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A systematic review of ambient heat and sleep in a warming climate

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ABSTRACT

Climate change is elevating nighttime and daytime temperatures worldwide, affecting a broad continuum of behavioral and health outcomes. Disturbed sleep is a plausible pathway linking rising ambient temperatures with several observed adverse human responses shown to increase during hot weather. This systematic review aims to provide a comprehensive overview of the literature investigating the relationship between ambient temperature and valid sleep outcomes measured in real-world settings, globally. We show that higher outdoor or indoor temperatures are generally associated with degraded sleep quality and quantity worldwide. The negative effect of heat persists across sleep measures, and is stronger during the hottest months and days, in vulnerable populations, and the warmest regions. Although we identify opportunities to strengthen the state of the science, limited evidence of fast sleep adaptation to heat suggests rising temperatures induced by climate change and urbanization pose a planetary threat to human sleep, and therefore health, performance, and wellbeing.

1. Introduction

There is accumulating evidence that climate change is contributing to the increase of health risks and notably heat-related illnesses and mortality [1–5]. Beyond mortality, hotter ambient temperatures and heat extremes are associated with increased injuries [6,7], hospitalizations [8], mental health issues [9], health-care costs [10], as well as worsened cognitive performance [11], sentiment [4], labor productivity [12], and activity days [13]. One proposed pathway of the association between ambient temperature and health outcomes is disrupted sleep [14–16]. Shorter sleep duration, poor sleep quality and sleep disorders (e.g., insomnia, sleep apnea) are prospectively associated with the development of cardiovascular [17] and metabolic diseases [18], cancer risks [19], mental health disorders [20], and accidents [21]. Although the environmental causes of sleep disruption are multi-factorial (e.g., light and noise pollution) [22,23], it is likely that rising ambient temperatures due to ongoing climate change will impair sleep in the hottest seasons of the year at a global scale, barring further adaptation [14,24].

Exposure to hot and cold ambient temperatures demand the human body to mount a thermoregulatory response to maintain a core body temperature rhythm within the normal range required to support physiological functioning and sound sleep [25–27]. Extreme heat can alter human core body temperature outside its normal range when air temperatures exceed that of fully vasodilated skin (35 °C), with elevated heat-health risks apparent well-below this threshold [3,28–30]. Further, sleep onset is closely coupled with nighttime core body temperature decline [25]. In hot sleeping environments, heat production can exceed heat loss beyond tolerable levels, increasing core body temperature and disturbing the natural sleep–wake cycle with increased wakefulness [26]. In daily life, ambient heat can impact core body temperature (and thus sleep) through at least two plausibly interacting pathways: (*i*) direct exposure during the day imposing thermal strain, cardiovascular strain

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Glossary

PSG	polysomnography
AHI	apnea-hypopnea index
WASO	wake after sleep onset
SE	sleep efficiency
TST	total sleep time
NREM	non-rapid eye movement
RDI	respiratory disturbance index

and/or dehydration which may carry over into the nocturnal resting period [3], and (*ii*) exposure at night via a combination of nighttime ambient weather conditions and environmental heat transfer (i.e., the energy accumulated in the built environment, conducted and re-emitted in the bedroom at night) reducing the thermal gradient between the body and ambient environment [26,31,32].

The largest investigation of the effect of ambient temperature on sleep thus far – a study based on billions of repeated sleep measurements from sleep-tracking wristbands collected in 68 countries over two years – found that increased nighttime ambient temperature shortens sleep duration, primarily through delayed sleep onset, with stronger negative effects during summer months, in lower-income countries, in warmer climate regions, among older adults, females and after controlling for individual and spatiotemporal confounders [24]. These results confirmed those from two previous large-scale nationally representative analyses of self-reported sleep outcomes from the United States [33,34], with one showing that a +1 °C increase in monthly nighttime ambient temperatures produces an increase of approximately three nights of subjective insufficient sleep per 100 individuals per month [33]. Minor et al. (2022) and Obradovich et al. (2017) also included climate change impact projections, and both estimated that rising ambient temperatures may negatively impact human sleep through the year 2100 under both moderate and high greenhouse gas concentration scenarios, with impacts scaling with the level of emissions barring further adaptation [24,33].

Critically, climate change and other anthropogenic environmental changes related to increased heat exposure, including urban heat island expansion, are altering outdoor ambient temperatures where populations reside. Although sound and sufficient slumber underpins human functioning, the current prevalence of insufficient or poor sleep is already elevated in high-income countries (e.g., above 50% in the US, 31% in Europe and 23% in Japan) [35]. Although population sleep data is still sparse globally [36,37] and insufficient sleep prevalence estimates are relatively lower for low (7%)- and middle (8.2%)-income countries [38], a recent study found that habitants from those countries disproportionally suffered greater sleep loss due to heat [24], suggesting heightened vulnerability to elevated temperatures (i.e., reduced or missing access to personal or collective cooling strategies) [39]. In parallel, the 1.5 °C global temperature threshold above the pre-industrial climate is expected to be exceeded by 2040 under most scenarios of the Intergovernmental Panel for Climate Change, including the increasingly plausible "Shared Socioeconomic Pathway" SSP2-4.5 [40]. Although there is some evidence of adaptation to increasing temperatures in high-income countries for heat-attributed mortality [41], temperature projections for the coming decades indicate increasing heat risks for both current and future generations [42–46]. In this context, having a precise and comprehensive understanding of the influence of ambient temperature and extreme heat on sleep is crucial.

Earlier reviews documented the effects of a broad range of climate change outcomes on sleep (see Ref. [14] which included six studies about the specific role of ambient temperature and heat), the influence of the bed micro-environment on sleep physiology [26,47,48], as well as the specific role of humidity in sleep regulation measured mostly in laboratory settings [49]. However, no previous systematic review has described the state of the literature on the effect of ambient temperature on sleep in humans under real-life conditions (i.e., observational studies conducted in real-life environments), in contrast with laboratory studies that experimentally manipulate both behavior and temperature in the micro-environment [50–52]. This systematic review aims to identify and summarize the literature on ambient temperature, notably heat, and sleep outcomes in a warming world. Specifically, we aim to synthesize the available evidence and research gaps on this topic to inform researchers seeking to explore new facets of the temperature-sleep association, as well as decision makers and interventionists trying to promote climate adaptation.

2. Methods

Methods for collecting and summarizing data met the standards of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [53]. The study protocol was registered in PROSPERO (CRD42021284139).

