City and Environment Interactions 29 (2026) 100284

Contents lists available at ScienceDirect

City and Environment Interactions

journal homepage: www.sciencedirect.com/journal/city-and-environment-interactions

Short Communication

When the sun goes down, heat vulnerability remains

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ARTICLE INFO

Keywords:
Nighttime temperature
Social vulnerability
Climate change
Climate shelters
Tropical nights
Torrid nights
Public health

ABSTRACT

Continuously rising temperatures due to climate change allow extreme heat-related risks to persist throughout the entire day. While daytime and nighttime heat are well distinguished in climate research, the social inequities and adaptation strategies linked to nighttime heat remain overlooked. This short communication proposes a multidimensional perspective to nighttime heat, combining recent climate data, vulnerability analysis and urban adaptation strategies. Using Barcelona, Spain, as a city of reference, we discuss how localized urban heat islands, limited access to climate shelters, and stressors like traffic noise levels intersect to shape heat risk and climate injustice at night. Building an equitable climate resilience to nighttime heat means not only mapping where heat remains at night but also designing strategies for night hours and broadening how heat vulnerability is assessed. This piece calls on both researchers and practitioners to consider climate science, social equity and urban policy through a nighttime lens, and consequently, to ensure a more comprehensive way to support vulnerable population groups.

1. Introduction

Climate change is augmenting the frequency, duration and intensity of extreme temperature events, escalating the threats to human health [20]. This prolonged exposure to higher temperatures can overwhelm the body's thermal regulation mechanisms [13,21], increasing the risk of illness and death, as demonstrated by the 2022 European warm summer that caused over 60,000 fatalities across several countries [8]. However, the impacts of increased heat are not distributed evenly, and certain population groups are bearing a disproportionate burden. For example, older adults, young children, outdoor workers and people living in socioeconomic disadvantage are more vulnerable due to higher exposure, more sensitivity and/or lower adaptive capacity [36]. This challenge is particularly acute in cities, which already host more than half of the world's population and experience higher temperatures than surrounding areas due to the urban heat island (UHI) effect [24].

There is a growing body of physical climate research worldwide that distinguishes between daytime and nighttime heat and their effects (e.g., [23]). Yet, few studies or policies explicitly consider how nighttime temperatures interact with multidimensional vulnerability and adaptation. Ho et al. [17] highlight that heat-vulnerability mapping still overlooks spatiotemporal temperature variability, the fine-scale social and environmental complexity of cities, and links to governmental action plans. Nighttime is when most people are at home, and the body is meant to rest and recover from daytime heat, since it is typically the coolest period of the day. When temperatures remain high at night, it can increase the risk of physical and mental health issues. He et al. [16] associated days characterized by hot nights with a 50 % increase in relative mortality risk compared to days with cooler nights. Hot nighttime conditions may also disproportionately affect already vulnerable groups. For instance, the impact of each one-degree increase in nighttime temperature on sleep loss among older adults (>65) is more than twice as large as the corresponding effect observed among middle-aged adults (25–65) [26]. Additionally, compared to men, women face a significantly higher risk of nighttime heat-related stroke [15].

An incomplete understanding of nighttime vulnerability can thus constrain the knowledge that can be translated into appropriate adaptation measures, such as urban heat-health planning. With this piece, we

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https://doi.org/10.1016/j.cacint.2025.100284
Received 18 September 2025; Received in revised form 29 November 2025; Accepted 11 December 2025
Available online 12 December 2025

seek to highlight the importance of examining nighttime[2] heat in urban settings through a multidimensional lens that brings together climate exposure, social vulnerability and adaptation strategies. To ground our discussion, we drew on Barcelona as a reference city, examining its nighttime summer temperature trends, both current and projected (Section 2.1), the specific vulnerabilities that emerge after sunset (Section 2.2), and one of the city's pioneering initiatives to mitigate heat stress: the continuing expansion of a climate shelters network (Section 2.3). We hope these insights can inform more equitable approaches to building climate resilience at night and encourage both researchers and practitioners to give greater attention to this period of the day in cities where climate change is intensifying nighttime heat.

2. Barcelona summer nights: Where heat and vulnerability intersect

The following sections explore vulnerability to heat – as the interaction of exposure, sensitivity, and adaptive capacity – focusing on how these dimensions play out at night in Barcelona with its unique climate, geographic and social perspective. Situated on Spain's northeastern coast, Barcelona is the country's second-largest city, with around 1.7 million residents and a high population density of 16,637.5 inhabitants per km^2 [18]. Barcelona is divided into ten districts and 73 neighborhoods with residential areas covering the majority at 56 % of the territory, followed by parking zones at 10.1 %, and commercial spaces at 7.2 % [2]. The city has a Mediterranean climate (Köppen-Geiger classification: Csa), featuring mild rainy winters and hot, dry summers [33].

