Cox and Snell pseudo-r^2 value. Plots showing each model fit alongside the data are available in the Supplementary Information, along with a table indicating the computed thresholds and model fit parameters and metrics. We compare the modelled percentiles and the predefined theoretical EWE thresholds over daily meteorological readings from Dagoretti Corner and Moi Air Base (Figs. 1–4). These figures included counts of self-reported daily impacts.

Limitations

Study findings must be considered in light of limitations. Surveys captured information about women's experiences of EWEs with a single date format and not multiple events of the same type in 1 month or multiday events. These data, therefore, are probably reporting frequency counts of women's experiences of EWEs well below actual daily counts—potentially introducing bias from misspecification. In month seven, we changed the measure to allow women to select several dates on a calendar. Data from months 7–18 incorporate improved accuracy regarding dates of EWE experience.

Given the lack of validated measures for EWE impact, we used verbatim response options and qualitative group-coding methods to develop impact categories. While appropriate, it is hard to know if these measures adequately capture the necessary information to understand and define EWEs and their impacts on women in these communities. This highlights a need for research on measures for capturing information about EWEs and their impacts.

The location of the KMD stations, 1–2 km away from the informal settlements, may have also contributed to the poor fit for the temperature-based models. Research indicates that temperatures are hotter in these settlements than at nearby stations[21]. Thus, women might report the impacts of heat-related events on days with temperatures well below the station-based predefined EWE thresholds because they are experiencing hotter temperatures in the settlements. Future studies should consider setting up thermometers to measure temperature locally within settlements.

Finally, we acknowledge possible bias related to study team member positionality[30]. We represent a range of racial, national, socio-economic, social, employment, age and gender identities in Kenya and the United States. The principal investigator (PI) and Kenyan team members lived in Nairobi before, during and after data collection, carried out previous research in these settlements and speak both Swahili and English. Only the 16 team members collecting data live within the informal settlements. To mitigate this, the team worked with these 16 women throughout the study design, data collection, analysis, interpretation and manuscript editing process.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The data supporting this study's findings are available at: https://github.com/scw2154/NCC_DefiningExtremes (ref. 30).

Code availability

Code supporting the analyses run in this study are available at https://github.com/scw2154/NCC_DefiningExtremes (ref. 30).

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Author contributions

S.C.W. guided overall conceptual design for the study and analysis and preparation of the manuscript. M.R.W. contributed to data analysis, drafting of sections of the manuscript and revising the manuscript. L.P.

contributed to data analysis and review and editing of the manuscript. A.K.B. contributed to data analysis and preparation of manuscript. M.D. directed and oversaw study implementation and data collection. L.P.T. guided data analysis and visualization and review and editing of manuscript. E.U., C.L. and L.O. drafted and reviewed sections of the manuscript. S.A.O. contributed to study implementation, data collection and analysis. R.M. conceived the study with S.C.W. and collected and analysed data. S.S.W. oversaw drafting of sections of the manuscript and revising of this manuscript. All authors read and approved this manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Samantha C. Winter.

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Corresponding author(s): Samantha C. Winter

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Reporting Summary

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Software and code

Policy information about availability of computer code

Data collection	Social-behavioral (impact) data were collected using the Qualtrics Offline Surveys application.
Data analysis	Code supporting the analyses run in this study are available at https://github.com/scw2154/NCC_DefiningExtremes:

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The data supporting this study's findings are available at:
https://github.com/scw2154/NCC_DefiningExtremes.

Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	Our study design and sample focus specifically on women. Women in informal settlements, including in Kenya—the site of our study—are not only more likely to suffer more and/or worse mental health and violence-related outcomes than men as a result of climate change and related extreme weather events (EWEs), they also have more limited access to health, mental health, and violence-related services—potentially critical interventions for coping with or mediating climate-related intimate partner violence (IPV) and mental health outcomes—compared to men living in the same communities. Thus, we believe it is critical to prioritize the identification of points for climate-related mental health and violence intervention and adaptation for women in informal settlements at this time. Additionally, research suggests that gender roles and unequal power relations influence how interpersonal violence, especially IPV, and climate-related mental health issues evolve and play out in relationships differently for men and women.
Population characteristics	Participants had to be 18 years or older (actual age range: 18-79), speak English or Swahili (lingua franca), and be residents (not visitors) of informal settlements.
Recruitment	A probability sample of 800 women in Kibera (n=400) and Mathare (n=400) was drawn using a sampling method previously executed by the authors and used in similar survey sampling in informal settlements, globally. The study used publicly-available satellite imagery and boundary data for the settlements and villages available through Open- StreetMap (.osm). A fishnet grid was superimposed on the OpenStreetMaps in ArcGISPro version 3.0. Each fishnet grid cell was 9 square meters (3m x 3m)—the approximate size of a tin or mud house or a room in a high-rise. A random selection function was used to identify 400 random grid cells for sampling in each informal settlement. GPS coordinates for 50 random grid cells, each, were loaded onto 16 community data collector's (CDC) tablets. CDCs used Google Earth and Google Maps on their tablets to navigate to the closest household to the GPS coordinate. The quasi-random "last birthday" method was then used to identify one woman within each randomly selected household to invite to participate. If all women in the selected household refused to participate, the CDC navigated to the next nearest household.
Ethics oversight	This study has been approved by the Columbia Internal Review Board (IRB-AAAU0353); the Scientific Ethics Review Unit at the Kenya Medical Research Institute (Protocol No. 4476); and the Kenya National Commission on Science, Technology and Innovation (License No. NACOSTI/P/22/19316).

Note that full information on the approval of the study protocol must also be provided in the manuscript.

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Behavioural & social sciences study design

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Study description	Study data, collected between September 1st, 2022 and February 28th, 2023, are part of a longitudinal, quantitative study investigating associations and mediating effects between climate, mental health, and violence in informal settlements in Kenya. The study included monthly household-level surveys collected from 800 women living in informal settlements in Nairobi.
Research sample	Participants in this study are women-identified residents of informal settlements (Kibera and Mathare) in Nairobi, Kenya over the age of 18 years (actual age range: 18-79).
Sampling strategy	A probability sampling strategy was used. Described above in the recruitment section. Following recommendations for time-series analyses, we conducted statistical power calculations using a Monte Carlo power analysis for a one-lag vector, vector auto-regression (VAR) in MatLab 2019b to predict the necessary sample required for VAR time series mediation analyses with covariates and 18 time points. Assuming 20% missing/incomplete data and an alpha of 0.05, a sample of 800 was estimated to yield a power of 80% with a medium effect size (f2 = .15).
Data collection	Household-level surveys were collected by 16 trained women residents (community data collectors: CDCs) of Kibera (8) and Mathare (8). CDCs were trained on the principles of ethical research, quantitative data collection, study protocols, and the World Health Organization's (WHO) ethical and safety recommendations for research on violence against women and sensitive topics. In accordance with these recommendations, investigators, local collaborators, and CDCs agreed on safety protocols if a participant reported violence and adverse mental health outcomes. The 60–90-minute survey was collected one-on-one in participants' homes, and responses were recorded on password-protected study tablets using the Qualtrics Offline Surveys application. A quality assurance exercise conducted before study initiation and at six months ensured objectivity and best practices in survey implementation. Each CDC was observed conducting an interview. Any variances or changes in the protocol were discussed, and the

	CDC was retrained in that portion of the interview. Meteorological data (24-hour maximum and minimum temperatures and accumulated precipitation/rainfall) were provided by the Kenya Meteorological Department.
Timing	Data for this study were collected between September 1st, 2022 and February 28th, 2023--representing the first six months an an on-going 18-month longitudinal study.
Data exclusions	No data were excluded from analysis.
Non-participation	As of February 28, 2023 (six months after study began), we had 764 of the original 800 participants remaining in the study (95.5% retention rate).
Randomization	Randomization was not used in this study.

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