2.1. Inclusion and exclusion criteria

Studies were included if they: (*i*) reported associations between objective indicators of ambient temperature and valid sleep outcomes measured in real-life, environments; (*ii*) included adults, adolescents, or children (although outside the scope of this systematic review, see Ref. [54] for a relevant study involving infants); and (*iii*) were peer-reviewed. Eligible measures of sleep included: self-reported (subjective) sleep questionnaires; accelerometer-based actigraphy and commercial-grade activity monitors (e.g., fitness bands and sleep-tracking wearable devices); sleep sensors and polysomnography. This selection criteria thus excluded sleep-adjacent articles such as those interested in the association between ambient temperature and the prescription of hypnotics, which are only indirectly related to sleep issues [55]. Eligible measures for temperature were narrowed to objective records via weather stations, climate reanalysis data or indoor temperature sensors; this criterion excluded articles interested in the associations between sleep outcomes and seasons without measuring ambient temperature [56], subjective perceptions of temperature [57] or using climate classifications (i.e., Koppen's weather climate classification) [58]. We excluded articles with valid measures of both sleep and temperature when the association between the two outcomes was insufficiently reported (e.g., association plotted with insufficient details to be numerically interpreted and reported) [59], or simply not tested (i.e., some articles include measures of temperature and sleep but focus on other outcomes) [60,61]. Because we focused on ambient temperature and sleep outcomes measured in real-life contexts, experimental studies manipulating in-laboratory temperatures were also excluded [50–52]. Beyond heat manipulation, those experimental studies often include invasive skin and rectal temperature measures as well as behavioral constraints and thus can neither be considered ecologically valid in the context of daily life nor the present review.

2.2. Data sources and searches

Studies were identified by searching PubMed, Scopus, JSTOR, GreenFILE, GeoRef and PsycARTICLES between March and April 2022, and then updated in February 2023 (pre-submission) and December 2023 (during the revision). Search strategies and algorithms are available in the supplemental material. Relevant reviews and articles cited in the introduction were also scanned. Specific journals were also inspected, in the sleep literature (e.g., *Sleep; Sleep Medicine*, *Journal of Sleep Research*) and the environmental health domain (e.g., *Environment International*, *Environmental Research Letters*, *Environmental Health Perspectives, The Lancet Planetary Health*). After duplicates were removed, titles and abstracts of all studies identified were examined independently by three authors (GC, KM, PB) to determine those meeting the selection criteria.

2.3. Data extraction and synthesis

An a priori data extraction form was developed and tested with 5 articles. Data were coded from each paper by three coders (KM, EC, PB) and double checked by a single coder (GC). The following information was extracted: first author's name, sample region and period, study design, main research question, estimation strategy, temperature and sleep assessment methods and outcomes, the inclusion of relevant control variables, main results, conclusion, and relevant additional information. A narrative synthesis of the literature was then performed. We did not perform meta-analyses given the diversity of study designs, temperature and sleep outcomes and the statistical strategies used. A preliminary synthesis was conducted by the first authors (GC, KM) and then discussed and revised by all authors.

2.4. Quality rating and risk of bias

We used the items from the Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies [62] as a basis to develop a custom list of 14 quality criteria relevant to the question of ambient temperature and sleep. For each criterion, we indicated whether or not the study met the requirement (i.e., binary outcome, yes/no). Criteria are displayed in Table 1 below.

3. Results

3.1. Descriptive findings

As depicted in the study flowchart (Fig. 1), a first iteration resulted in a total of 1735 independent records. After screening title and abstract, 58 articles were inspected in closer detail and 36 articles were included in the present review.

Included articles were published in journals from diverse academic disciplines, including public health, sleep, physiology, engineering, economics, environmental science and medicine. The oldest article retrieved was published in 1992 and the most recent one 31 years later, in 2023. Fig. 2 illustrates the countries in which the studies were performed; the US is the most represented country. In terms of participants' characteristics, studies included samples of various ages from ~13 years old to nearly 80 years old. As for identified sex, most studies reported at least ~20/30% female sample composition, while females were not included in three studies [63–65]. Most studies were correlational but some articles used intensive repeated measurements and appropriate statistical methods to estimate covariation between exogenous changes in temperatures and sleep outcomes within-participants, and thus were labelled as quasi-experimental studies here [24,33,34,63,66–72].

Table 2 and Supplementary Table 1 provide, respectively, a brief and detailed description (constrained by the scope of the current review) of each individual study included. Outdoor ambient temperature was measured via weather stations in 20 articles and indoor temperature was measured using local sensors installed in the home environment (e.g., HOBO temperature data logger, Thermochrons iButtons logger) in 15 articles. One study measured and reported results for both indoor (via local sensor) and outdoor (via weather station) temperature outcomes (see Table 2) [73]. Sleep measures showed a greater diversity of assessment methods with 14 articles using self-reported questionnaires or diaries [33,34,68–70,72–80], 12 studies using commercial activity monitors [24,66,67,71,78,79,81–86], six studies using polysomnography [64,76,87–90], six studies using research-grade accelerometers [65,70,80,91–93] and three studies using specific sleep sensors [63,94,95] (see Table 2). Beyond assessment methods, 20 articles used daily (24-h) aggregated measures of temperature, the remaining 16 articles focused on average or minimum nighttime temperature (see Supplementary Table 1, column "sample period"). For sleep, outcomes ranged from subjective sleep duration [34], perception of insufficient sleep [33] or sleep quality [77] to accelerometer-derived signals providing information about sleep efficiency or wakefulness after sleep onset [70] as well as sleep-related outcomes measured via polysomnography such as sleep stages [89] and sleep disorders (e.g., episodes of sleep apnea) [87].

Fig. 3 illustrates the range of observed ambient temperatures and latitudes for each of the studies in this review. Aggregating these ranges suggests a greater observational density for hotter compared to colder temperatures (bottom heat bar, Fig. 3A) and for northern latitudes compared to both the equatorial region and the southern hemisphere (right heat bar, Fig. 3B) and the Arctic. Notably, just six of the studies investigated temperature-related sleep responses in the Tropics, even though the region is home to approximately 40% of the global human population (blue histogram, Fig. 3B) [24,64,68,69,72,76]

As shown in Table 3, study quality was generally low to moderate as assessed by the 14-item research quality checklist developed for this systematic review (i.e., the quality criteria were only met by ~30% of all cells, marked in the table in green). Although there was a high degree of heterogeneity between studies in terms of evaluated quality, some specific criteria were rarely met by the extant literature such as the combined measurement and analysis of both indoor and outdoor temperatures (estimated by only one prior study), the inclusion of personal cooling strategies (e.g., air conditioning, fans), or other time-varying meteorological controls (e.g., humidity, cloud cover) that might otherwise confound inference between temperature and sleep.

Table 1
Quality criteria.

Item 1	For exposures that can vary in amount or level, did the study examine different levels of the exposure as related to the outcome and allow for a non-linear or semi-parametric response?
Item 2	Was the association between temperature and sleep assessed more than once over time at the within-participant level?
Item 3	Was within-participant variance accounted for in the analyses?
Item 4	Were sleep and temperature outcomes measured over the whole year?
Item 5	Were seasons and/or day length measured and adjusted statistically for their impact on the relationship between exposure(s) and outcome(s)?
Item 6	Were temporal variables, such as the day of the study, day of the year or day of the week, measured and adjusted statistically for their impact on the relationship between exposure(s) and outcome(s)?
Item 7	Was humidity measured and adjusted statistically for its impact on the relationship between exposure(s) and outcome(s)?
Item 8	Was wind speed measured and adjusted statistically for its impact on the relationship between exposure(s) and outcome(s)?
Item 9	Was cloud cover measured and adjusted statistically for its impact on the relationship between exposure(s) and outcome(s)?
Item 10	Was precipitation measured and adjusted statistically for its impact on the relationship between exposure(s) and outcome(s)?
Item 11	Were indoor and outdoor temperatures measured and analyzed together?
Item 12	Was the association between the exposure and the outcome tested at different lags?
Item 13	Was the utilization of air conditioning, fans and/or other indoor personal cooling technologies measured and analyzed?
Item 14	Was sleep measured with both subjective and device-derived indicators?