2.1. Exposure: A warming climate amplified by the urban heat island effect

In Spain, the number of tropical nights (minimum nighttime temperature > 20 °C) has risen markedly over the past five decades [12], with especially pronounced increases along the Mediterranean coast [31]. In Barcelona, the average annual temperature has increased by 1.8 °C since the end of the 18th century, a warming rate larger than the global average (1.1 °C), with an average rise of 0.08 °C per decade [3]. In 2022, 2023, and 2024, the city recorded 105, 82, and 86 tropical nights, and 14, 13, and 23 torrid/equatorial nights (minimum nighttime temperature > 25 °C), respectively [3]. Moreover, 2022 and 2024 experienced two and 2023 one heatwave, defined as periods of at least three consecutive days during which the maximum temperature exceeds the 98th percentile of the three hottest months of the year [3]. Notably, in Barcelona, high relative humidity further exacerbates discomfort from elevated nighttime temperatures [12].

Due to its urban land use, geographic location, and high population density, Barcelona experiences strong UHI effect especially at night, which has increased over the past decade [3]. The UHI effect is visible in the city's temperature records for the months of June to August in the years 2022, 2023, and 2024. Although this three-year period is relatively short for climate analysis, it was selected to illustrate recent conditions from a climate justice perspective rather than to examine long-term links between UHI and climate change. Using data[3] from the three meteorological weather stations operated by the Catalan Meteorological Service (Data provided by MeteoCat via Dades Obertes Catalunya[4]) located within the city (Observatori Fabra, El Raval, and Zona Universitària, Fig. 3a), we see that nighttime temperatures in Barcelona were consistently high from June through August in the past three years. In June, minimum temperatures typically exceeded 19 °C, while in July and August they were often above 22 °C (Fig. 1). In Fig. 1, we can observe that the median minimum temperatures recorded at the three stations, over the three years and between 8:30 PM and 6:00 AM[5] in June, July and August, reveal notable differences in temperature patterns. El Raval recorded the highest temperatures, with Zona Universitària following a similar pattern, while Observatori Fabra consistently had the lowest nighttime temperatures. While the coolest period generally occurred between 2:30 and 4:30 AM, minimum temperatures at El Raval and Zona Universitària reveal a pronounced nighttime UHI effect. El Raval remains consistently warmer than Observatori Fabra, with a 1 °C difference during the day that rises to around 3 °C at night. Cooling is also slower in El Raval, further highlighting the intensity of the nighttime UHI.

These temperature differences are likely explained by the distinct geographical settings of the three weather stations [35]. Variation in UHI intensity across the city points to unequal exposure to nighttime heat depending on where people live. Observatori Fabra, situated 6.5 km inland from the Mediterranean and 411 m above sea level, is surrounded by vegetation and remains relatively isolated from dense urban infrastructure. As a result, it is less exposed to the UHI effect. In contrast, the El Raval station is located just 33 m above sea level in the compact, densely built-up city center with very few green spaces.

The comparisons between the temperature profiles across the different stations show that the UHI effect is particularly pronounced at night, especially during the periods when the lowest temperatures occur, with central areas (El Raval) remaining significantly warmer than peripheral locations (Observatori Fabra). In dense urban settings, shading and reflective surface materials can limit daytime heating, but these areas are still prone to heat retention and reduced radiative cooling, which leads to elevated nighttime temperatures.

To understand how this situation might evolve, we used climate information obtained from the latest Euro-CORDEX simulations with a resolution of 0.11 degrees, which were generated by downscaling CMIP5 GCM projections and have been analysed as part of the European research project Impetus4Change.[6] Fig. 2 shows the tropical and torrid nights indicators and their trend until the end of the 21st century. While the climate model output should not be used in a deterministic way, i.e. we cannot be certain of the number of tropical and torrid nights, we can be confident in their increasing trend.[7] For example, by 2050, tropical nights are projected to have a 36 % increase compared to 2020, and by the end of the century, the number is projected to double (Fig. 2). In the second half of the century, we start to see a steady increase in the number of equatorial nights. This shows that extremely hot nights will become more common in the future, and we can also hypothesize that these ambient conditions will be amplified by the UHI.