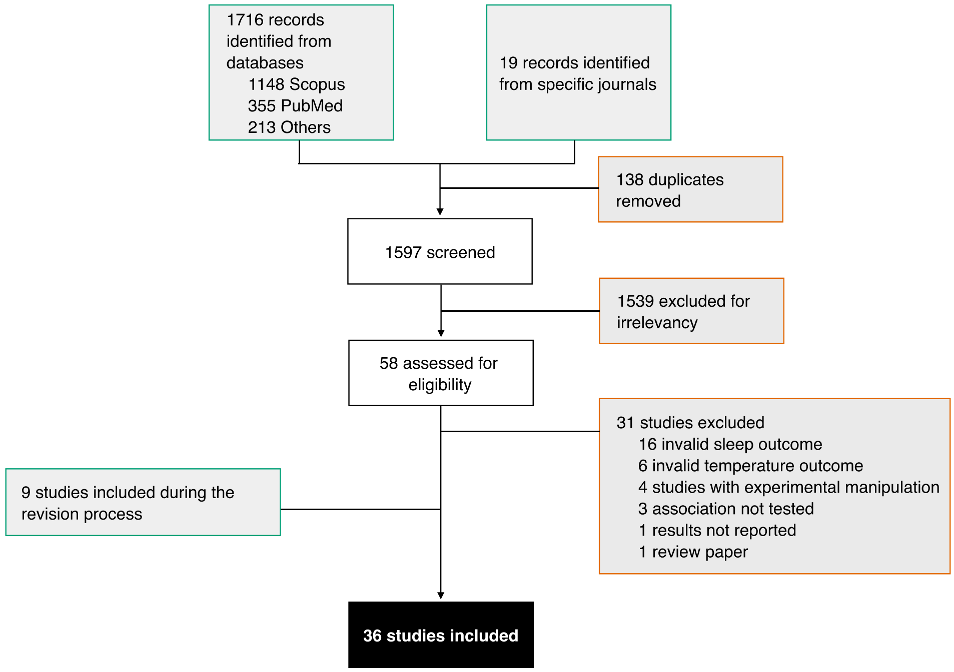

Fig. 1. Study flowchart.

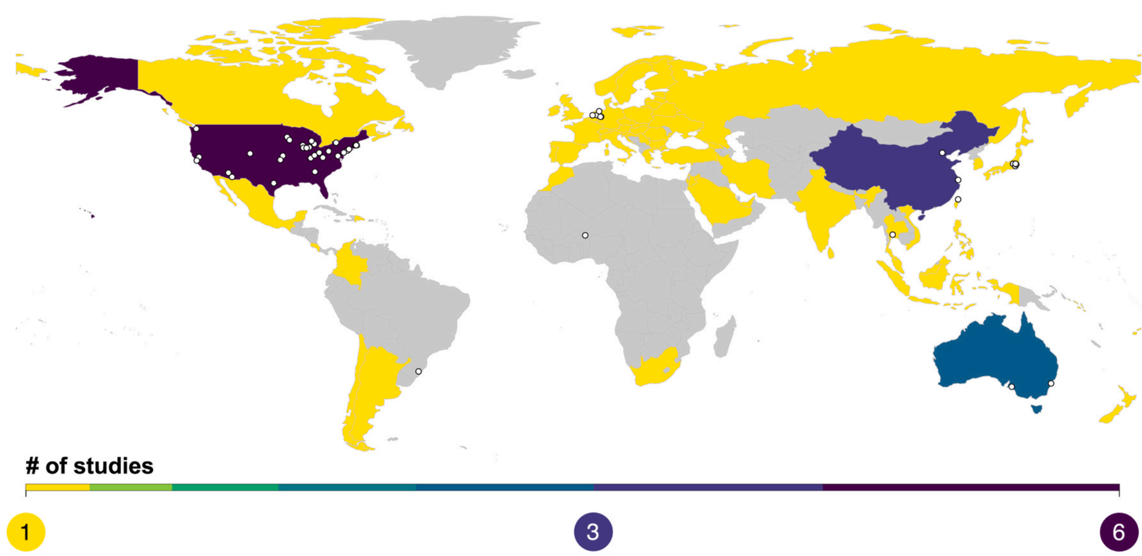

Fig. 2. World map of included studies. Multi-center studies are represented here at the national (colored areas) and local (city circles) scale.

3.2. Narrative synthesis of the association between ambient temperature and sleep

Overall, most studies (i.e., 29 articles, 81%) concluded that higher temperatures were associated with poorer sleep (see Table 2). Among the seven remaining studies: (*i*) two observed a positive effect of temperature on sleep, with one study performed in China reporting a positive association between temperature and self-reported sleep duration [75], another performed in Brazil, showing that apnea-hypopnea index was inversely correlated with ambient temperature [88]; (*ii*) three other studies were not explicit in their conclusion about this specific temperature-sleep association, with one not observing a significant association between temperature and sleep duration (but delayed sleep timing) [71], another observing a significant association between temperature and the number of awakenings but focusing on sleep adaptation in expatriates (not the impact of heat) [64], and a third focusing on sleep as a mediator of the association between temperature and health [68]; (*iii*) two studies also found a non-significant association between indoor temperature and sleep duration [84], as well as as indoor temperature and sleep apnea [90].

If we specifically focus on the nine higher quality studies that fulfilled at least half of the methodological quality criteria [24,33,67,69,71,72,80,85,96], eight concluded that higher temperature was associated with poorer sleep outcomes. Specifically, a majority (5 in 8) of the subset of studies that measured sleep duration found evidence that higher ambient temperatures were associated with shorter sleep [24,33,67,69,85]; all (3 of 3) studies that included sleep efficiency as an outcome found that higher temperature was associated with less efficient sleep [80,85,96]; and all (2 of 2) studies found a significant relationship between temperature and altered sleep timing [24,71]. Similarly, 9 of 11 quasi-experimental studies capable of identifying plausibly causal effects found that high outdoor ambient temperatures

Table 2
Short summary of included studies.

Study	Country	Temperature assessment	Sleep assessment	Sleep outcome	Impact of increased temperature
An, 2018 N = 12,000	China	Weather station	Questionnaire	Sleep duration	Positive
Bai, 2023 N = 8,628	Taiwan	Weather station	PSG	AHI	Not significant
Baniassadi, 2023 N = 50	US	Local sensor	Activity monitor	SE; Sleep duration; Body movements	Negative
Basner, 2023 N = 62	US	Local sensor	Research-grade accelerometer + Questionnaire	Sleep duration; SE; WASO; subjective sleep quality	Negative
Cassol, 2012 N = 7,523	Brazil	Weather station	PSG	AHI	Positive
Cedeño L., 2018 N = 44	US	Local sensor	Activity monitor	Sleep duration	Negative
Cepeda, 2018 N = 1,166	The Netherlands	Weather station	Research-grade accelerometer	Sleep duration	Negative
Ferguson, 2023 N = 368	Australia	Weather station	Activity monitor	Sleep duration	Negative
Fritz, 2022 N = 20	US	Local Sensor	Activity Monitor	Sleep duration; SE; sleep phases; sleep latency; awakenings; subjective sleep quality	Negative
Guo, 2023 N = 197	China	Local sensor	Activity monitor + Questionnaire	Sleep duration; SE; Sleep onset latency; number of awakenings; WASO; light and deep sleep; subjective sleep quality	Negative
Hailemariam, 2023 N = 35,070	Australia	Weather station	Questionnaire	Subjective sleep quality	Not explicit
Hashizaki, 2018 N = 1,856	Japan	Weather station	Other sensor	Sleep timing; WASO; SE	Negative
Hou, 2023 N = 41,416	China	Weather station	Questionnaire	Sleep duration and quality	Negative
Lappharat, 2018 N = 68	Thailand	Local sensor	Questionnaire + PSG	Subjective sleep quality; Sleep latency; Sleep duration; AHI	Negative
Li, 2020 N = 98	US	Weather station	Research-grade accelerometer + Questionnaire	WASO; SE; Sleep duration; Subjective sleep quality; Sleep latency	Negative
Liu, 2022 N = 5,204	Taiwan	Weather station	PSG	WASO; SE; AHI; sleep stages	Negative
Mattingly, 2021	US	Weather station	Activity monitor	Sleep duration and timing	Not explicit

N = 216					
Milando, 2022 N = 22	US	Local sensor	Activity monitor	Sleep duration	Not significant
Minor, 2022 N = 47,628	68 countries	Weather station	Activity monitor	Sleep duration and timing	Negative
Montmayeur, 1992 N = 6	Niger	Weather station	PSG	Sleep duration; Sleep stages and awakenings	Not explicit
Mullins, 2019 N = 4,120,514	US	Weather station	Questionnaire	Subjective sleep quality; Sleep duration	Negative
Obradovich, 2017 N = 765,000	US	Weather station	Questionnaire	Subjective sleep	Negative
Ohnaka, 1995 N = 40	Japan	Local sensor	Other sensor	Body movements	Negative
Okamoto, 2010 N = 19	Japan	Local sensor	Research-grade accelerometer	Sleep timing; Sleep duration; WASO; SE	Negative
Pandey, 2005 N = 43	US	Weather station	Questionnaire	Sleep latency; Awakenings; WASO; sleep duration	Negative
Quante, 2017 N = 669	US	Weather station	Research-grade accelerometer	Sleep duration and timing; WASO; SE	Negative
Quinn, 2016 N = 40	US	Weather station + Local sensor	Questionnaire	Subjective sleep	Negative
Tsuzuki, 2015 N = 8	Japan	Local sensor	Research-grade accelerometer	Sleep duration and timing; sleep latency; WASO; SE	Negative
van Loenhout, 2016 N = 113	The Netherlands	Local sensor	Questionnaire	Subjective sleep quality	Negative
Wang, 2022 N = 40,470	China	Weather station	Questionnaire	Subjective sleep quality	Negative
Weinreich, 2015 N = 1,773	Germany	Weather station	Other sensor	AHI	Negative
Williams, 2019 N = 51	US	Local sensor	Activity monitor	Body movements	Negative
Xiong, 2020 N = 48	Australia	Local sensor	Activity monitor	SE; Sleep stages	Negative
Xu, 2021 N = 41	China	Local sensor	Activity monitor	SWS	Negative
Yan, 2022 N = 40	China	Local sensor	Activity monitor; Questionnaire	Sleep duration; REM; WASO; SE; Light sleep; Deep sleep; Subjective sleep quality	Negative
Zanobetti, 2009 N = 3,030	US	Weather station	PSG	RDI	Negative

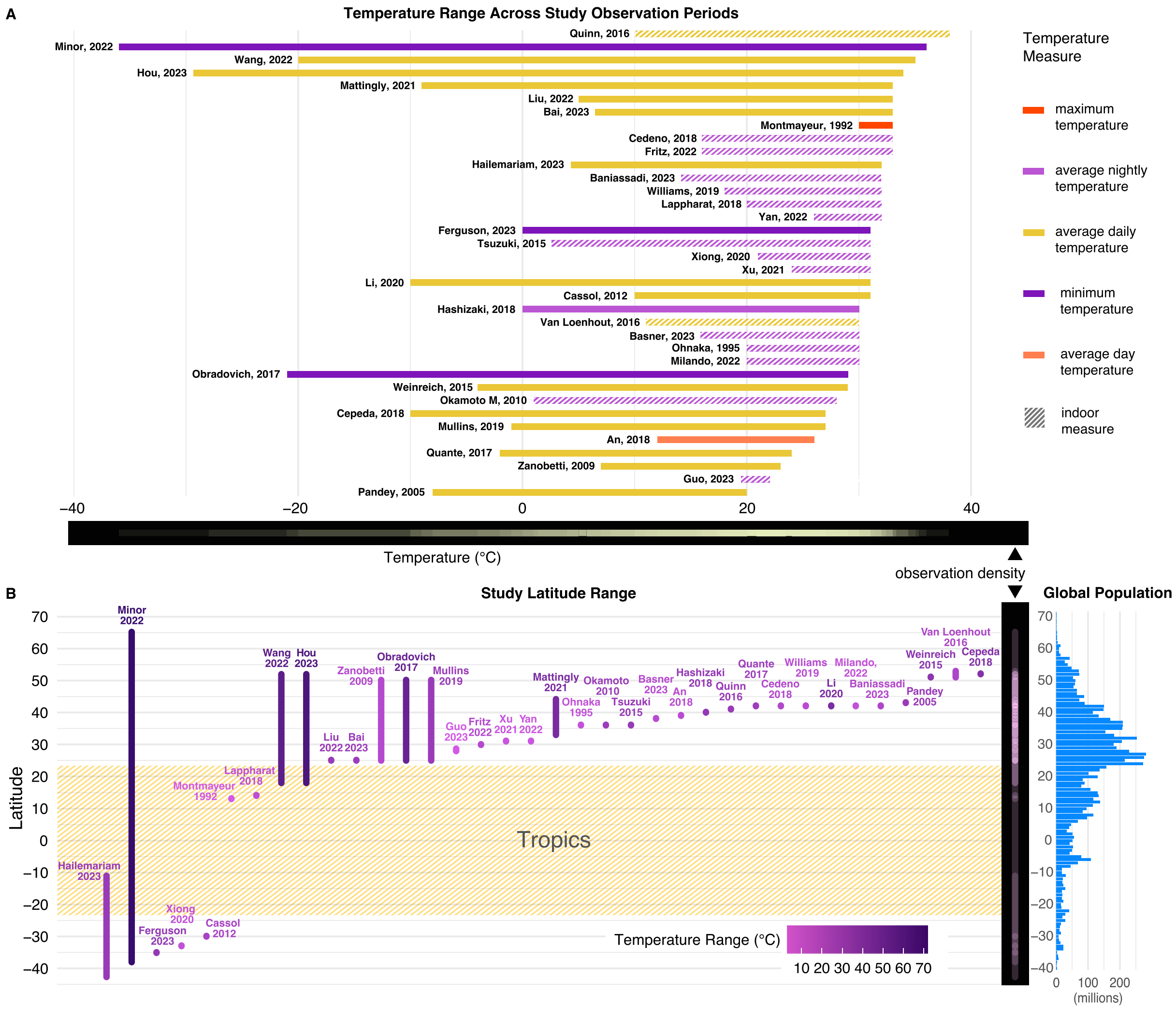

Fig. 3. Range of observed ambient temperatures (A) and latitudes (B) of included studies.

worsened sleep outcomes [24,33,34,63,66,67,69,72,96].