2.2. Sensitivity: Social dimensions of vulnerability to nighttime heat

As nighttime temperatures rise and the UHI intensifies local heat, the consequences are not only environmental but also social. Health risks from extreme heat are not equally distributed, as certain groups are

[2] Nighttime is defined as 8:30 PM-6:00 AM, corresponding to average summer (June-August) sunrise and sunset times. This period was chosen because tropical nights in Spain are most common during these months [12].

[3] Some half-hourly records were missing for Zona Universitària (36 observations) and for Raval (9 observations), making the missing data rates extremely low (<0.3 %) to bias our calculations of average minimum temperatures and the number of extremely hot nights.

[4] Data can be requested here: https://analisi.transparenciacatalunya.cat/Medi-Ambient/Dades-meteorol-giques-de-la-XEMA/nzvn-apee/about_data.

[5] Using hourly data provides a clearer and more accurate assessment of summer night conditions compared to studies that rely solely on minimum temperature [34].

[6] IMPETUS4CHANGE (I4C): improving near-term climate predictions for societal transformation. Project's website: https://impetus4change.eu/.

[7] The projections are not bias-corrected and do not have urban layer, hence the frequency of tropical/equatorial nights is likely underestimated.

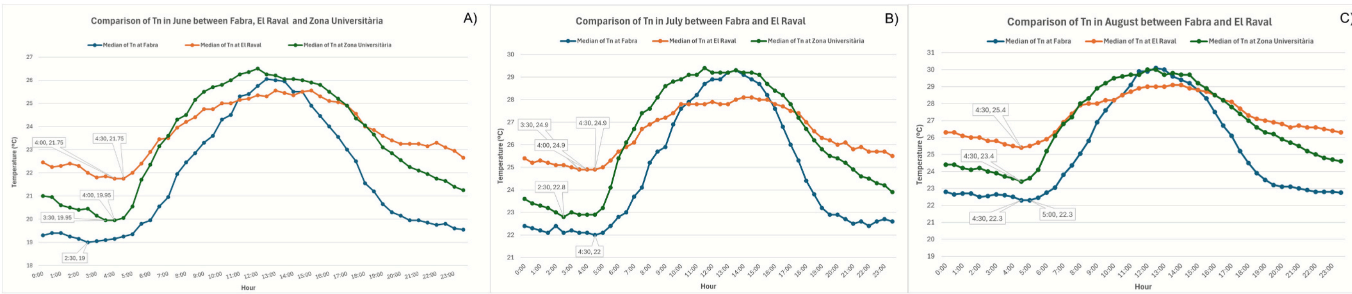

Fig. 1. Comparison of minimum temperatures (Tn) across the three weather stations in Barcelona in **(a)** June, **(b)** July and **(c)** August from 2022 to 2024. Nighttime is defined as 8:30 PM-6:00 AM, corresponding to average summer (June-August) sunrise and sunset times. **Data Source:** Data provided by MeteoCat via Dades Obertes Catalunya.