In terms of effect sizes, estimated effects appeared to vary in magnitude, with effects scaling across the temperature distribution (i.e., with larger effect sizes for studies focusing particularly on hot temperatures compared to those focusing on the full temperature spectrum). For instance, regarding sleep duration, a multi-country longitudinal study found that at the colder end of local temperature distributions, a +1 °C increase reduced time slept by just 0.20 min during winter months but sleep was reduced by 0.97 min per +1 °C during the last month of summer [24]. Single estimates integrating data over all seasons appear to fall in between: one single-city longitudinal study with a sample of middle-aged adults in Adelaide estimated that sleep declined by 0.37 min per +1 °C increase in outdoor nighttime minimum temperature, and a US-based nationally representative time use study conducted across all seasons estimated a linear sleep reduction of 0.45 min per +1 °C [34, 67]. By comparison, a Boston-based study conducted during a summer heatwave estimated a larger sleep reduction of 2.7 min per +1 °C increase in bedroom temperature for a sample of young adults [66]. A Shanghai-based study estimated a large magnitude reduction of 5.10 min in total sleep time per +1 °C increase in bedroom night time temperature for a sample of elderly participants [78]. Again, a longitudinal study found that high nighttime bedroom temperatures above 27 °C were associated with a 15.2 min reduction in device-measured sleep duration (23.4 min reduction in self-reported sleep duration) compared to nights with temperatures below 27 °C in a small sample of young adults residing in Austin, Texas, US [86].

Similarly, effect sizes for sleep efficiency vary across studies. For example, two independent Boston-based longitudinal studies of adults [96] and children [91] across all seasons reported a significant but minor decrease of −0.02% per +1 °C increase in outdoor average daily temperature. Other studies found larger effect sizes, such as a decrease of 3.40% when hourly summer nighttime bedroom temperatures exceeded 25 °C (compared to <21 °C) in a longitudinal US study of middle-aged adults [80]; another study found that an 8 °C increase in nighttime indoor ambient temperature (from 22 to 30 °C) was associated with a 10 percentage point drop in sleep efficiency (−1.25 pct. per +1 °C) among an urban sample of older adults with a relatively high standard of living [85].

Other notable results that further contextualize the temperature-sleep relationship include (*i*) the role of seasons, (*ii*) the impact of other weather and environmental variables, (*iii*) the presence of non-linear associations between temperature and sleep, (*iv*) the potential mechanisms explaining how temperature impacts sleep, (*v*) the specific role of indoor temperature beyond outdoor temperature, and (*vi*) the role of adaptation measures.

3.3. *Seasonality*

In regards to seasonality, several studies showed that the negative impact of ambient temperature on sleep was more pronounced in the

Table 3
Methodological quality.

	Item 1: non-linearity inspected	Item 2: exposure assessed more than once	Item 3: within-participant variation analyzed	Item 4: sleep and temperatures measured over the whole year	Item 5: seasonality or day length controlled	Item 6: temporal variables controlled	Item 7: humidity controlled	Item 8: wind speed controlled	Item 9: cloud cover controlled	Item 10: precipitation controlled	Item 11: indoor and outdoor temperature measured and analyzed	Item 12: lagged temperature effects inspected	Item 13: personal cooling technologies measured and analyzed	Item 14: sleep measured with questionnaires and devices
An, 2018	0	1	1	0	0	0	0	1	0	1	0	0	0	0
Bai, 2023	1	0	0	1	0	0	1	0	0	0	0	1	0	0
Baniassadi, 2023	1	1	1	1	1	1	1	0	0	0	0	0	0	0
Basner, 2023	1	1	1	0	0	1	1	0	0	0	0	0	1	1
Cassol, 2012	0	0	0	1	1	0	0	0	0	0	0	0	0	0
Cedeño L, 2018	0	1	1	0	0	0	0	0	0	0	0	0	1	0
Cepeda, 2018	0	1	1	1	1	1	0	0	0	0	0	0	0	0
Ferguson, 2023	1	1	1	1	0	0	0	1	1	1	0	0	0	0
Fritz, 2022	0	1	0	0	0	0	0	0	0	0	0	0	0	1
Guo, 2023	0	1	0	0	0	0	1	0	0	0	0	0	0	1
Hailemariam, 2023	1	1	1	0	1	1	0	0	0	0	0	0	0	0
Hashizaki, 2018	1	1	1	1	1	1	0	0	0	0	0	0	0	0
Hou, 2023	1	1	1	1	1	1	1	1	0	1	0	0	0	0
Lappharat, 2018	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Li, 2020	1	1	1	1	0	1	0	0	0	0	0	1	0	1
Liu, 2022	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Mattingly, 2021	0	1	1	1	1	0	1	1	1	0	0	0	0	0
Milando, 2022	0	1	0	0	0	1	0	0	0	0	0	0	0	1
Minor, 2022	1	1	1	1	1	1	1	1	1	1	0	1	0	0
Montmayeur, 1992	0	1	0	0	0	0	0	0	0	0	0	1	0	0
Mullins, 2019	1	0	0	1	1	1	1	0	0	1	0	0	0	0
Obradovich, 2017	1	0	0	1	1	1	1	0	1	1	0	0	0	0
Ohnaka, 1995	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Okamoto M, 2010	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Pandey, 2005	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Quante, 2017	1	0	0	1	1	0	0	1	0	1	0	0	0	1
Quinn, 2016	0	1	1	1	0	0	0	0	0	0	0	0	0	0
Tsuzuki, 2015	0	1	0	1	0	0	0	0	0	0	0	0	0	1
Van Loenhout, 2016	0	1	1	0	0	0	0	0	0	0	1	0	0	0
Wang, 2022	1	1	1	0	1	1	1	1	0	1	0	1	1	0
Weinreich, 2015	1	0	0	0	1	0	1	0	0	0	0	1	0	0
Williams, 2019	1	1	1	0	0	0	0	0	0	0	0	0	1	1
Xiong, 2020	0	1	0	0	0	0	0	0	0	0	0	0	0	1
Xu, 2021	0	1	0	0	0	0	1	0	0	0	0	0	0	1
Yan, 2022	0	1	0	0	0	0	1	0	0	0	0	0	1	1
Zanobetti, 2009	0	0	0	1	1	0	1	1	1	1	0	0	0	0

hottest months of the year [24,33,63,79,93,94], although one study failed to replicate this effect [87]. A study conducted in the Netherlands highlighted that the seasonality of sleep duration – with people sleeping less during summer and more during winter – appeared to be mainly driven by ambient temperature (i.e., the percentage of variance explained by seasons decreased significantly when temperature was controlled for) [92]. However, another study conducted across the US, found that seasons and day length were the only significant variables associated with sleep duration over 3 principal components mainly representing temperature, wind, humidity and cloud coverage (all of these derived components were not significantly associated with sleep duration) [71]. However, all subjects in this last study were information technology workers working in thermally controlled indoor offices, potentially buffering against outdoor thermal exposures.

3.4. Effect modification with other weather variables

Other weather outcomes such as humidity, precipitation, cloud cover or wind speed were included as control variables in several studies [24,34,71,75]. In the largest device-based study included in this review [24], authors showed that (*i*) the impact of temperature on sleep duration was independent from other weather variables and that (*ii*) higher levels of precipitation, wind speed and cloud coverage marginally increase sleep duration while both low and high levels of relative humidity significantly reduce sleep duration. Additionally, high diurnal temperature range (the difference between daily maximum and minimum temperature) further reduced sleep duration, albeit to a lesser degree than high night-time temperature [24]. A separate single-location device-based study found an inverse U-shape relationship between bedroom relative humidity and elderly sleep efficiency [85]. Concerning humidity specifically, several experimental studies previously showed that the combination of high levels of indoor humidity and heat create the worst conditions for sleep [32,97]. At high ambient temperature, high levels of humidity compromise the body's evaporative cooling thermoregulatory response and thus increase the risk of heat stress and hyperthermia, possibly challenging the nocturnal core body temperature decline [49]. Although evidence remains sparse, one article included in our review investigated the combined effect of heat and relative humidity on sleep, finding that higher heat index values progressively reduced sleep duration [24].

3.5. Functional form of the temperature-sleep association

Regarding the functional forms that the temperature-sleep association may take, most studies assumed a linear response but several studies found non-linear associations (see Table 3). For example, one global-scale study observed a monotonic decline in sleep duration as night-time temperature increased, but uncovered an inflection point (i.e., a steeper decline) at 10 °C, with progressively larger effects at higher temperatures [24]. Interestingly, the same study found that the marginal effect of ambient temperature on sleep loss was over twice as large in the warmest climate regions compared to the coldest areas, consistent with the kinked functional form identified. A second study found a U-shaped association between nighttime temperature and wake after sleep onset, as well as an inverse U-shaped functional form for sleep efficiency, with the lowest level of wake after sleep onset and higher sleep efficiency in the range 10–15 °C [63]. By comparison, a single-city longitudinal analysis later identified an inverse U-shaped relation between indoor ambient temperature and sleep efficiency and a U-shaped relation with sleep restlessness (ratio of time spent tossing and turning to time spent asleep), with the highest sleep efficiency for older adults evident in the indoor temperature range of 20–25 °C [85].

3.6. Potential mechanisms

Several researchers have discussed putative causal mechanisms linking temperature and sleep or the role of sleep as a mediator of the association between heat and other health and behavioral outcomes [14,15,98,99], although evidence remains limited in this regard. Two studies inferred that body skin temperature may be one of the mechanisms linking temperature and sleep outcomes in the elderly, with higher skin temperature associated with poorer sleep in studies conducted in Japan and China [78,97]. Two other studies investigated the interplay between temperature, sleep and mental health [34,69]. These studies proposed that sleep loss may be a plausible mechanism explaining the effect of higher temperature on mental health (i.e., emergency department visits for mental disorders, suicide attempts and depression), all of which exhibited consistent functional forms. However, the authors did not perform a formal mediation analysis to test this hypothesis, even though the second study separately showed that poor sleep experiences during the study were associated with higher self-reported depression and severe mental illness [69]. Another study showed that shorter sleep duration induced by higher temperature may be a mediating factor of the negative association between temperature and cognitive functions [66]. However, the mediation analysis was only significant for one of five cognitive outcomes assessed. The authors concluded that a small sample size precluded their analysis from yielding conclusive results about the mediating role of sleep in cognitive effects. Another study conducted primarily during winter and spring months tested the mediating role of self-reported sleep quality in the association between outdoor temperature and subjective general health in a large cohort of Australian adults; however, in this study self-reported sleep quality was not found to significantly mediate the ambient temperature-general health relationship (which the authors explain by a high penetration rate of air conditioning in their sample) [68].

However, the measurement-of-mediation approach is susceptible to likely confounding by unobserved factors that affect both the self-reported sleep quality mediator and the general health outcome [100]. None of the studies explicitly investigated whether physical activity, sedentary behavior, or dietary behaviors are involved in the temperature–sleep relationships identified. Evidence of potential effect modification by BMI and body morphological characteristics are also sparse, with one quasi-experimental study estimating that the effect of outside temperature on sleep duration was consistent across BMI subgroups [24].

3.7. Indoor and outdoor temperatures

Only two studies included in the systematic review combined measures and simultaneous analyses of indoor ambient temperature in parallel with outdoor temperature [73,77]. A first study, performed in The Netherlands, showed that outdoor temperature was no longer associated with self-reported sleep disturbances when also including indoor (bedroom) temperature in their model specification, with the latter being significantly associated with sleep disturbances [73]. Interestingly, the second study, conducted in New York, showed that indoor ambient temperature was systematically higher than outdoor temperature, even in summer and with 92 % of the sample reporting air conditioning ownership [77]. However, this study focused on the effect of indoor temperature and did not statistically control for outdoor temperature when testing the association with sleep, rendering it impossible to disentangle the effect of indoor *versus* outdoor temperature on sleep. A third study measured both indoor and outdoor temperature for elderly residents in Shanghai but only included indoor temperatures in the final analysis [78]. The range of reported indoor temperatures closely approximated the outdoor range. A separate study found greater sleep loss on days with larger diurnal temperature ranges and cumulatively larger lagged negative effects of outdoor ambient temperature on sleep loss, suggesting that interior environments may trap ambient heat and prolong temperature-related sleep loss [24].

3.8. Adaptation measures

Finally, only a minority of studies investigated behavioral or technological adaptations that might protect sleep from heat. One study, conducted in Sydney, Australia, showed that air conditioning was rarely operated compared to open windows and the use of fans, and that air conditioning did not interact with the study results showing that higher bedroom temperature was associated with poorer sleep [82]. Similarly, a separate study found that only a third of elderly participants activated their air conditioning units to cool their rooms at night [78]. Despite uniform air conditioning and fan access, higher bedroom temperatures were associated with large reductions in sleep quantity and quality. Another study showed that older adults did not report higher levels of hydration (i.e., drinking episodes) when temperature increased, suggesting that participants lacked adaptive behavioral strategies [81]. One study also investigated whether people adapt to night-time sleep impacts with compensatory sleep during the day (napping), week (catch up sleep) or across summer months (intra-annual acclimatization), but did not find any evidence of sleep adaptation [24]. This same study also found that residents already living in warmer climate regions were more affected per degree of temperature increase than those living in colder areas, suggestive of limited long-run adaptation. This may indicate an upper threshold for human physiology and appears similar to the pattern observed for the temperature-mortality relationship in Europe [45].