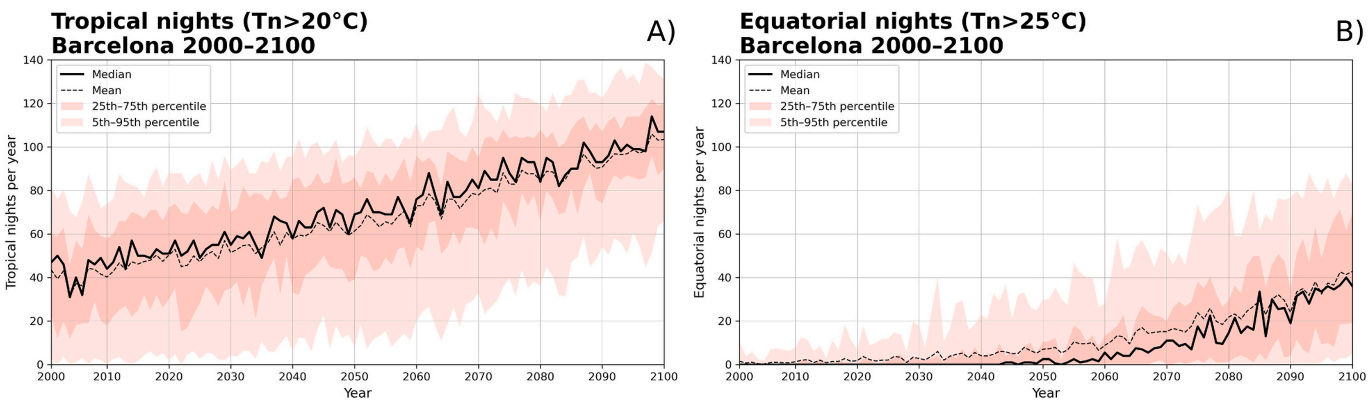

Fig. 2. Future climate model from 2000 to 2100 of **(a)** tropical nights and **(b)** equatorial nights. Black solid lines show the multi-model median, and dashed lines the multi-model mean. Dark shading covers the Interquartile Range (25th-75th percentile) and light shading the range between the 5th and 95th percentiles.

more vulnerable due to different conditions. Assessing heat vulnerability, therefore, requires examining the socioeconomic profile of the population along with features of the built environment and environmental stressors [29]. Many social factors contribute to heat risk, but for illustration, age and energy poverty are particularly relevant in Barcelona. The elderly population is growing, with those aged 65 and over now comprising a quarter of the (city) population [19]. Overall, this population is projected to rise from around 335,000 in 2025 to 432,0700 by 2044, a 29 % increase [19]. Energy poverty further compounds vulnerability, with an estimated 51.4 % of Barcelona's population living in households without air conditioning or unable to use it when needed [25].

The built environment also influences vulnerability. Of particular concern is the scarcity and uneven distribution of green spaces, given their role in mitigating urban heat at night through different mechanisms [32,38]. In Barcelona, over 80 % of residents live in areas that fall below the green space levels recommended by the World Health Organization (WHO), which advises that green spaces of at least 0.5 ha should be accessible within 300 m of residences [9]. Other factors, such as inadequate housing, also affect thermal comfort; about 90 % of Barcelona's buildings were constructed before 1980 and do not comply with modern energy efficiency standards [30].

It is also important to consider how various other environmental stressors, such as ambient noise and air quality, combine to affect nighttime vulnerability. For example, an action often recommended at night is opening windows for ventilation and heat dissipation. However, that increases exposure to environmental noise and air pollution, both mainly deriving from traffic in Barcelona [1,7]. Many streets in the city reach nighttime noise levels above 45 dB(A), potentially posing negative health impacts [1,37]. Additionally, while nighttime nitrogen dioxide concentrations (the main air contaminant coming from traffic) are much lower than during the day, they still exceed WHO recommendations in some streets [7,10]. This points to the importance of including different factors when evaluating nighttime heat-related vulnerability.

2.3. *Adaptation strategies: The example of the climate shelters network*

The multiple facets of vulnerability highlighted earlier justify the need for the city to implement targeted adaptation strategies to reduce heat-related risks among vulnerable populations at night. In recent years, mainly through the city's justice-oriented climate plan (Pla Clima) [3]), Barcelona City Council has expanded and diversified its heat-related actions, including adding shade and water points, and developing a network of climate shelters. Although significant progress has been made in proposing and implementing adaptation measures to heat, we consider that these actions may not be fully effective in addressing heat-related risks at night.

One key pioneer initiative is the creation of a city-wide climate shelter network in 2019, encompassing different types of spaces such as libraries, museum foyers and school playgrounds. Climate shelters are public urban infrastructures that help cities adapt to extreme weather by offering spaces where residents can take refuge during episodes of extreme temperatures, such as air-conditioned indoor facilities or green and shaded areas [5]. However, climate shelters are an example of an action where less attention is paid to nighttime conditions. Mombelli et al. [27] raised the need for longer opening hours during peak heat periods to better meet public needs. Indeed, we can find only 20 out of over 405 shelters that operate during the nighttime period (8:30 PM to 6:00 AM) [4]. Equally, all but one of the nighttime shelters (the Barcelona Emergency and Social Emergencies Center) are outdoor spaces, primarily parks and gardens. With this in mind, aspects such as perceived safety or crime rates at night may also influence whether residents feel comfortable using these spaces, an issue that warrants further consideration. Overall, we can see that the availability and diversity of shelters remain limited, particularly when considering nighttime accessibility and comfort.

3. Insights and implications

The next two subsections present two recommendations grounded in the three previously discussed aspects (exposure, sensitivity, and adaptation strategies), illustrated using Fig. 3a and 3b.

3.1. Need to reexamine the characterization of vulnerable groups when mapping vulnerability at night

One way to capture multiple vulnerability factors is through composite indices. In Barcelona, a key example is the Climate Change Vulnerability Index (CCVI) calculated by the Urban Sustainability area of the Barcelona Institute of Regional and Metropolitan Studies on behalf of the Metropolitan Area of Barcelona (AMB). It aims to identify areas that are more likely to face concentrated climate risks, such as more frequent extreme heat and heatwaves, as well as populations that are more vulnerable to the impacts of climate change [14].[8] The CCVI is a composite index which ranges from 0 to 100 for each census tract, considering 17 indicators such as available green space, age, household income and access to solar energy.

The CCVI offers valuable insights into the distribution of potential vulnerabilities across Barcelona. For instance, in Fig. 3a, by overlaying the CCVI and the weather stations, we see some areas with high CCVI are close to the El Raval station, where we observed the highest values of summer nighttime temperatures. When viewed through a nighttime lens, it brings further reflection: are there additional indicators that should be considered to better capture heat risks and vulnerabilities after sunset? Other aspects, such as environmental stressors (ambient noise levels and air pollution) or safety concerns, as highlighted previously in this commentary, could be relevant, but are not yet included in the CCVI.

Like other available indices, the CCVI was not specifically designed to capture nighttime vulnerability but could readily address this dimension with existing data. For instance, incorporating noise exposure into nighttime heat vulnerability assessments reveals a critical yet often overlooked trade-off: in urban areas, residents are forced to choose between opening windows to cool down and closing them to block out disruptive noise. In Barcelona, noise levels above 45 dB(A) are often observed near major roads, particularly in central areas that also show higher CCVI [1] (Fig. 3b). This trade-off can affect sleep quality and overall health during heatwaves at night. Beyond noise, other important factors are left out of standard assessments and could be interesting to investigate further: accessibility to night-time public transport and access to health or social support services during night hours. While this commentary does not cover indoor conditions, it is worth noting that people spend most nights indoors, making work that links these conditions to nighttime ambient temperatures especially relevant [39]. Many studies rely on heat-event measures based on outdoor temperatures; however, indoor overheating, especially at night, can pose significant health risks [22]. Relying solely on outdoor data may misclassify actual exposure, highlighting the importance of incorporating indoor measurements, such as bedroom environmental conditions, for more accurate estimation of heat exposure and its health effects [11].

3.2. Need for specific nocturnal adaptation strategies for heat resilience

To improve the effectiveness of heat mitigation strategies, it is essential to consider how well these interventions during nighttime are fit for purpose. Vulnerability to extreme heat often persisting at night may be less intuitive, and thus support services are more limited during that period of the day. Moreover, vulnerability is a dynamic process that changes over time [28], rendering the provision of justice-oriented adaptation approaches particularly challenging [6]. In this piece, we focused on the example of nighttime climate shelters. In Fig. 3a, while overlaying shelter locations with the CCVI and in line with Amorim-Maia et al. [5], who advocate for adopting an intersectional lens when designing refuge infrastructures, we observe that areas with high CCVI lack shelters during nighttime hours, thereby potentially exacerbating climate injustice. Approximately one-third (35 %) of the climate shelters open at night are not accessible within 500 m of areas with very high CCVI (above 61 CCVI index) (Fig. 3a).

Other heat adaptation measures implemented in the city may also vary in their effectiveness during nighttime hours. For example, water-based cooling interventions, such as spaces with water games, are primarily designed for daylight operations [3]. This example, along with climate shelters, highlights the importance of applying a nighttime lens when evaluating the real-world utility of existing strategies and underscores the need for urban policies that explicitly address nocturnal heat exposure.

4. Conclusion

This short communication brings attention to the often-overlooked issue of nighttime heat, viewed through the lens of urban vulnerability. Insights from Barcelona underscore the value of integrating data on exposure, sensitivity, and adaptation strategies to better grasp how different climate and non-climate factors could impact health and, crucially, how these may be different to those during the daytime. We showed a sharp rising trend in nighttime extremes and advocated for including night-specific factors in the vulnerability analysis, like street noise levels or the perception of safety. We also suggested the need for city's strategies aimed at ensuring comfort (beyond a thermal one) all night long to address potential inequalities in climate adaptation measures. Going forward, one may consider examining these data and patterns at a finer, neighborhood-level scale to contextualize the city's areas better and identify specific hotspots of nighttime heat vulnerability. Our insights are relevant to other European cities such as Milan, Athens, or Lisbon, which share conditions with Barcelona of rising nighttime temperatures and high population density. We thus encourage researchers and practitioners to keep nighttime heat vulnerability in mind, especially with hotter summers ahead.