3.9. Narrative synthesis for available climate change projections

Two studies investigated whether warming nighttime temperatures due to climate change would increase the incidence of insufficient sleep in the future [24,33]. Obradovich et al., 2017 calculated the impact of nighttime temperature anomalies for 2050 and 2099 for the Representative Concentration Pathways “high greenhouse gas (GHG) concentration” scenario (RCP8.5; IPCC) and the United States based on a large empirical self-reported sleep dataset [33]. Assuming no further adaptation and that the same functional sleep response persists in the future climate, these authors inferred that climate change may cause between 6 and 14 additional nights of insufficient sleep per 100 individuals by 2050 and 2099, with the greatest increase in climate change-induced nights of insufficient sleep evident in areas of the western and northern United States. Assuming that future adaptation responses do not exceed those observed across the diverse global climate regions examined in the recent historical record, Minor et al., 2022 projected the impact of climate change on sleep for two scenarios: the end-of the century GHG stabilization scenario (RCP4.5) and the increasing GHG concentration scenario (RCP8.5), using empirical sleep data from 68 countries [24]. Their globally averaged, population-weighted projections indicate that by 2099, sleep loss due to non-optimal ambient temperatures might range between approximately 50 h per year in a stabilized GHG concentration scenario (RCP4.5) to 58 h under a less plausible increasing GHG scenario (RCP8.5). By the end of the century, the authors separately estimate that individuals might experience 13 (RCP4.5) to 15 (RCP8.5) excess short (<7 h) nights of sleep per person per year attributable to non-optimal ambient temperatures. These last simulations also indicate that global inequalities in the impact of climate change on sleep loss may scale with future greenhouse gas concentrations, with the warmest regions of the world disproportionately impacted. The authors reported that future sleep loss may also be larger for certain demographics that were less represented in their sample composition, referring to their subgroup analyses that found larger marginal effects for residents from lower-income countries (by a factor of approximately 3), older adults (by a factor of 2) and women (~25% higher) [24].

4. Discussion

Projection studies estimate that, with ongoing climate change, the number of nights with insufficient sleep may significantly increase by the end of the century [24,33]. Since the global prevalence of poor sleep is already high, it is crucial to develop a detailed and comprehensive understanding of the effect of temperature on sleep. The present systematic review, which includes 36 original articles, shows that higher outdoor or indoor ambient temperatures, expressed either as daily mean or nighttime temperature, are negatively associated with various sleep outcomes worldwide. This negative effect of higher ambient temperature on sleep is stronger in the warmest months of the year, among vulnerable populations, notably in the elderly, and in the warmest areas of the world. This result seems consistent across various sleep indicators including sleep quantity, quality and timing and measured via various means including questionnaires, polysomnography, research-grade or commercial activity monitors (see Table 2 and Supplementary Table 1 for a summary of the results). Although the heat-related results are in accordance with those from previous reviews focused on experimental studies manipulating indoor temperatures [26], studies investigating both cold and hot outdoor ambient temperatures have found elevated sleep duration during colder temperatures, suggesting that people may be better at adapting to low ambient temperature than to high ambient heat [24,34,74,85].

The methodological quality of most studies included in the present systematic review is relatively low (see Table 3). The current literature is notably limited by a relatively poor consideration of key potential individual, spatiotemporal and social confounders. For instance, only 42% (15/36) of the studies statistically adjusted for location-specific seasonality (see Table 3), even though seasonality is associated with changes in daylight, environmental characteristics and behaviors that may also influence or otherwise spuriously associate with sleep. Although the impact of temperature on sleep appears robust – even when controlling for other weather variables (i.e., precipitation, cloud cover, humidity, wind speed, diurnal temperature range), only few studies properly handle these covariates [24,33,34,67,69,71,72,87]. The negative association between ambient temperature and sleep also remains significant when controlling for adaptation measures such as the utilization of air conditioning, but this should also be further explored [34,72,77,78]. Additionally, only 17% (6/36) of the studies assessed the plausible lagged effects of ambient temperature conditions on sleep in addition to the contemporaneous effect (see Table 3) [24,64,70,72,90,94].

Moreover, the relative importance of indoor and outdoor ambient temperatures remains remarkably unclear and virtually unassessed. According to the only study that accounted for both measures, indoor temperature (i.e., measured in the bedroom), more than outdoor temperature, appeared to drive the relationship between ambient heat and sleep [73]. Furthermore, the evidence summarized in this review suggests that the effect size of high indoor temperature tends be markedly larger than high outdoor temperature of the same degree, suggesting that studies examining outdoor temperature and sleep relationships may indeed yield conservative estimates of the ambient heat-related sleep burden. It is worth highlighting that climate change is shifting the underlying distribution of local outdoor temperatures, yet adaptation will continue to transpire both outdoors and indoors through environmental, social and behavioral adjustments. Thus, both ambient temperature measures likely impact human sleep through potentially distinct and/or overlapping pathways that should be investigated in future research, both independently – and where possible – in combination. Similarly, it’s unclear how daytime and nighttime temperatures interact to impact sleep. To our knowledge, only one study tested this effect and found that a higher diurnal temperature range was independently associated with decreased sleep duration [24].

The quality assessment performed for this review helps to draw a set of recommendations for future studies. First, researchers and funding agencies should pursue large-scale cooperative projects leveraging repeated person-level sleep measures (including, but not limited to personal sensing technologies) and longitudinal study designs across larger, and more globally diverse populations, and for longer periods of unobtrusive observation [101]. The geographic distribution of studies conducted so far does not cover the global distribution of the human population (Figs. 2 and 3B). Drawing on these time series data, researchers should explicitly control for time-invariant between-individual differences to identify within-person temperature-sleep responses.

Second, key spatiotemporally-varying factors should be more consistently controlled in future studies, including daily precipitation, percentage of cloud cover, relative humidity, average wind speed, local climatological conditions for these meteorological variables, and potentially, other relevant ambient environmental factors (e.g., air pollution, day length, etc.) [24]. Further, for quasi-experimental study designs that seek to identify plausibly causal effects from as good as random variation in ambient temperature fluctuations in real-life environments, researchers should control for location-specific seasonality as well as socio-temporal trends by accounting for day of study-specific shocks due to calendar-induced behavioral changes and macro events that might spuriously associate with both temperature and sleep outcomes.

Third, future studies should strive to investigate the effects of indoor *versus* outdoor temperatures and diurnal *versus* nighttime temperatures on sleep [73]. Fourth, studies should consider the lagged and cumulative effects of temperature and other meteorological variables on sleep outcomes. Fifth, behavioral and technological adaptation measures should be more consistently measured and included in analyses; this includes hydration, behaviors related to sleep hygiene and the utilization of fans or air conditioners [31,66,81]. Sixth, non-linearity in the association between temperature and sleep, as well as other meteorological controls, should be systematically inspected and reported [24]. Seventh, a priority should be given to vulnerable populations who received scant attention so far, including habitants of low-income countries, individuals with low financial resources within high-income countries, women in the peripartum period [102], developing infants and children [54,91,103], residents living in the Tropics or southern hemisphere (Fig. 3B), residents living in extremely cold and hot environments (Fig. 3A), homeless and incarcerated populations with limited environmental controls, individuals with mental health disorders, and those with sleep disorders such as insomnia and restless legs syndrome [57].

Moreover, and as argued before [15,98], more mechanistic studies are still very much needed to both better understand (*i*) the potential mediators of the temperature-sleep association beyond physiological parameters (e.g., mental health) [9], and (*ii*), although not the main focus of this systematic review, the contribution of sleep issues in the pathway between ambient temperatures and health outcomes (e.g., mortality) [29,104]. Given the congruence between the recently identified temperature-sleep functional response and temperature-mental health functional forms [11,24,33,34,69,105], carefully designed field experiments that enable rigorous assessments of mediation while also experimentally shutting down other temperature-sensitive pathways are needed to inform well-targeted policy responses that bolster heat and sleep resilience. Finally, only 28% (10/36) of the studies in this review investigated temperature-sleep relationships across multiple cities or geographic regions simultaneously [24,33,34,69,71–73,79,87,94], and only one featured multiple countries [24]. Since spatial and temporal autocorrelation are likely high within regional and small area studies – likely introducing bias to results and interpretation [106] – researchers should strive to carry out research investigations and multi-country collaborations across diverse geographic regions while statistically accounting for spatially and temporally correlated errors.

4.1. Limitations

This review was subject to several limitations. First, due to the sparsity of studies per sleep outcome reviewed, variety of sleep outcomes collected, and diversity of study designs employed we were unable to conduct a meta-analysis, opting instead to perform a synthesis of results for each sleep outcome. Second, this review intentionally focused on epidemiological sleep evidence collected outside of controlled sleep laboratory environments to focus on the ecological settings and circumstances where humans interact with ambient thermal conditions in their natural environments and normal routines. Beyond providing correlational evidence, the subset of quasi-experimental studies reviewed are indicative of a causal pathway extending from high ambient temperatures to altered sleep outcomes in daily living [24,33,34,63,66–69,71,72,96]. However, despite providing useful insight about the total effect of outdoor ambient temperature on sleep outcomes, such non-mechanistic studies cannot elucidate the underlying intermediary links that make up this pathway (see for example) [26]. We outline suggestions for implicit mediation studies in the Fostering Adaptation section of this review [100].

Third, since this review focused on real-world ambient thermal exposures and in-situ sleep measurements, most studies employed sleep measurement methods other than the gold standard of polysomnography. Measures deriving from commercial monitors and actigraphs have been shown to have acceptable sensitivity but poor specificity [107–109], yet have demonstrated acceptable accuracy for sleep duration detection and in situ climate behavioral analyses [101,110]. Such mobile monitors are immune to the recall biases of self-reported sleep measures, are better suited for longitudinal in-situ measurements than polysomnography, and can further enable within-person analyses that control for all time-invariant between-individual (and between-device) differences by design. However, wearables can contribute to behavioral changes during initial use, with a recent randomized crossover trial finding that wearable use marginally improved sleep quality in the first week but did not change sleep duration [111]. Importantly, the estimated ambient heat and sleep relationships summarized here appear largely consistent across diverse modes of measurement, longer periods of observation, different sleep-tracking devices – including actigraphs, wristbands and rings – and varied study designs including longitudinal analyses and quasi-experimental studies featuring large-scale samples representing entire countries and multiple climate regions.

4.2. Fostering adaptation

Beyond observational studies, there is an urgent need for interventional studies aiming to foster heat adaptation at different levels, from interventions focused on individuals to environmental and structural modifications [112,113]. At the individual level, evidence-based sleep hygiene measures should be tested in well-designed randomized field experimental trials to see whether such behavioral measures can foster adaptation to ambient heat. This includes general sleep health measures, such as the avoidance of caffeine, nicotine, alcohol and daytime naps, stress management, sleep timing regularity, management of bedroom noise and artificial light [114]. Additionally, heat-specific behavioral adaptations should also be assessed, including cool to lukewarm showers before bedtime [115], evening sauna use and acclimatization routines [113], the use of fans (when relative humidity <30%) [31,116,117], water sprays, daytime hydration, reduced bedding, and light cotton clothing [102,118]. Traditional lifestyle interventions, such as the promotion of regular physical activity, are also crucial given the role of physical fitness towards heat adaptation [119,120]. These interventions could be implemented through traditional randomized controlled trials or using innovative designs such as just-in-time interventions using weather forecasts that might be particularly relevant for responding to heatwaves [121,122]. At the societal level, equitable adaptation should be promoted [123]. Environmental interventions such as urban greening [124], urban water features, passive cooling and improved buildings' insulation and ventilation systems should also be rigorously assessed in terms of their capacity to promote and protect sleep health and hygiene during periods of transient and sustained heat [31,125].

5. Conclusion

The present systematic review shows that higher temperatures are generally associated with worse sleep outcomes worldwide. Given the absence of solid evidence on fast sleep adaptation to heat, rising ambient temperatures induced by climate change pose a serious threat to human sleep and therefore human health, performance, and wellbeing. Although this work identified several methodological limitations of the extant literature, a strong body of higher quality evidence from both this systematic review and previous experimental studies converge on the negative impact of elevated temperatures on sleep quality and quantity. Pertinent to policymakers, planners and sleep researchers, the intensity of night-time warming is projected to continue to exceed daytime warming in most populated areas [29,126–128], while urbanization will likely further exacerbate night-time ambient heat exposure for most of humanity [129]. Even if these relationships and their associated pathways can be refined further through future well-designed observational studies as we advise here, we argue that interventional studies and field experiments are now urgently needed to foster adaptation and safeguard the essential restorative role of sleep in a hotter world.

5.1. Practice points

1) Hot outdoor as well as indoor ambient temperatures are associated with short and disrupted sleep, with higher temperatures linked to progressively larger sleep impacts.
2) Evidence from multiple geographic areas suggest that temperature increases are associated with larger sleep deficits for the elderly, those living in lower socioeconomic contexts, and for those already residing in warmer climate regions.
3) Given limited evidence of short-to-medium term sleep adaptation to warming, ongoing anthropogenic changes to the climate system and urbanization patterns will likely harm human sleep quality and quantity.
4) Both higher quality longitudinal, multi-center studies with vulnerable populations, and in-situ randomized controlled trials to assess effective adaptive interventions are needed to protect sleep from heat.

5.2. Research agenda

Future research should seek to:

1) employ repeated measures and quasi-experimental designs to estimate person-level responses to ambient temperature across the life course at the local, regional, national, and global levels.
2) assess which subpopulations are at the highest risk of experiencing adverse sleep outcomes during ambient heat exposure.
3) investigate the heat-sensitivity of sleep quality and quantity among patients with prior sleep-wake disorders.
4) test climate adaptive environmental, technological, and behavioral interventions that can break the chain between heat exposure and adverse sleep outcomes.

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Conflicts of interest

The authors do not have any conflicts of interest to disclose.

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Appendix A. Supplementary data

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