CRediT authorship contribution statement

Jiayang Hu: Writing – review & editing, Writing – original draft, Visualization, Investigation, Conceptualization. **Florence Gignac:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Conceptualization. **Sam Pickard:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Paloma Trascasa Castro:** Writing – review & editing, Writing – original draft, Visualization. **Eren Duzenli:** Writing – review & editing, Writing – original draft, Visualization. **Dragana Bojovic:** Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [Florence Gignac reports financial support was provided by Horizon Europe project Impetus4Change. Sam Pickard, Paloma Trascasa Castro, Eren Duzenli, Dragana Bojovic reports financial support was provided by Horizon Europe project Impetus4Change. If there are other authors,

[8] The CCVI map can be found on the AMB website: https://ide.amb.cat/Visor/?title=%C3%8Dndex+de+vulnerabilitat+al+canvi+clim%C3%A0tic+%28IVAC%29&resource=ags%3Ahttps%3A%2F%2Fide.amb.cat%2Fservei%2Fcatalunya%2Findex_vulnerabilitat_canvi_climatic%2Frest&locale=ca.

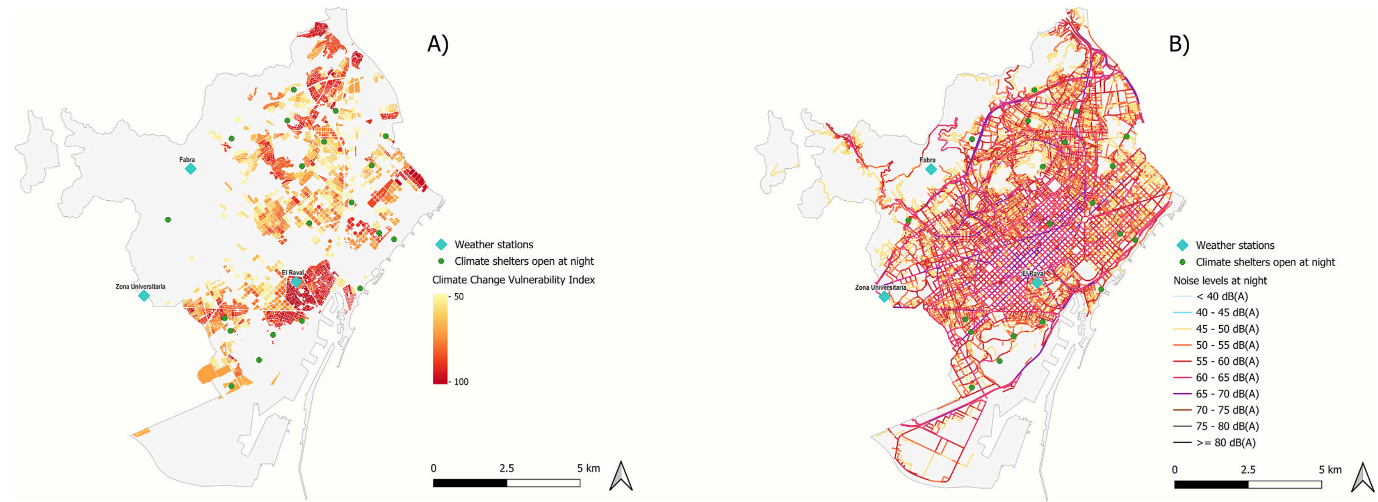

Fig. 3. (a) Census tracts with Climate Change Vulnerability Index (CCVI) higher than 50, distribution of climate shelters open at night and location of official weather stations in Barcelona. **(b)** night noise levels from 11 PM to 7 AM **Source:** Adapted from Ajuntament de Barcelona (AdB) and Metropolitan Area of Barcelona (AMB).

they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.].

Acknowledgments

This work was supported by the Horizon Europe project Impetus4-Change (grant nr. 101081555). D.B. acknowledges her AI4S fellowship within the "Generación D" initiative by Red.es, Ministerio para la Transformación Digital y de la Función Pública, for talent attraction (C005/24-ED CV1), funded by NextGenerationEU through PRTR. We would also like to thank Miquel Ninyerola Casals for his support and supervision, together with D.B., S.P., and F.G., of J.H.'s master's thesis entitled "Analyzing the approach to climate change vulnerability in the city of Barcelona", from which this commentary takes its roots.

Data availability

Data will be made available on request.

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